Climate Change 2014: Impacts, Adaptation, and Vulnerability

SUMMARY FOR POLICYMAKERS

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INTRODUCTION

Human interference with the climate system is occurring,[1] and climate change poses risks for human and natural systems (Figure SPM.1). The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change and how risks can be reduced through mitigation and adaptation.

Compared to past WGII reports, the WGII AR5 assesses a substantially larger knowledge base of relevant scientific, technical, and socioeconomic literature. Increased literature from all regions has facilitated comprehensive assessment across a broader set of topics and sectors, with expanded treatment of human systems, adaptation, and the ocean. [1.1, Figure 1-1]

Section A of this summary characterizes observed impacts, vulnerability and exposure, and responses to date. Section B examines the range of future risks and potential benefits. Section C considers principles for effective adaptation and the broader interactions among adaptation, mitigation, and sustainable development. Box SPM.1 defines central concepts, and Box SPM.2 introduces terms used to convey the degree of certainty in key findings. Chapter references in square brackets and in footnotes indicate support for findings, paragraphs of findings, figures, and tables in this summary.

Figure SPM.1: Climate-related hazards, exposure, and vulnerability interact to produce risk. Changes in both the climate system (left) and development processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. [19.2, Figure 19-1]

Boxes SPM.1 and SPM.2 are included at the end of the SPM text.

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

A-1. Observed Impacts, Vulnerability, and Exposure

Observed impacts of climate change are widespread and consequential. Recent changes in climate have caused impacts on natural and human systems on all continents and across the oceans.[2] Evidence of climate change impacts is strongest and most comprehensive for natural systems, although some impacts in human systems have also been attributed to climate change. See Figure SPM.2 for a summary of observed impacts and indicators of a changing climate, illustrating broader trends presented in this section.[3]

Figure SPM.2: Widespread indicators of a changing climate. (A) Global patterns of observed climate change impacts, at regional, subregional, and more local scales. For categories of attributed impacts, symbols indicate affected systems and sectors, the relative contribution of climate change (major or minor) to the observed change, and confidence in attribution. (B) Glacier mass budgets from all published measurements for Himalayan glaciers, also showing global average glacier mass budget estimates from WGI AR5 4.3 with shading indicating ±1 standard deviation. The blue box for each Himalaya measurement has a height of ±1 standard deviation centered on its average (and ±1 standard error for multi-annual measurements). Himalaya-wide measurement (red) was made by satellite laser altimetry. (C) Locations of substantial drought- and heat-induced tree mortality around the globe over 1970-2011. (D) Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900-2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given for each category. (E) Summary of estimated impacts of observed climate changes on yields over 1960-2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given for each category. [Figures 3-3, 4-7, 7-2, 18-3, and MB-2]

[1] WGI AR5 2.2, 6.3, 10.3-6, 10.9
[2] Attribution of observed impacts in the WGII AR5 links responses of natural and human systems to climate change, not to anthropogenic climate change, unless explicitly indicated.
[3] 18.1, 18.3-6

In response to ongoing climate change, terrestrial and marine species have shifted their ranges, seasonal activities, migration patterns, and abundance, and have demonstrated altered species interactions (*high confidence*). Increased tree mortality, observed in many places worldwide, has been attributed to climate change in some regions. While recent warming contributed to the extinction of many species of Central American amphibians (*medium confidence*), most recent observed terrestrial-species extinctions have not been attributed to recent climate change, despite some speculative efforts (*high confidence*). Natural climate change at rates much slower than current anthropogenic change has led to significant ecosystem shifts, including species emergences and extinctions, in the past millions of years.[4]

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources and quality (*medium confidence*). Glaciers continue to shrink in many regions due to climate change (*high confidence*). Climate change has caused permafrost warming and thawing in high-latitude and high-elevation mountain regions.[5]

Negative impacts of climate change on crop and terrestrial food production have been more common than positive impacts, which are evident in some high-latitude regions (*high confidence*). Recent periods of rapid food and cereal price increases have indicated that current markets in key producing regions are sensitive to climate extremes.[6]

In recent decades, climate change has *likely* contributed to human ill-health although the present world-wide burden of ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. There has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*).[7]

Vulnerability and exposure

Differences in vulnerability and exposure arise from non-climatic stressors and multidimensional inequalities, which shape differential risks from climate change (*very high confidence*). See Box SPM.3.[8]

Impacts from recent extreme climatic events, such as heat waves, droughts, floods, and wildfires, demonstrate significant vulnerability and exposure of some ecosystems and many human systems to climate variability (*very high confidence*). These experiences are consistent with a significant adaptation deficit in developing and developed countries for some sectors and regions.[9]

Climate-related hazards constitute an additional burden to people living in poverty, acting as a threat multiplier often with negative outcomes for livelihoods (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, such as reductions in crop yields or destruction of homes, and indirectly through increased food prices and food insecurity. Limited positive observed impacts on poor people include isolated cases of social asset accumulation, agricultural diversification, disaster preparedness, and collective action.[10]

Violent conflict strongly influences vulnerability to climate change impacts for people living in affected places (*medium evidence, high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural capital, social capital, and livelihood opportunities.[11]

Box SPM.3. Multidimensional Inequality and Vulnerability to Climate Change

[4] 4.2-4, 5.3-5, 6.1, 6.3-5, 18.3, 18.5, 22.3, 24.4, 25.6, 28.2, 30.4-5, Boxes 4-2, 4-3, 25-3, CC-CR, and CC-MB
[5] 3.2, 4.3, 18.3, 18.5, 24.4, 26.2, 28.2, Tables 3-1 and 25-1, Figures 18-2 and 26-1
[6] 7.3, 18.4, 22.3, 24.4, 26.5, Figures 7-2, 7-3, and 7-7
[7] 11.4-6, 18.4, 22.3, 24.4, 25.8, 26.6, 28.2
[8] 8.2, 9.3, 12.2, 13.1-2, 14.1-3, 19.6, 26.8, Box CC-GC
[9] 3.2, 4.2-3, 8.1, 9.3, 10.7, 11.3, 11.7, 13.2, 14.1, 18.6, 22.3, 25.6-8, 26.6-7, 28.4, 30.5, 30.7, Tables 18-3 and 23-1, Figure 26-2, Boxes 4-3, 4-4, 25-5, 25-6, 25-8, and CC-CR
[10] 8.2-3, 9.3, 11.3, 13.1-3, 22.3, 24.4, 26.8
[11] 12.5, 19.4, 19.6

People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized are often highly vulnerable to climate change and climate change responses (*medium evidence*, *high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socioeconomic status, income, and exposure, including, for example, discrimination on the basis of gender, class, ethnicity, age, and (dis)ability. The full spectrum of these processes and their context-specific interactions shape multidimensional vulnerability and differential capacities and opportunities of individuals, households, and communities.[12]

A-2. Adaptation Experience

Adaptive human responses can be motivated by observed and projected climate change impacts and by broader vulnerability-reduction and development objectives.

Adaptation is already occurring and is becoming embedded in some planning processes (*high confidence*). Engineered and technological adaptation options are the most commonly implemented adaptive responses. There is increasing recognition of the value of ecosystem-based, institutional, and social measures, including provision of social protection measures, and of linkages with disaster risk reduction. Selection of adaptation options continues to emphasize incremental adjustments and co-benefits and is starting to emphasize flexibility and learning (*medium evidence, medium agreement*). Most evaluations of adaptation have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or actual adaptation actions (*medium evidence, high agreement*).[13]

Governments at various scales are starting to develop adaptation plans and policies, and adaptation experience is accumulating across regions (*high confidence*).

- In Africa, most national governments are initiating governance systems for adaptation, and in predominantly isolated efforts, disaster risk management, adjustments in technologies and infrastructure, ecosystem-based approaches, conservation agriculture, and livelihood diversification are reducing vulnerability.[14]
- In Europe, adaptation policy has been developed across scales, with some adaptation planning integrated into coastal and water management and into disaster risk management.[15]
- In Asia, adaptation practices have sometimes provided livelihood benefits, and adaptation has been facilitated through integrated water resource management.[16]
- In Australasia, planning for sea-level rise and, in southern Australia, for reduced water availability is becoming widely adopted, although implementation faces major constraints, especially for transformational responses at local and community levels.[17]
- In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level, with some proactive adaptation anticipating future impacts for longer-term investments in energy and public infrastructure.[18]
- In Central and South America, ecosystem-based adaptation including protected areas, conservation agreements, and community management of natural areas is increasingly common, with benefits for improvements in livelihoods and preservation of traditional cultures.[19]
- In the Arctic, residents have a history of adapting to change, but the rate of climate change and complex inter-linkages with societal, economic, and political factors represent unprecedented challenges for northern communities.[20]
- In small islands, diverse physical and human attributes and their sensitivity to climate-related drivers have been inconsistently integrated into adaptation planning.[21]

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[12] 8.1-2, 8.5, 9.3-4, 10.9, 11.1, 11.3-5, 12.2-5, 13.2-3, 14.6, 18.4, 19.6, 23.5, 25.8, 26.6, 26.8, 28.4, Box CC-GC
[13] 4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3-4, 15.2-4, 17.2-3, 21.3, 21.5, 22.3-5, 23.7, 25.4, 26.8-9, 30.6, Boxes 25-1, 25-2, 25-9, and CC-EA
[14] 11.7, 22.4, Box CC-EA
[15] 11.7, 23.7, Box 23-3
[16] 11.7, 24.4
[17] 25.4, 25.10, Table 25-2, Boxes 25-1, 25-2, and 25-9
[18] 26.7-9
[19] 27.3
[20] 28.2, 28.4
[21] Table 29-3, Figure 29-1

A-3. The Decision-making Context

Responding to climate-related risks involves making decisions and taking actions in the face of continuing uncertainty about the extent of climate change and the severity of impacts in a changing world, with potential limits to the effectiveness of incremental approaches (*high confidence*). Iterative risk management is a useful framework for decision-making in situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple influences changing over time, such as climate and non-climatic stressors. See Figure SPM.3. Assessment of the full range of potential future impacts, including low-probability outcomes with large consequences, is central to understanding future risks and the benefits and tradeoffs of alternative risk management actions. The increasing complexity of adaptation actions across scales and contexts means that institutional learning and monitoring are important components of effective adaptation.[22]

Figure SPM.3: Illustration of iterative risk management. [Figure 2-1]

The benefits of mitigation and adaptation occur over different timeframes (*high confidence*). Figure SPM.4 illustrates projected climate futures under scenarios RCP2.6 and 8.5, along with observed temperature changes. Projected global temperature increase over the next few decades is similar across emission scenarios (Figure SPM.4B).[23] During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. Societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increase diverges across emission scenarios (Figure SPM.4B and 4C).[24] For this longer-term era of climate options, near-term and longer-term mitigation and adaptation, as well as development pathways, will determine the risks of climate change. Near-term choices thus affect the risks of climate change throughout the 21st century.[25]

Figure SPM.4: Observed and projected changes in annual average temperature. (A) Observed temperature trends from 1901-2012 determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. Observed data (range of grid-point values: -0.53 to 2.50°C over period) are from WGI AR5 Figures SPM.1 and 2.21. (B) Observed and simulated variations in past and projected future global annual average temperature relative to 1986-2005. Black lines show the GISTEMP, NCDC-MLOST, and HadCRUT4.2 estimates from observational measurements. Blue and red shading denotes the ±1.64 standard deviation range based on simulations from 32 models for RCP2.6 and 39 models for RCP8.5; blue and red lines denote the ensemble mean for each scenario. For future projections, light-gray vertical bands specify an indicative timeframe (2030-2040) for the near-term era of committed climate change and an indicative timeframe (2080-2100) for the longer-term era of climate options. [Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7] (C) CMIP5 multi-model mean projections of annual average temperature changes for 2081-2100 under RCP2.6 and 8.5, relative to 1986-2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data (range of grid-point values across RCP2.6 and 8.5: 0.06 to 11.71°C) from WGI AR5 Figure SPM.8, with full description of methods in Box CC-RC. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]

Adaptation planning and implementation at a range of scales are contingent on values, objectives, and risk perceptions (*high confidence*). Some types of adaptation options, such as insurance or large-scale infrastructure

[22] 2.1-4, 3.6, 14.1-3, 15.2-3, 15.5, 16.2-4, 17.2, 20.6, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1 and 25-2
[23] WGI AR5 11.3
[24] WGI AR5 12.4 and Table SPM.2
[25] 2.5, 21.2-3, 21.5, Box CC-RC

projects, may differentially affect stakeholders. Recognition of diverse interests, values, and expectations, including local and indigenous knowledge, can benefit decision-making processes.[26]

Decision support is most effective when it is sensitive to context, taking into account the diversity of different types of decisions, decision processes, and constituencies (*robust evidence, high agreement*). Organizations bridging science and policy play an important role in the communication and transfer of climate-related knowledge, such as information on risks combining physical climate science and assessments of impacts, adaptation, and vulnerability (*medium evidence, high agreement*).[27]

Scenarios are useful tools for characterizing possible future socioeconomic pathways, climate change and its risks, and policy implications (*high confidence*). Climate change risks vary substantially across plausible alternative development pathways, and the relative importance of development and climate change varies by sector, region, and time period. Both development and climate change are important determinants of possible outcomes. Modeled future impacts assessed in this report are generally based on climate-model projections using the Representative Concentration Pathway (RCP) and the older IPCC Special Report on Emission Scenarios (SRES) scenarios.[28]

Uncertainties about future vulnerability, exposure, and responses of human and natural systems can be larger than uncertainties in regional climate projections, and they are beginning to be incorporated in assessments of future risks (*high confidence*). Understanding future vulnerability, as well as exposure, of interlinked human and natural systems is challenging due to the number of relevant socioeconomic factors, which have been incompletely considered to date. These factors include wealth and its distribution across society, patterns of aging, access to technology and information, labor force participation, the quality of adaptive responses, societal values, and mechanisms and institutions to resolve conflicts. Cross-regional phenomena are also important for understanding the ramifications of climate change at regional scales.[29]

B) FUTURE RISKS AND OPPORTUNITIES FOR ADAPTATION

This section presents future risks and more limited potential benefits across sectors and regions, examining how they are affected by the magnitude and rate of climate change and by development choices. It also points to opportunities for reducing risks through mitigation and adaptation. The section describes risks and potential benefits over the next few decades, the near-term era of committed climate change, and in the second half of the 21st century and beyond, the longer-term era of climate options.

B-1. Key Risks across Sectors and Regions

Many risks of climate change warrant consideration. Key risks, in particular, are potentially severe impacts relevant to “dangerous anthropogenic interference with the climate system,” as described in Article 2 of the United Nations Framework Convention on Climate Change. Key risks can involve potentially large or irreversible consequences, high probability of consequences, and/or limited adaptive capacity. Key risks are integrated into five overarching reasons for concern (RFCs) in Box SPM.4.

Key risks that span sectors and regions (*high confidence*) include the following, each of which contributes to one or more RFC.[30]

i. Risk of death, injury, and disrupted livelihoods in low-lying coastal zones and small island developing states, due to sea-level rise, coastal flooding, and storm surges.[31] [RFC 1-5]
ii. Risk of food insecurity linked to warming, drought, and precipitation variability, particularly for poorer populations.[32] [RFC 2-4]

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[26] 2.2-4, 12.3, 15.2, 16.2-4, 16.5-7, 17.2-3, 21.3, 22.4, 25.4, 25.8, 26.7, 26.9, 28.2, 28.4, Table 15-1, Boxes 16-1, 16-4, and 25-7
[27] 2.1-4, 8.4, 14.4, 16.2-3, 16.5, 21.2-3, 21.5, 22.4, Box 9-4
[28] 1.1, 1.3, 2.2-3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC; WGI AR5 Box SPM.1
[29] 11.3, 21.3-5, 25.3-4, 25.11, 26.2
[30] 19.2-4, 19.6, Table 19-4, Boxes 19-2 and CC-KR
[31] 5.4, 8.1-2, 13.1-2, 19.2-4, 19.6-7, 24.4-5, 26.7-8, 29.3, 30.3, Tables 19-4 and 26-1, Figures 7-4 and 26-2, Boxes 25-1, 25-7, and CC-KR
[32] 3.5, 7.4-5, 11.3, 11.6, 13.2, 19.3-4, 19.6, 22.3, 24.4, 25.5, 25.7, 26.5, 26.8, 27.3, Table 19-4, Boxes CC-KR and CC-VW

iii. Risk of severe harm for large urban populations due to inland flooding.[33] [RFC 2 and 3]
iv. Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions.[34] [RFC 2 and 3]
v. Systemic risks due to extreme events leading to breakdown of infrastructure networks and critical services.[35] [RFC 2-4]
vi. Risk of loss of marine ecosystems and the services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic.[36] [RFC 1-5]
vii. Risk of loss of terrestrial ecosystems and the services they provide for terrestrial livelihoods.[37] [RFC 1, 3, and 4]
viii. Risk of mortality, morbidity, and other harms during periods of extreme heat, particularly for vulnerable urban populations.[38] [RFC 2 and 3]

Mitigation of greenhouse gas emissions over the next few decades can substantially reduce risks of climate change in the second half of the 21st century (*high confidence*). Examples include reduced risk of negative agricultural yield impacts, of water scarcity, of major challenges to urban settlements and infrastructure from sea-level rise, and of adverse impacts from heat extremes, floods, and droughts in areas where increased occurrence of these extremes are projected. Under all assessed scenarios for mitigation and adaptation, some risk from residual damages is unavoidable (*very high confidence*).[39]

Large magnitudes of warming increase the likelihood of severe, pervasive, and challenging impacts. Risks associated with global temperature rise in excess of 4°C relative to preindustrial levels include potential adverse impacts on agricultural production worldwide, potentially extensive ecosystem impacts, and increasing species extinction risk (*high confidence*), as well as possible crossing of thresholds that lead to disproportionately large earth system responses (*low confidence*). The precise levels of climate change sufficient to trigger tipping points (critical thresholds) remain uncertain, but the likelihood of crossing tipping points in the earth system or interlinked human and natural systems decreases with reduced greenhouse gas emissions (*medium confidence*).[40]

Box SPM.4. Human Interference with the Climate System

Human interference with the climate system is occurring, yet determining whether this interference is dangerous, as relevant to Article 2 of the UNFCCC, involves both risk assessment and value judgments. This report assesses risks across contexts and through time, providing a basis for value judgments about the level of climate change at which risks become dangerous.

Five integrative reasons for concern (RFCs) provide a framework for summarizing key risks across sectors and regions. First identified in the IPCC Third Assessment Report, the reasons for concern illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. An updated assessment of risks for each reason for concern is presented below and in Box SPM.4 Figure 1. All temperature changes are given relative to 1986-2005 ("recent").[41]

(1) ***Unique and threatened systems:*** Some unique and threatened systems, including ecosystems and cultures, are at risk from climate change at recent temperatures. The number of such systems at risk of severe consequences increases at warming of 1°C. Many species and systems with limited adaptive capacity are subject to very high risks at warming of 2°C, particularly Arctic sea ice systems and coral reefs (*high confidence*).

(2) ***Extreme weather events:*** Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are moderate at recent temperatures (*high confidence*) and high at 1°C warming (*medium confidence*).

[33] 3.2, 3.4-5, 8.1-2, 13.2, 19.6, 25.10, 26.3, 26.7-8, 27.3, Tables 19-4 and 26-1, Boxes 25-8 and CC-KR
[34] 3.2, 3.4-5, 8.2, 9.3, 12.2, 13.2, 19.3, 19.6, 24.4, 25.7, 26.8, Table 19-4, Boxes 25-5 and CC-KR
[35] 8.1-2, 10.2-3, 12.6, 19.6, 23.9, 25.10, 26.7-8, 28.3, Table 19-4, Boxes CC-KR and CC-HS
[36] 5.4, 6.3, 7.4, 9.3, 19.5-6, 22.3, 25.6, 27.3, 28.2-3, 29.3, 30.5-7, Table 19-4, Boxes CC-OA, CC-CR, CC-KR, and CC-HS
[37] 4.3, 19.3-6, 22.3, 25.6, 27.3, 28.2-3, Tables 19-4 and 23-2, Boxes CC-KR and CC-WE
[38] 8.1-2, 11.3-4, 13.2, 19.3, 19.6, 23.5, 24.4, 25.8, 26.6, 26.8, Tables 19-4 and 26-1, Boxes CC-KR and CC-HS
[39] 3.4-5, 16.3, 16.6, 17.2, 19.7, 20.3, 25.10, Tables 3-2, 8-3, and 8-5, Boxes 13-2, 16-3, and 25-1
[40] 4.2-3, 11.8, 19.5, 19.7, 26.5, Box CC-HS
[41] 18.6, 19.6

(3) ***Distribution of impacts:*** Risks for disproportionately affected people and communities are generally greatest in low-latitude, less-developed areas, and are moderate at recent temperatures because of regionally differentiated climate-change impacts on food production (*medium* to *high confidence*). Developed countries also have highly vulnerable populations. Based on risks for regional crop production and water resources in some countries, risks become high for warming above 2°C (*medium confidence*).

(4) ***Global aggregate impacts:*** Risks to the overall global economy and Earth's biodiversity become moderate for warming between 1-2°C (*medium confidence*) and high around 3°C, reflecting warming-dependent increases in risks of economic impacts (*low confidence*) and extensive biodiversity loss with concomitant loss of ecosystem services (*high confidence*).

(5) ***Large-scale singular events:*** With increasing warming, some physical systems or ecosystems may be at risk of abrupt and drastic changes. Risks of such tipping points become moderate between 0-1°C, due to early warning signs that both coral reef and Arctic systems are already experiencing irreversible regime shifts. Risks become high between 1-4°C, with a disproportionate increase in risks as temperature increases between 1-2°C, due to the potential for commitment to a large and irreversible sea-level rise from ice sheet loss (*medium confidence*).

Box SPM.4 Figure 1: (Right panel) The dependence of risks associated with reasons for concern on the level of climate change, updated based on assessment of the literature and expert judgments. Purple shading, introduced in this assessment, indicates very high risk of severe impacts and the presence of significant irreversibilities combined with limited adaptive capacity. [Figure 19-4] (Left panel) Observed and simulated variations in past and projected future global annual average temperature relative to 1986-2005, as in Figure SPM.4. [Figure RC-1, Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7]

B-2. Sectoral Risks and Potential for Adaptation

Climate change will amplify climate-related risks to natural and human systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change will also reduce some climate-related risks and have some potential benefits.

Freshwater resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas emissions (*robust evidence, high agreement*). By the end of the 21st century, the number of people exposed annually to a 20th-century 100-year river flood is projected to be three times greater for RCP8.5 than for RCP2.6. In presently dry regions, drought frequency will *likely* increase by the end of this century under RCP8.5 (*medium confidence*).[42]

Climate change will reduce renewable surface water and groundwater resources significantly in most dry subtropical regions, exacerbating competition for water among sectors (*robust evidence, high agreement*). In contrast, water resources will increase at high latitudes. Each degree of warming is projected to decrease renewable water resources by at least 20% for an additional 7% of the global population. Climate change is projected to reduce raw water quality and pose risks to drinking water quality, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; reduced dilution of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence, high agreement*). Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can address uncertainty due to climate change (*limited evidence, high agreement*).[43]

Terrestrial and freshwater ecosystems

A large fraction of terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, over-exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-

[42] 3.4-5, 26.3, Tables 3-2 and 25-1, Box 25-8; WGI AR5 12.4
[43] 3.2, 3.4-6, 22.3, 25.5, 26.3, Table 3-2, Boxes 25-2 and CC-WE

range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) (*medium confidence*). See Figure SPM.5. Management actions can reduce, but not eliminate, risks to ecosystems and can increase ecosystem adaptability, for example through reduction of other stresses and habitat fragmentation, maintenance of genetic diversity, assisted translocation, and manipulation of disturbance regimes (*high confidence*).[44]

Within this century, magnitudes and rates of climate change associated with RCP4.5, 6.0, and 8.5 pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the boreal-tundra Arctic system and the Amazon forest, leading to substantial additional climate change (*medium confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation (*high confidence*). Tree mortality and associated forest dieback will occur in many regions in the next one to three decades (*medium confidence*), with forest dieback posing risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity.[45]

Figure SPM.5: Rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention, indicating climate velocities for temperature. White boxes with black bars indicate medians and ranges of observed rates of displacement for trees, plants, mammals, birds, plant-feeding insects, and freshwater mollusks. For RCP2.6, 4.5, 6.0, and 8.5 for 2050-2090, horizontal lines show climate velocity for the global-land-area average and for large flat regions. Species groups with displacement rates below each line are projected to be unable to track climate in the absence of human intervention. [Figure 4-5]

Coastal systems and low-lying areas

Due to sea-level rise throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*).[46]

By 2100, due to climate change and development patterns and without adaptation, hundreds of millions of people will be affected by coastal flooding and displaced due to land loss (*high confidence*). The majority affected will be in East, Southeast, and South Asia. The relative costs of adaptation vary strongly among and within regions and countries for the 21st century (*high confidence*). Some low-lying developing countries and small island states are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of GDP.[47]

Marine systems

By mid 21st century, spatial shifts of marine species will cause species richness to increase at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium confidence*). See Figure SPM.6A. Animal displacements are projected to lead to high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas. Open-ocean net primary production is projected to redistribute and to fall globally by 2100 under RCP8.5. Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*).[48]

Ocean acidification poses risks to ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species (*medium* to *high confidence*). Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potential consequences for fisheries and livelihoods. See Figure SPM.6B. Ocean acidification occurs in combination with other environmental changes, both globally (e.g.,

[44] 4.3-4, 25.6, 26.4, Box CC-RF
[45] 4.2-3, 25.6, Figure 4-8, Boxes 4-2, 4-3, and 4-4
[46] 5.3-5, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1
[47] 5.3-5, 24.4
[48] 6.3-5, 7.4, 25.6, 28.3, 30.6-7, Boxes CC-MB and CC-PP

warming, decreasing oxygen levels) and locally (e.g., pollution, eutrophication) (*high confidence*). Simultaneous environmental drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species.[49]

Figure SPM.6: Climate change risks for fisheries. (A) For 2°C increase from preindustrial levels using SRES A1B (≈RCP6.0), projected global redistribution of maximum catch potential of 1000 species of exploited fishes and invertebrates, comparing the 10-year averages 2001-2010 and 2051-2060, without analysis of potential impacts of overfishing. (B) Marine mollusk and crustacean fisheries (estimated catch rates ≥0.005 tonnes per sq. km) and known locations of warm- and cold-water corals, depicted on a global map showing the distribution of ocean acidification in 2100 under RCP8.5. [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across corals, mollusks, and crustaceans, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each pCO_2 category are as follows: RCP4.5 for 500-650 μatm, RCP6.0 for 651-850 μatm, and RCP8.5 for 851-1370 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]

Food production systems and food security

Without adaptation, local temperature increases of 1°C or more above preindustrial levels are projected to negatively impact yields for the major crops (wheat, rice, and maize) in tropical and temperate regions, although individual locations may benefit (*medium confidence*). With or without adaptation, climate change will reduce median yields by 0 to 2% per decade for the rest of the century, as compared to a baseline without climate change. These projected impacts will occur in the context of rising crop demand, projected to increase by about 14% per decade until 2050. See Figure SPM.7 for a summary of projected changes in crop yields over the 21st century. Risks are greatest for tropical countries, given projected impacts that exceed adaptive capacity and higher poverty rates compared with temperate regions. Climate change will progressively increase inter-annual variability of crop yields in many regions.[50]

On average, adaptation improves yields by the equivalent of ~15-18% of current yields, but the effectiveness of adaptation is highly variable (*medium confidence*). Positive and negative yield impacts projected for local temperature increases of about 2°C above preindustrial levels maintain possibilities for effective adaptation in crop production (*high confidence*). For local warming of about 4°C or more, differences between crop production and population-driven demand will become increasingly large in many regions, posing significant risks to food security even with adaptation.[51]

Figure SPM.7: Summary of projected changes in crop yield as a function of time with and without adaptation, across studies for all regions. Data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. [Figure 7-5]

Urban areas

Heat stress, extreme precipitation, inland and coastal flooding, and drought and water scarcity pose risks in urban areas for people, assets, economies, and ecosystems, with risks amplified for those lacking essential infrastructure and services or living in exposed areas (*very high confidence*). Reducing basic service deficits and building resilient infrastructure systems could significantly reduce exposure and vulnerability in cities and urban areas. Urban adaptation benefits from effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, appropriate financing and institutional development, and increased capacity of low-income groups and vulnerable communities and their partnerships with local governments (*medium confidence*).[52]

Rural areas

[49] 5.4, 6.3, 6.5, 22.3, 25.6, 28.3, 30.5, Boxes CC-CR, CC-OA, and TS.7
[50] 7.4, 22.3, 24.4, 25.7, 26.5, Figures 7-4, 7-5, 7-6, and 7-7
[51] 7.5, 22.3, 25.7, 26.5, Tables 7-2 and 11-3, Figures 7-4, 7-5, 7-7, and 7-8
[52] 3.5, 8.2-4, 22.3, 24.4-5, 26.8, Boxes 25-9 and CC-HS

Major future rural impacts will be felt in the near-term and beyond through impacts on water supply, food security, and agricultural incomes, including shifts in production of food and non-food crops in many areas of the world (*high confidence*). Price rises, which may be induced by climate shocks as well as other factors, have a disproportionate impact on the welfare of the poor in rural areas, such as female-headed households and those with limited access to modern agricultural inputs, infrastructure, and education. Options exist for adaptations within international agricultural trade (*medium confidence*).[53]

Key economic sectors and services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance will be large relative to the impacts of climate change (*medium evidence, high agreement*). Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence, high agreement*). Climate change will affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More frequent and/or severe weather disasters for some regions and/or hazards will increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation.[54]

Global mean temperature increase of 2.5°C above preindustrial levels may lead to global aggregate economic losses between 0.2 and 2.0% of income (*medium evidence, medium agreement*). Losses increase with greater warming, but little is known about aggregate economic impacts above 3°C. Impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable, and aggregate impacts hide large differences between and within countries. The incremental economic impact of emitting a tonne of carbon dioxide lies between a few dollars and several hundreds of dollars per tonne of carbon (*robust evidence, medium agreement*). Estimates vary strongly with the assumed discount rate, with larger ranges for lower discount rates.[55]

Human health

Until mid-century, climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*), and climate change throughout the 21st century will lead to increases in ill-health in many regions, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires; increased likelihood of under-nutrition resulting from diminished food production in poor regions; risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases. Positive effects will include modest improvements in cold-related mortality and morbidity in some areas due to fewer cold extremes, shifts in food production, and reduced capacity of disease-carrying vectors (*medium confidence*), but globally, positive impacts will be outweighed by the magnitude and severity of negative impacts (*high confidence*). The most effective adaptation measures for health in the near-term are programs that implement basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). For RCP8.5 by 2100, the combination of high temperature and humidity in some areas for parts of the year will compromise normal human activities, including growing food or working outdoors (*high confidence*).[56]

Human security

Climate change over the 21st century will have significant impacts on forms of migration that compromise human security (*medium evidence, high agreement*). Populations that lack the resources for mobility and

[53] 9.3, 25.9, 26.8, Box 25-5
[54] 3.5, 10.2, 10.7, 10.10, 25.7, 26.7, Box 25-7
[55] 10.9
[56] 8.2, 11.3-8, 19.3, 22.3, 25.8, 26.6, Figure 25-5, Box CC-HS

migration often experience higher exposure to weather-related extremes, in both rural and urban areas, particularly in low-income countries. Expanding opportunities for mobility can reduce vulnerability, but altered migration flows can also create risks as well as potential benefits for migrants and for sending and receiving regions and states.[57]

Climate change indirectly increases risks from violent conflict in the form of civil war, inter-group violence, and violent protests by exacerbating well-established drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Statistical studies show that climate variability is significantly related to these forms of conflict. Poorly designed adaptation and mitigation strategies can increase risks from violent conflict.[58]

Climate change over the 21st century will lead to new challenges to states and will increasingly shape national security policies (*medium evidence, medium agreement*). Small-island states and other states highly vulnerable to sea-level rise face major challenges to their territorial integrity. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and migration of fish stocks, have the potential to increase rivalry among states. The presence of robust institutions can manage many of these rivalries to reduce conflict risks.[59]

Livelihoods and poverty

Throughout the 21st century, climate change impacts will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate change will exacerbate poverty in low and lower-middle income countries and create new poverty pockets in upper-middle- to high-income countries with increasing inequality. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food will be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk management may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty.[60]

B-3. Regional Key Risks and Potential for Adaptation

Risks will vary across regions and populations, through space and time, dependent on myriad factors including the extent of mitigation and adaptation. Key regional risks identified with *medium* to *high confidence* are presented in Table SPM.1. Projected changes in climate and increasing atmospheric CO_2 will have positive effects for some sectors in some locations. For extended summary of regional risks and the more limited potential benefits, see Technical Summary section B-3 and Chapters 21-30.

Table SPM.1: Key regional risks from climate change and the potential for reducing risks through mitigation and adaptation. Risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature, as detailed in supporting chapter sections. Each key risk is characterized as very low to very high for three timeframes: the present, near-term (here, assessed over 2030-2040), and longer-term (here, assessed over 2080-2100). Assessed risk levels integrate probability and consequence over the full range of possible outcomes, acknowledging the importance of differences in values and objectives in interpretation of the assessed risk levels. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels, illustrating the potential role of mitigation in reducing risks. For the present, risk levels are estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the future, risk levels are estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Relevant climate variables are indicated by icons. Risk levels are not necessarily comparable, especially across regions, because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse regional contexts.

[57] 9.3, 12.4, 19.4, 22.3, 25.9
[58] 12.5, 13.2, 19.4
[59] 12.5-6, 23.9, 25.9
[60] 8.1, 8.4, 9.3, 10.9, 13.2-4, 22.3, 26.8

C) MANAGING FUTURE RISKS AND BUILDING RESILIENCE

Managing the risks of climate change involves decisions with implications for future societies, economies, environment, and climate. This section evaluates adaptation as a means to build resilience, as well as limits to adaptation, the role of transformation, and climate-resilient pathways. Figure SPM.8 provides an overview of responses for addressing climate change.

Figure SPM.8: An overview of overlapping entry points and approaches, as well as core considerations, in responding to climate change, as assessed in the WGII AR5. Bracketed references indicate sections of this summary with corresponding assessment findings.

C-1. Principles for Effective Adaptation

Adaptation is highly regionally and context specific, with no single approach for reducing risks appropriate across all settings (*medium confidence*). Effective risk reduction and adaptation strategies consider the dynamics of vulnerability and exposure and their linkages with development and climate change (*high confidence*). Specific examples of responses to climate change are presented in Table SPM.2.[61]

Table SPM.2: Managing the risks of climate change: entry points, strategies, and adaptation options. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples given can be relevant to more than one category. [14.2-3, Table 14-1]

From individuals to governments, actors across scales and regions have complementary roles in enabling adaptation planning and implementation (*high confidence*), for example through increasing awareness of climate change risks, learning from experience with climate variability, and achieving synergies with disaster risk reduction. Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities and households and in managing risk information and financing (*medium evidence, high agreement*). National governments can coordinate adaptation by local and subnational governments, creating legal frameworks, protecting vulnerable groups, and providing information, policy frameworks, and financial support (*robust evidence, high agreement*). Public action can influence the degree to which private parties undertake adaptation actions.[62]

In many cases, a first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate through low-regrets measures and actions emphasizing co-benefits (*high confidence*). Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human livelihoods, social and economic well-being, and environmental quality. See Table SPM.2. Integration of adaptation into planning and decision-making can promote synergies with development.[63]

Multiple simultaneous constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: uncertainty about projected impacts; limited financial and human resources; limited integration or coordination of different levels of governance; different perceptions of risks; inadequate responses from political institutions; competing values; absence of adaptation leaders and champions; and limited tools to monitor adaptation effectiveness. Underestimating the complexity of adaptation as a social process can create unrealistic expectations.[64]

Poor planning, overemphasizing short-term outcomes, or discounting or failing to consider all consequences can result in maladaptation (*medium evidence, high agreement*). Maladaptation can increase the vulnerability or exposure of the target group in the future, or the vulnerability of other locations or sectors.[65]

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[61] 2.1, 8.3-4, 13.1, 13.3-4, 15.2-3, 15.5, 16.2-3, 16.5, 17.2, 17.4, 19.6, 21.3, 22.4, 26.8-9, 29.6, 29.8
[62] 2.1-4, 3.6, 8.3-4, 9.3-4, 14.2, 15.2-3, 15.5, 16.2-5, 17.2-3, 22.4, 24.4, 25.4, 26.8-9, 30.7, Tables 21-1, 21-5, & 21-6, Boxes 16-1, 16-2, & 25-7
[63] 3.6, 8.3, 9.4, 11.2, 14.3, 15.2-3, 17.2, 20.4, 20.6, 22.4, 24.4-5, 25.4, 25.10, 27.3-5, 29.6, Boxes 25-2 and 25-6
[64] 3.6, 4.4, 8.4, 9.4, 13.2-3, 14.2, 15.2-3, 15.5, 16.2-3, 16.5, 17.2-3, 22.3-5, 23.6-7, 24.5, 25.4, 25.10, 26.8-9, 30.6, Boxes 16-1, 16-3, and CC-EA
[65] 14.6, 15.5, 17.2-3, 22.4

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include risk sharing and transfer mechanisms, loans, public-private finance partnerships, payments for environmental services, improved resource pricing (e.g., water markets), charges and subsidies including taxes, norms and regulations, and behavioral approaches. Risk financing mechanisms across scales, such as insurance and risk pools, contribute to increasing resilience to climate extremes and climate variability, but can also provide disincentives, cause market failure, and decrease equity. The public sector often plays a key role as regulator, provider, or insurer of last resort.[66]

Global adaptation cost estimates are substantially greater than current adaptation funding and investment, particularly in developing countries, suggesting a funding gap and a growing adaptation deficit (*medium confidence*). The most recent global adaptation cost estimates suggest a range from 70 to 100 US$ billion per year in developing countries from 2010 to 2050 (*low confidence*). Important omissions and shortcomings in data and methods render these estimates highly preliminary (*high confidence*).[67]

C-2. Climate-resilient Pathways and Transformation

Climate-resilient pathways are sustainable-development trajectories that combine adaptation and mitigation to reduce climate change and its impacts. They include iterative processes to ensure that effective risk management can be implemented and sustained (*high confidence*). Prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation.[68]

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits that emerge from the interaction among climate change and biophysical and socioeconomic constraints (*high confidence*). Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, current failures to address emerging impacts are already eroding the basis for sustainable development.[69]

Significant co-benefits, synergies, and tradeoffs exist between mitigation and adaptation and between alternative adaptation responses; interactions occur both within and across regions (*very high confidence*). Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, but tools to understand and manage these interactions remain limited. For instance, increasing bioenergy crop cultivation poses risks to ecosystems and biodiversity, although contributions of biomass energy to mitigation reduce climate-related risks (*high confidence*). Examples of mitigation actions with adaptation co-benefits include (i) improved energy efficiency and cleaner energy sources, leading to reduced local emissions of health-damaging climate-altering air pollutants, and (ii) reduced energy and water consumption in urban areas through greening cities and recycling water.[70]

Transformations in political, economic, and technological systems resulting from changes in paradigms and goals can facilitate adaptation and mitigation and promote sustainable development (*high confidence*). Transformational adaptation is an important consideration for decisions involving long life- or lead-times, and it can be a response to adaptation limits. It includes adaptation at greater scale or magnitude, introduction of new technologies or practices, formation of new structures or systems of governance, or shifts in the location of activities. Societal debates over risks from forced and reactive transformations as opposed to deliberate transitions to sustainability may place new and increased demands on governance structures to reconcile conflicting goals and visions for the future.[71]

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[66] 10.7, 10.9, 13.3, 17.4-5, Box 25-7
[67] 17.4
[68] 1.1, 2.5, 13.4, 20.2-4, 20.6, Figure 1-5
[69] 1.1, 11.8, 13.4, 16.2-7, 17.2, 20.2-3, 20.5-6, 25.10, 26.5, 26.9, Boxes 16-1, 16-3, and 16-4
[70] 2.5, 3.7, 4.2-4, 8.4, 9.3, 11.9, 13.3, 17.2, 19.3-4, 20.2-5, 21.4, 22.6, 23.8, 24.6, 25.7, 25.9, 26.8-9, 27.3, 29.6-8, Boxes 25-2, 25-9, 25-10, CC-WE, and CC-RF
[71] 1.1, 2.1, 2.5, 8.4, 14.1, 14.3, 16.2-7, 17.3, 20.5, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1, 16-4, and TS.8

Box SPM.1. Terms Critical for Understanding the Summary[72]

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

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

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Impacts: Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health status, ecosystems, economic, social, and cultural assets, services (including environmental), and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea-level rise, are a subset of impacts called physical impacts.

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

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

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

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

The degree of certainty in each key finding of the assessment is based on the type, amount, quality, and consistency of evidence (e.g., data, mechanistic understanding, theory, models, expert judgment) and the degree of agreement. The summary terms to describe evidence are: *limited*, *medium*, or *robust*; and agreement: *low*, *medium*, or *high*.

Confidence in the validity of a finding synthesizes the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*.

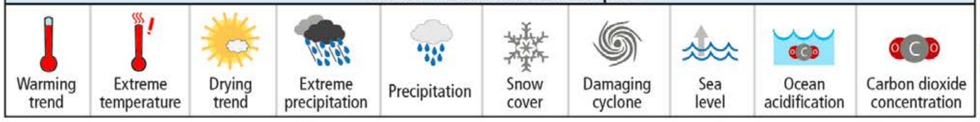
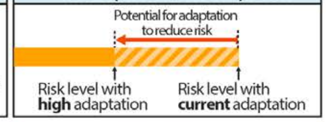
The likelihood, or probability, of some well-defined outcome having occurred or occurring in the future can be described quantitatively through the following terms: v*irtually certain*, 99–100% probability; *extremely likely*, 95–100%; *very likely*, 90–100%; *likely*, 66–100%; *more likely than not*, >50–100%; *about as likely as not*, 33–66%; *unlikely*, 0–33%; *very unlikely*, 0–10%; *extremely unlikely*, 0–5%; and *exceptionally unlikely*, 0–1%. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence. Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

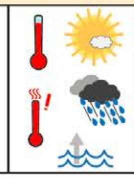
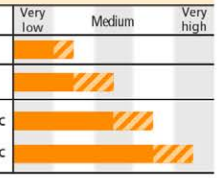
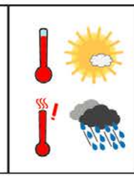
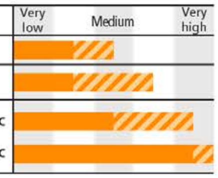
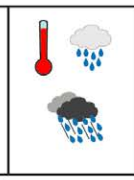
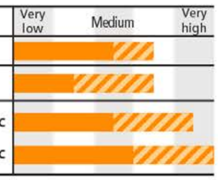
[72] Reflecting progress in science, some definitions differ in breadth and focus from the definitions used in the AR4 and other IPCC reports.

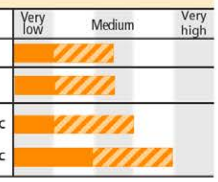
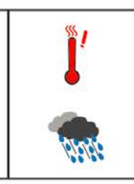
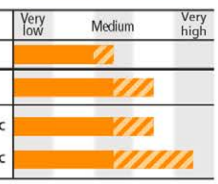
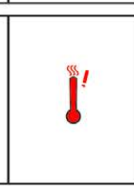
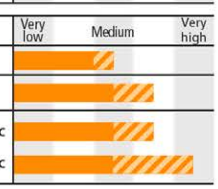
Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bold key finding apply to subsequent statements in the paragraph, unless additional terms are provided.

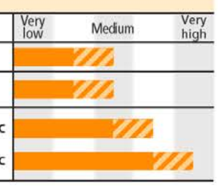
[1.1, Box 1-1]

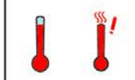
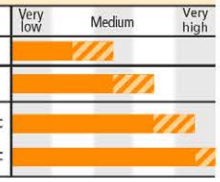
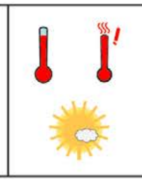
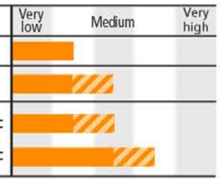
Table SPM.1.

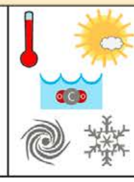
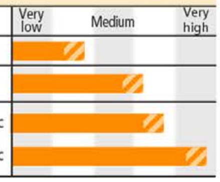
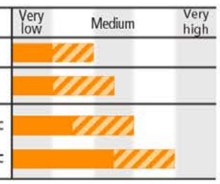
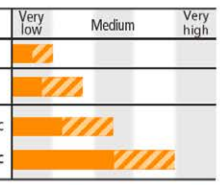
Climate-related drivers of impacts	Risk & potential for adaptation
	

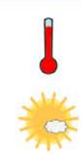
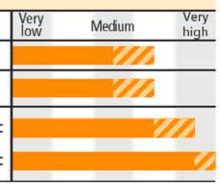
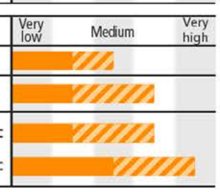
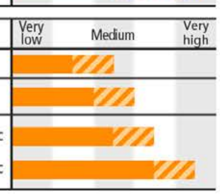
Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Africa					
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future (*high confidence*)	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance		22.3-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Reduced crop productivity with strong adverse effects on regional, national, and household food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*)	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation) • Enhancing smallholder access to credit and other critical production resources and diversifying livelihoods • Strengthening institutions at local to regional levels to support agriculture and gender-oriented policy support		22.3-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*)	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors		22.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Europe					
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization and by increasing sea levels and peak river discharges (*high confidence*)	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns		23.2-3, 23.7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand (*high confidence*)	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Further adaptation possible through solar desalinization with mitigation co-benefits		23.4, 23.7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, and air quality (*medium confidence*)	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infratructure • Reductions in emissions to improve air quality • Improved wildfire management		23.3, 23.5-7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Asia					
Increased flooding leading to widespread damage to infrastructure and settlements in Asia (*medium confidence*)	• Exposure reduction via effective land-use planning, selective relocation, and structural measures • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Assistance to vulnerable sectors and households		24.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
		Asia (continued)			
Increased risk of heat-related mortality (*high confidence*)	• Heat health warning systems • Urban planning to reduce heat islands • Improvement of the built environment		24.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*)	• Disaster preparedness including early-warning systems and local response strategies		24.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
		Australasia			
Significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia (*high confidence*)	• Ability to adapt naturally is limited especially for species that occupy narrow climatic ranges and fragmented habitats. • Main human adaptation options are to reduce other pressures (e.g., pollution, runoff, fishing, tourism, introduced predators and pests) and improve early warning systems. Assisted colonization and other direct interventions such as shading of reefs have been proposed but remain untested at scale.		25.6, 25.10	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*)	• Significant adaptation deficit in some regions to current flood risk. • Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Table 25-1, Boxes 25-8 and 25-9	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damage towards the upper end of projected sea-level-rise ranges (*high confidence*)	• Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. • Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		25.6, 25.10, Box 25-1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
		North America			
Loss of ecosystem integrity, property loss, human morbidity, and mortality due to wildfires (*high confidence*)	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity.		26.4, 26.8, Box 26-2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Heat-related human mortality (*high confidence*)	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is often limited among the most vulnerable individuals and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, heat warnings, cooling centers, greening, and high albedo surfaces.		26.6, 26.8	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment from river and coastal urban floods (*high confidence*)	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea-level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions.		26.2-4, 26.8	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Central and South America					
Water availability in semi-arid and glacier-melt-dependent regions and flooding in urban areas due to extreme precipitation (*high confidence*)	• Water-supply deficit replacement and improved land use • Urban flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control		27.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high
Decreased food production and food quality (*medium confidence*)	• Development of new crop varieties more adapted to changes in CO_2, temperature, and drought • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land use change		27.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Small Islands					
Loss of livelihoods, coastal settlements, and infrastructure in small islands (*high confidence*)	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Figure 29-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas in small islands (*high confidence*)	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		29.4, Table 29-1; WGI AR5 13.5, Table 13.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
The Ocean					
Distributional shift in fish and invertebrate species, and decrease in fishery catch potential at low latitudes, e.g., in equatorial upwelling and coastal boundary systems and sub-tropical gyres (*high confidence*)	• Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their ongoing latitudinal shifts. • Human adaptation options: Large-scale translocation of industrial fishing activities following the regional decreases (low latitude) vs. possibly transient increases (high latitude) in catch potential; Flexible management that can react to variability and change; Improvement of fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication; Expansion of aquaculture.		6.3, Box CC-MB	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high
Reduced biodiversity, fisheries abundance, and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, e.g., in coastal boundary systems and sub-tropical gyres (*high confidence*)	• Evidence of rapid evolution by corals is very limited. Some corals may migrate to higher latitudes, but entire reef systems are not expected to be able to track the high rates of temperature shifts. • Human adaptation options are limited to reducing other stresses, mainly by enhancing water quality, and limiting pressures from tourism and fishing. These options will delay human impacts of climate change by a few decades, but their efficacy will be severely reduced as thermal stress increases.		5.4, 6.4, 30.3, 30.5, Box CC-CR	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high
Coastal inundation and habitat loss due to sea-level rise and intensified precipitation events, e.g., in coastal boundary systems and sub-tropical gyres (*medium* to *high confidence*)	• Human adaptation options are limited to reducing other stresses, mainly by reducing pollution and limiting pressures from tourism, fishing, and aquaculture. • Loss of ecosystems such as sea grass, mangroves, and coral reefs can be reduced by reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients.		5.5, 30.5-6, Box CC-CR	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low / Medium / Very high

Table SPM.2.

Overlapping Entry Points	Category	Examples	Chapter Reference(s)
Vulnerability reduction through development & planning ***Including many low-regrets measures***	**Human development**	Improved access to education, nutrition, health facilities, energy, safe settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1-3, 14.2-3, 22.4
	Poverty alleviation	Insurance schemes; Social safety nets & social protection; Disaster risk reduction; Improved access to & control of local resources, land tenure, & storage facilities.	8.3, 9.3, 13.1-3, Box 8-4
	Livelihood security	Income, asset, & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Enhanced agency; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	7.5, 13.1-3, 22.3-4, 23.4, 26.5, 27.3, 29.6, Table 24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Improved drainage; Flood & cyclone shelters; Building codes; Storm & wastewater management; Transport & road infrastructure improvements.	8.2-4, 11.7, 14.3, 15.3-4, 22.4, 24.4, 25.4, 26.6, 28.4
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Dam management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Assisted translocation; Manipulation of disturbance regimes; Community-based natural resource management.	4.3-4, 8.3, 22.4, Table 3-3, Boxes 4-2, 4-3, 8-2, 15-1, 25-8, 25-9, & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure, & services; Managing development in flood prone & other high risk areas; Urban upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1, 8.3-4, 22.4, 23.7-8, 27.3, Box 25-8
Adaptation ***Including incremental & transformational adjustments***	**Structural/ physical**	***Engineered & built-environment options:*** Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5-6, 5.5, 8.2-3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2, & 25-8
		Technological options: New crop & animal varieties; Traditional technologies & methods; Efficient irrigation; Water-saving technologies; Conservation agriculture; Food storage & preservation facilities; Hazard mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling.	7.5, 8.3, 9.4, 10.3, 15.3-4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6-7, Table 25-2, Boxes 20-5 & 25-2
		Ecosystem-based options: Ecological restoration; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted migration or managed translocation; Ecological corridors; Ex situ conservation & seed banks; Community-based natural resource management.	4.4, 5.5, 8.3, 9.4, 11.7, 15.3-4, 22.4, 23.6-7, 24.4, 25.6, 26.4, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2, & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5-6, 8.3, 9.3-4, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options:*** Financial incentives including taxes & subsidies; Insurance; Catastrophe bonds; Payments for ecosystem services; Water tariffs; Microfinance; Disaster contingency funds; Cash transfers.	8.3-4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7-8, 24.4, 25.4, 26.3, 27.3, Table 25-2, Box CC-CR
		Government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.2-4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2-4, 22.4, 23.7, 25.4, 25.8, 26.8-9, 27.3-4, 29.6, 30.6, Boxes 25-1, 25-2, & 25-9
	Social	***Educational options:*** Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing local & traditional knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3-4, 9.4, 11.7, 12.3, 15.2-4, 22.4, 25.4, 28.4, 29.6, Table 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development.	2.4, 5.5, 8.3-4, 9.4, 11.7, 15.2-4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, Table 25-2, Box 26-3
		Behavioral options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 11.7, 12.4, 22.3-4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	**Spheres of change**	***Practical:*** Social & technical innovations, behavioral shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 20.5, Box 25-5
		Political: Changes in the political, social, cultural, & ecological systems or structures that currently contribute to risk & vulnerability or impede practical transformations.	14.2-3, 20.5, 25.4, Table 14-1
		Personal: Changes in individual & collective assumptions, beliefs, values, & worldviews that influence climate change responses.	14.2-3, 20.5, 25.4, Table 14-1
Mitigation	See WGIII AR5.		

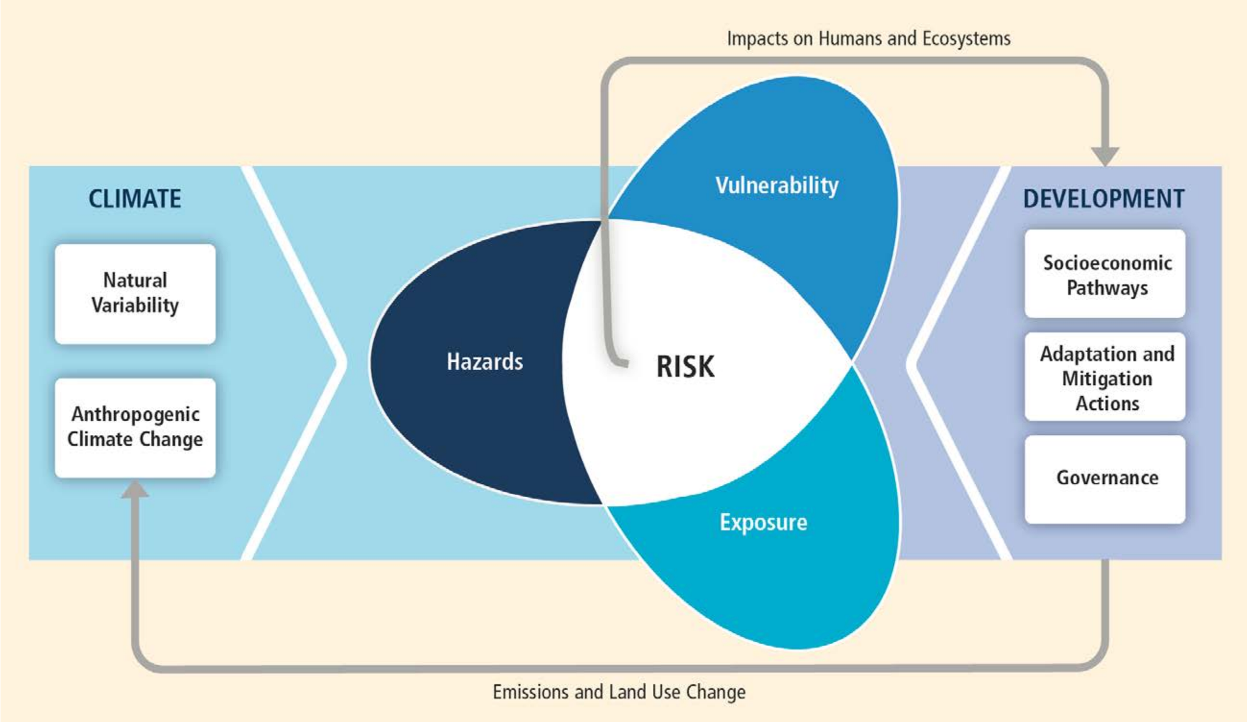
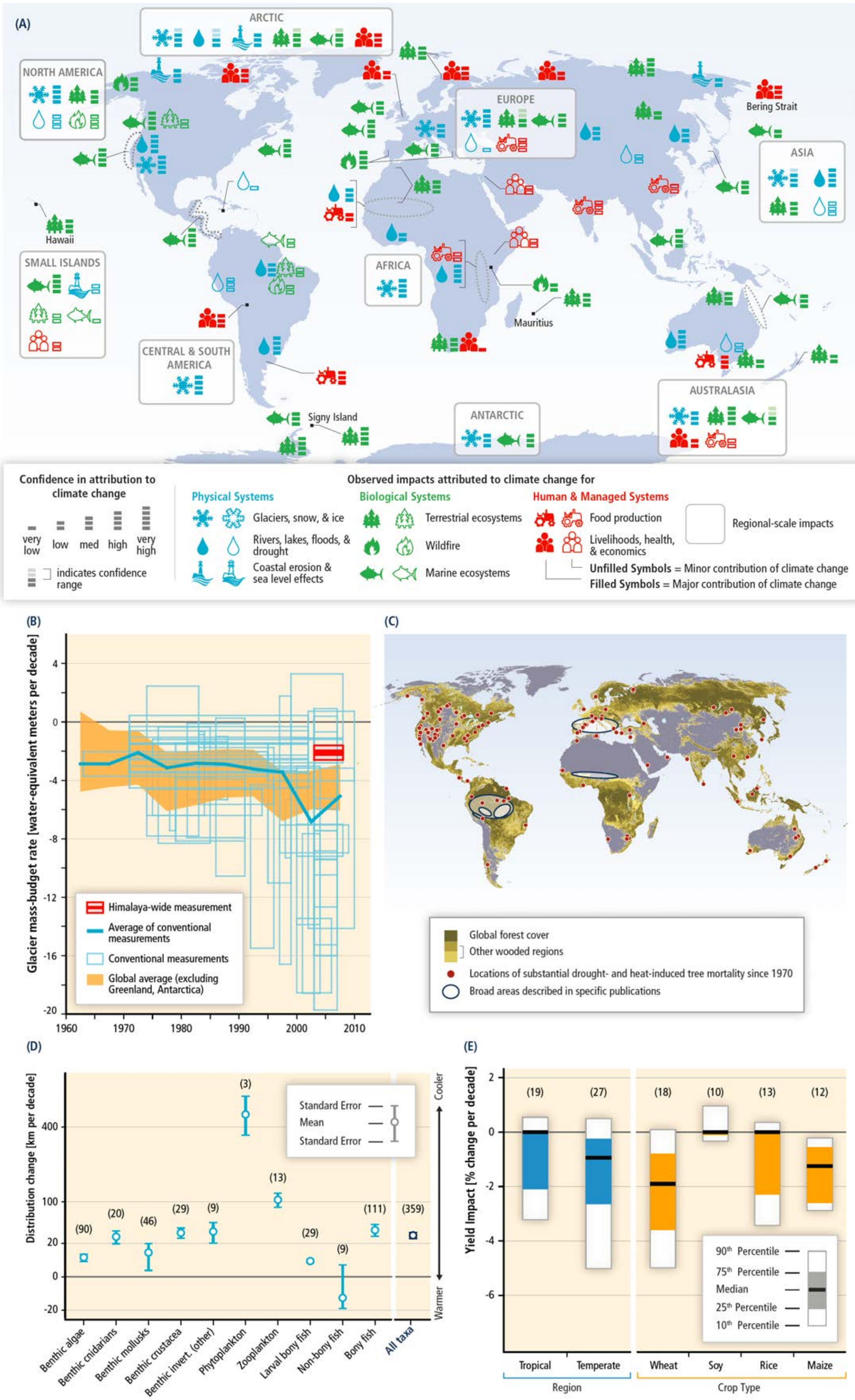

Impacts on Humans and Ecosystems
CLIMATE
Natural Variability
Anthropogenic Climate Change
Vulnerability
Hazards
RISK
Exposure
DEVELOPMENT
Socioeconomic Pathways
Adaptation and Mitigation Actions
Governance
Emissions and Land Use Change

Figure SPM.1.



(A)
ARCTIC
NORTH AMERICA
EUROPE
ASIA
Bering Strait
Hawaii
SMALL ISLANDS
AFRICA
Mauritius
CENTRAL & SOUTH AMERICA
Signy Island
ANTARCTIC
AUSTRALASIA
Confidence in attribution to climate change
very low
low
med
high
very high
indicates confidence range
Observed impacts attributed to climate change for
Physical Systems
Glaciers, snow, & ice
Rivers, lakes, floods, & drought
Coastal erosion & sea level effects
Biological Systems
Terrestrial ecosystems
Wildfire
Marine ecosystems
Human & Managed Systems
Food production
Livelihoods, health, & economics
Regional-scale impacts
Unfilled Symbols = Minor contribution of climate change
Filled Symbols = Major contribution of climate change
(B)
Glacier mass-budget rate [water-equivalent meters per decade]
4
0
-4
-8
-12
-16
-20
1960
1970
1980
1990
2000
2010
Himalaya-wide measurement
Average of conventional measurements
Conventional measurements
Global average (excluding Greenland, Antarctica)
(C)
Global forest cover
Other wooded regions
Locations of substantial drought- and heat-induced tree mortality since 1970
Broad areas described in specific publications
(D)
Distribution change [km per decade]
400
100
20
0
-20
(90)
(20)
(46)
(29)
(9)
(3)
(13)
(29)
(9)
(111)
(359)
Standard Error
Mean
Standard Error
Cooler
Warmer
Benthic algae
Benthic cnidarians
Benthic mollusks
Benthic crustacea
Benthic invert. (other)
Phytoplankton
Zooplankton
Larval bony fish
Non-bony fish
Bony fish
All taxa
(E)
Yield Impact [% change per decade]
2
0
-2
-4
-6
(19)
(27)
(18)
(10)
(13)
(12)
90th Percentile
75th Percentile
Median
25th Percentile
10th Percentile
Tropical
Temperate
Region
Wheat
Soy
Rice
Maize
Crop Type

Figure SPM.2.

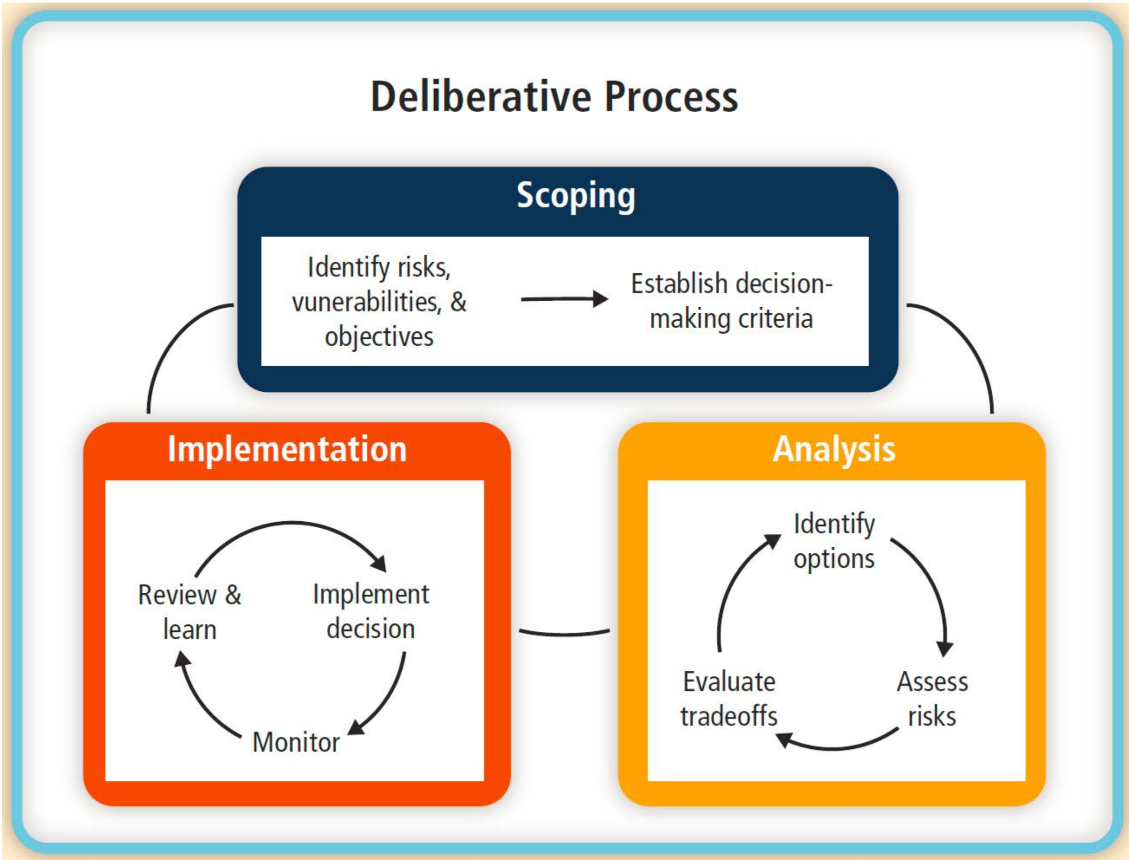

Deliberative Process
Scoping
Identify risks, vulnerabilities, & objectives
Establish decision-making criteria
Implementation
Review & learn
Implement decision
Monitor
Analysis
Identify options
Assess risks
Evaluate tradeoffs

Figure SPM.3.

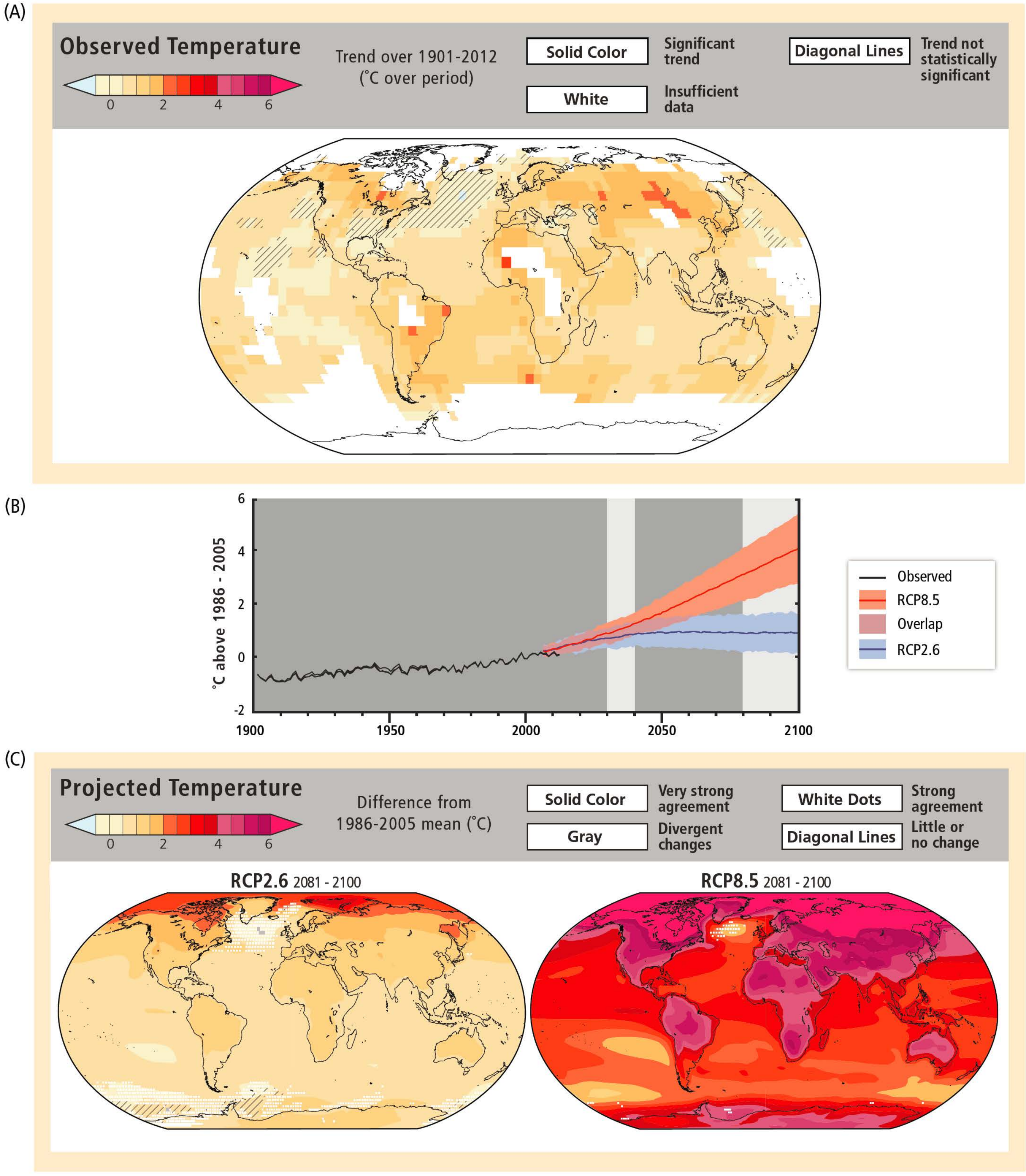
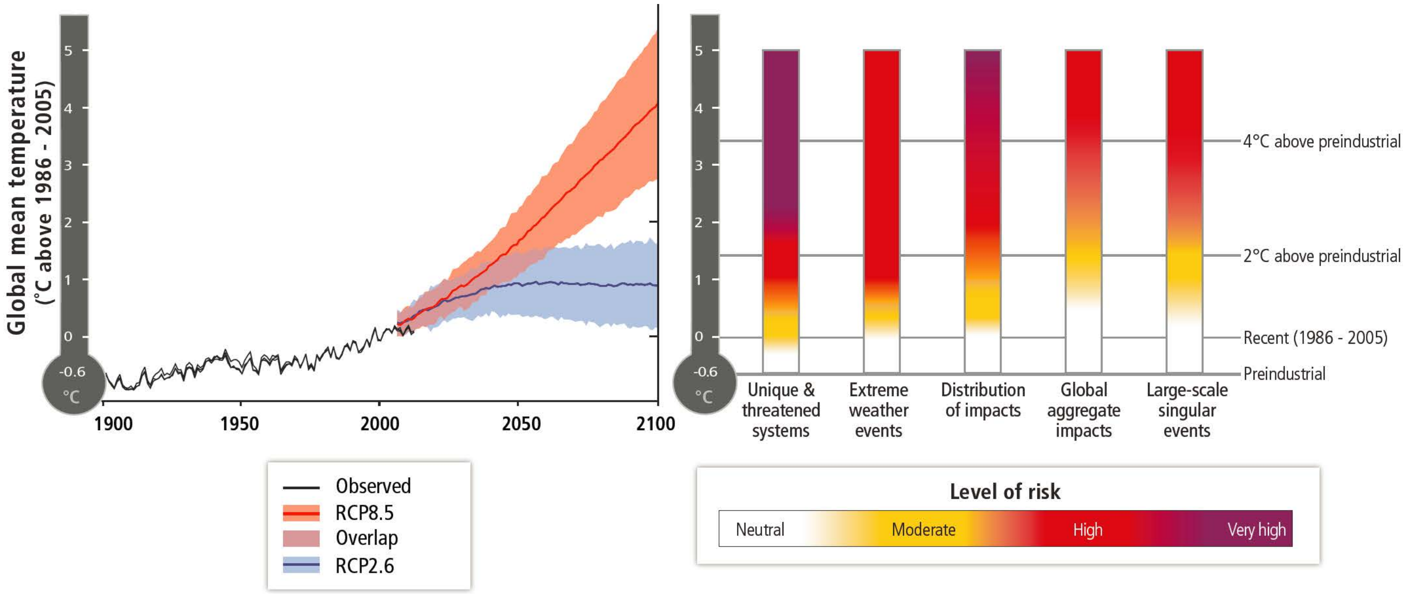

(A)
Observed Temperature
Trend over 1901-2012
(˚C over period)
0 2 4 6
Solid Color
Significant trend
White
Insufficient data
Diagonal Lines
Trend not statistically significant
(B)
°C above 1986 - 2005
6 4 2 0 -2
1900 1950 2000 2050 2100
Observed
RCP8.5
Overlap
RCP2.6
(C)
Projected Temperature
Difference from 1986-2005 mean (˚C)
0 2 4 6
Solid Color
Very strong agreement
Gray
Divergent changes
White Dots
Strong agreement
Diagonal Lines
Little or no change
RCP2.6 2081 - 2100
RCP8.5 2081 - 2100

Figure SPM.4.



Box SPM.4 Figure 1.

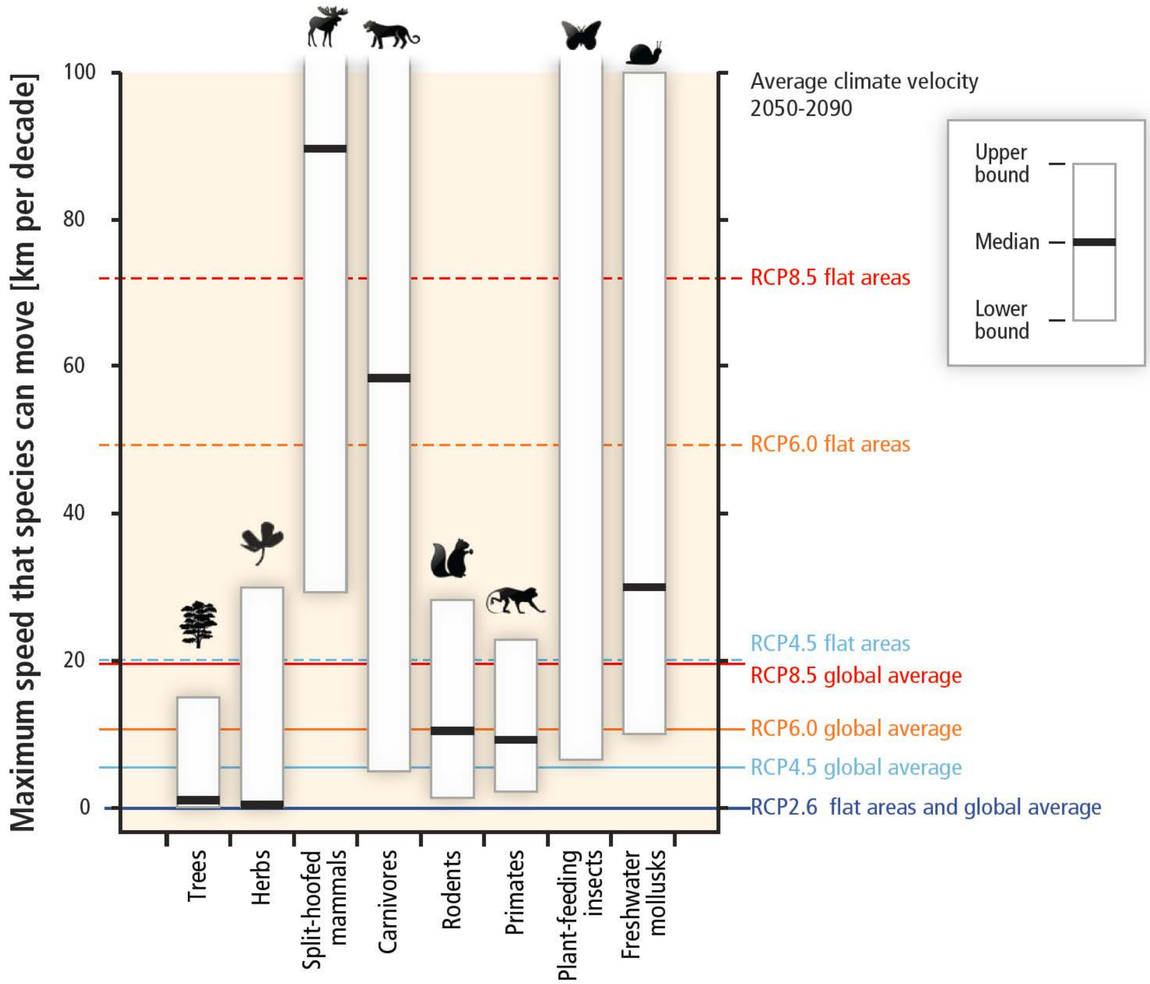
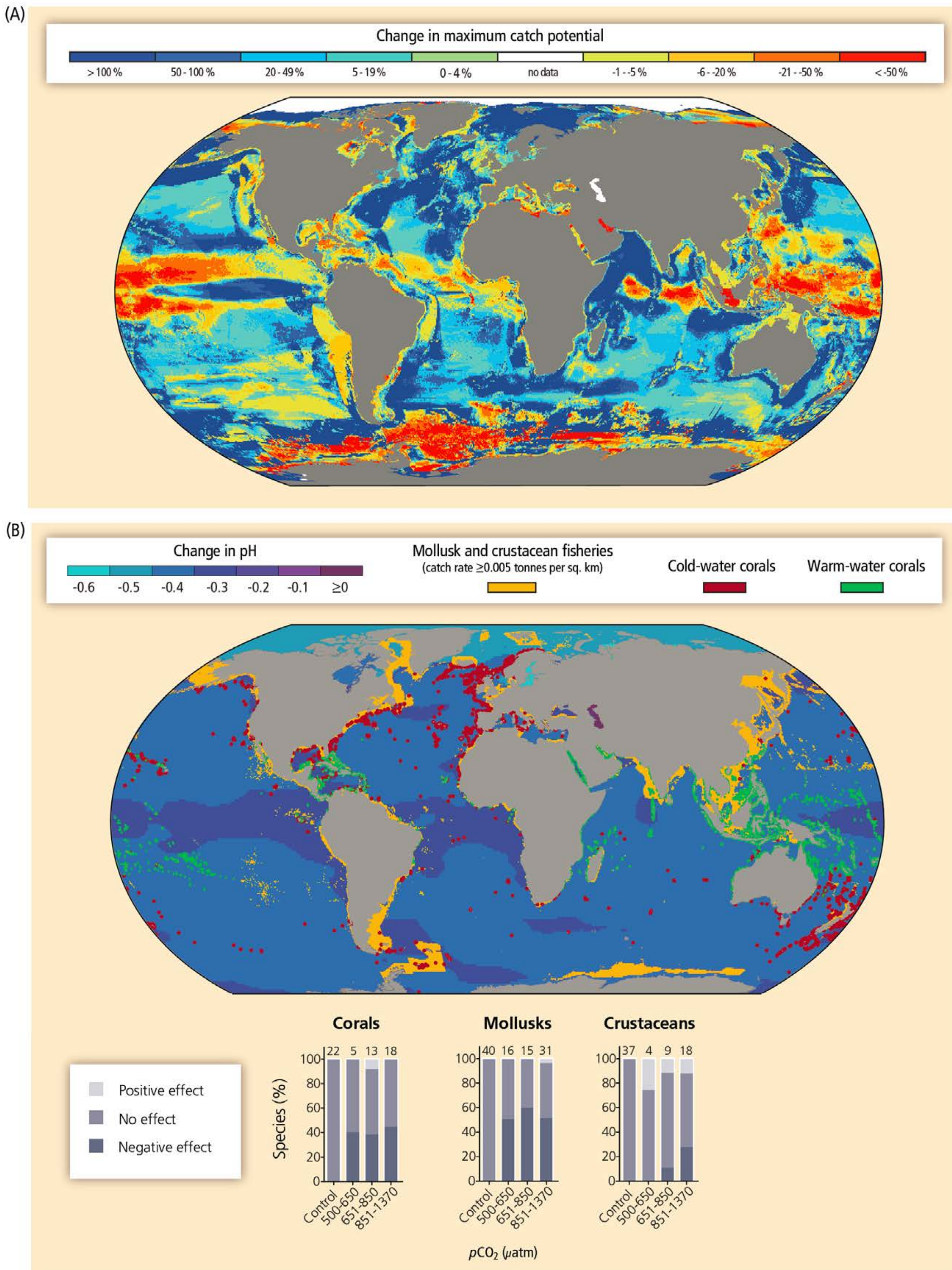

Maximum speed that species can move [km per decade]
100
80
60
40
20
0
Average climate velocity
2050-2090
Upper bound
Median
Lower bound
RCP8.5 flat areas
RCP6.0 flat areas
RCP4.5 flat areas
RCP8.5 global average
RCP6.0 global average
RCP4.5 global average
RCP2.6 flat areas and global average
Trees
Herbs
Split-hoofed mammals
Carnivores
Rodents
Primates
Plant-feeding insects
Freshwater mollusks

Figure SPM.5.



(A)
Change in maximum catch potential
> 100 %
50 - 100 %
20 - 49 %
5 - 19 %
0 - 4 %
no data
-1 - -5 %
-6 - -20 %
-21 - -50 %
< -50 %
(B)
Change in pH
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
≥0
Mollusk and crustacean fisheries
(catch rate ≥0.005 tonnes per sq. km)
Cold-water corals
Warm-water corals
Corals
Mollusks
Crustaceans
Positive effect
No effect
Negative effect
Species (%)
22 5 13 18
40 16 15 31
37 4 9 18
Control
500-650
651-850
851-1370
pCO2 (μatm)

Figure SPM.6.

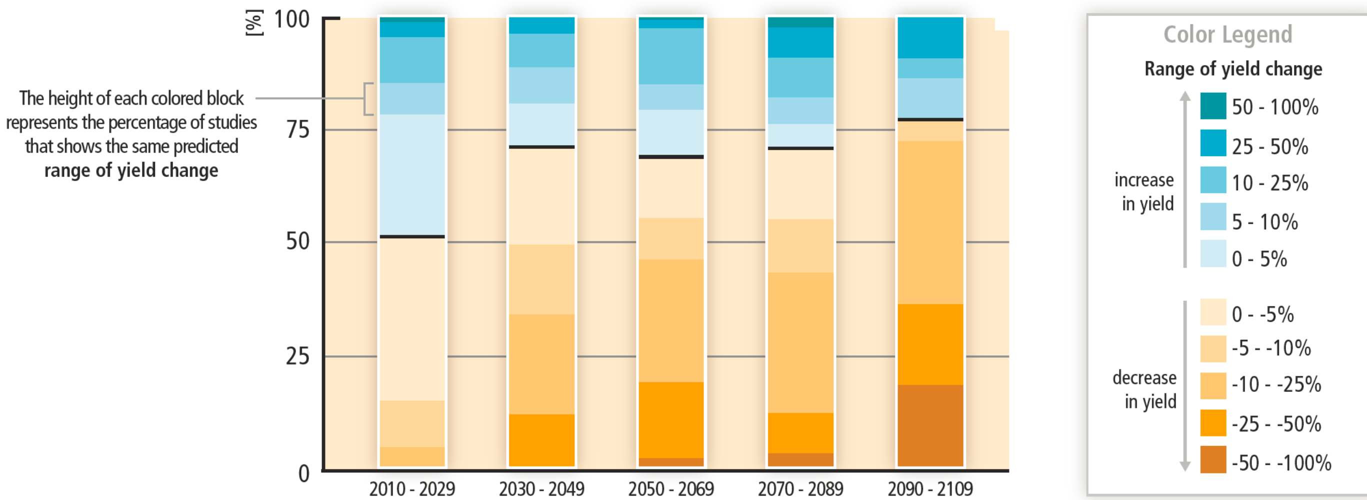

[%]
100
75
50
25
0
The height of each colored block represents the percentage of studies that shows the same predicted range of yield change
2010 - 2029
2030 - 2049
2050 - 2069
2070 - 2089
2090 - 2109
Color Legend
Range of yield change
increase in yield
50 - 100%
25 - 50%
10 - 25%
5 - 10%
0 - 5%
decrease in yield
0 - -5%
-5 - -10%
-10 - -25%
-25 - -50%
-50 - -100%

Figure SPM.7.

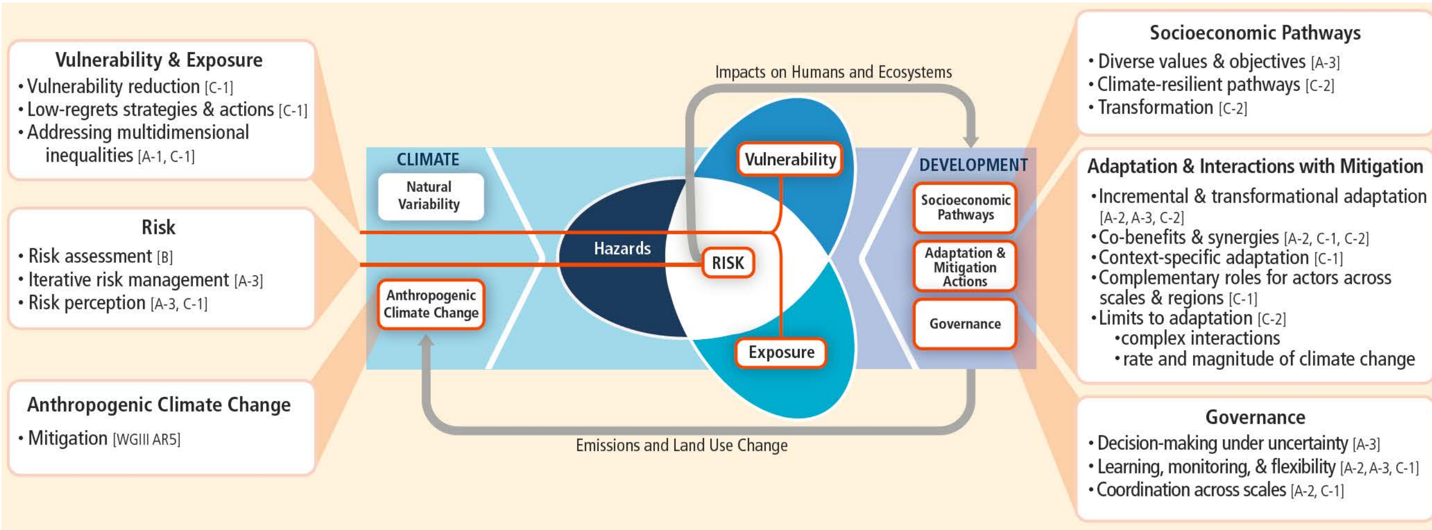

Vulnerability & Exposure
• Vulnerability reduction [C-1]
• Low-regrets strategies & actions [C-1]
• Addressing multidimensional inequalities [A-1, C-1]
Risk
• Risk assessment [B]
• Iterative risk management [A-3]
• Risk perception [A-3, C-1]
Anthropogenic Climate Change
• Mitigation [WGIII AR5]
CLIMATE
Natural Variability
Anthropogenic Climate Change
Impacts on Humans and Ecosystems
Hazards
Vulnerability
RISK
Exposure
Emissions and Land Use Change
DEVELOPMENT
Socioeconomic Pathways
Adaptation & Mitigation Actions
Governance
Socioeconomic Pathways
• Diverse values & objectives [A-3]
• Climate-resilient pathways [C-2]
• Transformation [C-2]
Adaptation & Interactions with Mitigation
• Incremental & transformational adaptation [A-2, A-3, C-2]
• Co-benefits & synergies [A-2, C-1, C-2]
• Context-specific adaptation [C-1]
• Complementary roles for actors across scales & regions [C-1]
• Limits to adaptation [C-2]
• complex interactions
• rate and magnitude of climate change
Governance
• Decision-making under uncertainty [A-3]
• Learning, monitoring, & flexibility [A-2, A-3, C-1]
• Coordination across scales [A-2, C-1]

Figure SPM.8.

Climate Change 2014: Impacts, Adaptation, and Vulnerability

TECHNICAL SUMMARY

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CONTENTS OF THE TECHNICAL SUMMARY

INTRODUCTION

Human interference with the climate system is occurring. [WGI AR5 2.2, 6.3, 10.3-6, 10.9] Climate change poses risks for human and natural systems (Figure TS.1). The assessment of impacts, adaptation, and vulnerability in the Working Group II contribution to the IPCC's Fifth Assessment Report (WGII AR5) evaluates how patterns of risks and potential benefits are shifting due to climate change and how risks can be reduced through mitigation and adaptation. It recognizes that risks of climate change will vary across regions and populations, through space and time, dependent on myriad factors including the extent of mitigation and adaptation.

[INSERT FIGURE TS.1 HERE
Figure TS.1: Climate-related hazards, exposure, and vulnerability interact to produce risk. Changes in both the climate system (left) and development processes including adaptation and mitigation (right) are drivers of hazards, exposure, and vulnerability. [19.2, Figure 19-1]]

Section A of this summary characterizes observed impacts, vulnerability and exposure, and responses to date. Section B examines the range of future risks and potential benefits across sectors and regions, highlighting where choices matter for reducing risks through mitigation and adaptation. Section C considers principles for effective adaptation and the broader interactions among adaptation, mitigation, and sustainable development.

Box TS.1 introduces the context of the WGII AR5, and Box TS.2 defines central concepts. To accurately convey the degree of certainty in key findings, the report relies on the consistent use of calibrated uncertainty language, introduced in Box TS.3. Chapter references in square brackets indicate support for findings, paragraphs of findings, figures, and tables in this summary.

_____ START BOX TS.1 HERE _____

Box TS.1. Context for the Assessment

For the past two decades, IPCC's Working Group II has developed assessments of climate change impacts, adaptation, and vulnerability. The WGII AR5 builds from the WGII contribution to the IPCC's Fourth Assessment Report (WGII AR4), published in 2007, and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), published in 2012. The WGII AR5 is presented in two volumes, reflecting an expanded literature basis and multidisciplinary approach, increased focus on societal impacts and responses, and continued comprehensive regional coverage. [1.1]

The number of scientific publications available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, allowing for a more robust assessment that supports policymaking (*high confidence*). The diversity of the topics and regions covered has similarly expanded, as has the geographic distribution of the authors contributing to the knowledge base for climate change assessments (Box TS.1 Figure 1). Authorship of climate-change publications from developing countries has increased, although it still represents a small fraction of the total. The unequal distribution of publications presents a challenge to the production of a comprehensive and balanced global assessment. [1.1, Figure 1-1]

[INSERT BOX TS.1 FIGURE 1 HERE
Box TS.1 Figure 1: Number of climate-change publications listed in the Scopus bibliographic database. (A) Number of climate-change publications in English (as of July 2011) summed by country affiliation of all authors of the publications and sorted by region. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (B) Number of climate-change publications in English with individual countries mentioned in title, abstract, or key words (as of July 2011) sorted by region for the decades 1981-1990, 1991-2000, and 2001-2010. Each publication can be counted multiple times if more than one country is listed. [Figure 1-1]]

Adaptation has emerged as a central area in climate change research, in country-level planning, and in implementation of climate change strategies (*high confidence*). The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. [1.1]

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement (Box TS.3). Each finding is supported by a traceable account of the evaluation of evidence and agreement. [1.1, Box 1-1]

_____ END BOX TS.1 HERE _____

_____ START BOX TS.2 HERE _____

Box TS.2. Terms Critical for Understanding the Summary

Core concepts defined in the WGII AR5 glossary and used throughout the report include the following terms. Reflecting progress in science, some definitions differ in breadth and focus from the definitions used in the AR4 and other IPCC reports.

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

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

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

Impacts: Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health status, ecosystems, economic, social, and cultural assets, services (including environmental), and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea-level rise, are a subset of impacts called physical impacts.

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

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

> ***Incremental adaptation:*** Adaptation actions where the central aim is to maintain the essence and integrity of a system or process at a given scale.
>
> ***Transformational adaptation:*** Adaptation that changes the fundamental attributes of a system in response to climate and its effects.

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

Resilience: The capacity of a social-ecological system to cope with a hazardous event or disturbance, responding or reorganizing in ways that maintain its essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.

_____ END BOX TS.2 HERE _____

_____ START BOX TS.3 HERE _____

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

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties, the WGII AR5 relies on two metrics for communicating the degree of certainty in key findings:

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

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

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

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

Term	**Likelihood of the outcome**
Virtually certain	99–100% probability
Extremely likely	95– 100% probability
Very likely	90–100% probability
Likely	66–100% probability
More likely than not	>50–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Extremely unlikely	0–5% probability
Exceptionally unlikely	0–1% probability

Where appropriate, findings are also formulated as statements of fact without using uncertainty qualifiers.

Within paragraphs of this summary, the confidence, evidence, and agreement terms given for a bold key finding apply to subsequent statements in the paragraph, unless additional terms are provided.

[1.1, Box 1-1]

_____ END BOX TS.3 HERE _____

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

This section presents observed effects of climate change, building from understanding of vulnerability, exposure, and climate-related hazards as determinants of impacts. The section considers the factors, including development and non-climatic stressors, that influence vulnerability and exposure, evaluating the sensitivity of systems to climate change. The section also identifies challenges and options based on adaptation experience, looking at what has motivated previous adaptation actions in the context of climate change and broader objectives. It examines current understanding of decision-making as relevant to climate change.

A-1. Observed Impacts, Vulnerability, and Exposure

Observed impacts of climate change are widespread and consequential. Recent changes in climate have caused impacts on natural and human systems on all continents and across the oceans.[1] This conclusion is strengthened by more numerous and improved observations and analyses since the AR4. For many natural systems on land and in the ocean, new or stronger evidence exists for substantial and wide-ranging climate change impacts. For human systems, effects of changing social and economic factors have often been larger than climate-change-related impacts, but despite this, some impacts in human systems have also been attributed to climate change. In many regions, impacts on natural and human systems are now detected even in the presence of strong confounding factors such as pollution or land use change. See Table TS.1 and Figure TS.2 for a summary of observed impacts and indicators of a changing climate, illustrating broader trends presented in this section. Most reported impacts of climate change are attributed to warming and/or to shifts in precipitation patterns. There is also emerging evidence of impacts of ocean acidification. Few robust attribution studies and meta-analyses have linked impacts in physical and biological systems to anthropogenic climate change. [18.1, 18.3-6]

[INSERT TABLE TS.1 HERE
Table TS.1: Examples of observed impacts attributed to climate change with *medium* (M) or *high* (H) confidence, indicating the relative contribution of climate change (major [C] or minor [c]) to the observed change, for natural and human systems across eight major world regions over the past several decades. [Tables 18-5, 18-6, 18-7, 18-8, and 18-9]]

[INSERT FIGURE TS.2 HERE
Figure TS.2: Widespread indicators of a changing climate. (A) Global patterns of observed climate change impacts, at regional, subregional, and more local scales. For categories of attributed impacts, symbols indicate affected systems and sectors, the relative contribution of climate change (major or minor) to the observed change, and confidence in attribution. (B) Glacier mass budgets from all published measurements for Himalayan glaciers, also showing global average glacier mass budget estimates from WGI AR5 4.3 with shading indicating ±1 standard deviation. The blue box for each Himalaya measurement has a height of ±1 standard deviation centered on its average (and ±1 standard error for multi-annual measurements). Himalaya-wide measurement (red) was made by satellite laser altimetry. (C) Locations of substantial drought- and heat-induced tree mortality around the globe over 1970-2011. (D) Average rates of change in distribution (km per decade) for marine taxonomic groups based on observations over 1900-2010. Positive distribution changes are consistent with warming (moving into previously cooler waters, generally poleward). The number of responses analyzed is given for each category. (E) Summary of estimated impacts of observed climate changes on yields over 1960-2013 for four major crops in temperate and tropical regions, with the number of data points analyzed given for each category. [Figures 3-3, 4-7, 7-2, 18-3, and MB-2]]

Differences in vulnerability and exposure arise from non-climatic stressors and multidimensional inequalities, which shape differential risks from climate change (*very high confidence*). See Box TS.4. Vulnerability and exposure vary over time and across geographic contexts. Changes in poverty or socioeconomic status, ethnic composition, age structure, and governance have had a significant influence on the outcome of past crises associated with climate-related hazards. [8.2, 9.3, 12.2, 13.1-2, 14.1-3, 19.6, 26.8, Box CC-GC]

[1] Attribution of observed impacts in the WGII AR5 links responses of natural and human systems to climate change, not to anthropogenic climate change, unless explicitly indicated.

Impacts from recent extreme climatic events, such as heat waves, droughts, floods, and wildfires, show significant vulnerability and exposure of some ecosystems and many human systems to climate variability (*very high confidence*). Impacts include the alteration of ecosystems and of food production, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. These experiences are consistent with a significant adaptation deficit in developing and developed countries for some sectors and regions. The following examples illustrate impacts of extreme weather and climate events experienced across regional contexts.

- In Africa, extreme weather and climate events including droughts and floods have significant impacts on economic sectors, natural resources, ecosystems, livelihoods, and human health. The floods of the Zambezi River in Mozambique in 2008, for example, displaced 90,000 people, and along the Zambezi River Valley, with approximately 1 million people living in the flood-affected areas, temporary displacement is taking on permanent characteristics. [22.3-4, 22.6]
- Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011). The Victorian heat wave (2009) increased heat-related morbidity and was associated with more than 300 excess deaths, while intense bushfires destroyed over 2,000 buildings and led to 173 deaths. Widespread drought in south-east Australia (1997-2009) and many parts of New Zealand (2007-2009; 2012-13) resulted in economic losses (e.g., regional GDP in the southern Murray-Darling Basin was below forecast by about 5.7% in 2007/08, and New Zealand lost about NZ$3.6b in direct and off-farm output in 2007-09). [3.2, 13.2, 25.6, 25.8, Table 25-1, Boxes 25-5, 25-6, 25-8]
- In Europe, extreme weather events currently have significant impacts in multiple economic sectors as well as adverse social and health effects (*high confidence*). [Table 23-1]
- In North America, most economic sectors and human systems have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*). Extreme heat events currently result in increases in mortality and morbidity (*very high confidence*), with impacts that vary by age, location, and socioeconomic factors (*high confidence*). Extreme coastal storm events have caused excess mortality and morbidity, particularly along the east coast of the United States, and the gulf coast of both Mexico and the United States. Much North American infrastructure is currently vulnerable to extreme weather events (*medium confidence*), with deteriorating water-resource and transportation infrastructure particularly vulnerable (*high confidence*). [3.2, 26.6-7, Figure 26-2]
- In the Arctic, extreme weather events have had direct and indirect adverse health effects for residents (*high confidence*). [28.2]

_____ START BOX TS.4 HERE _____

Box TS.4. Multidimensional Inequality and Vulnerability to Climate Change

People who are socially, economically, culturally, politically, institutionally, or otherwise marginalized in society are often highly vulnerable to climate change and climate change responses (*medium evidence, high agreement*). This heightened vulnerability is rarely due to a single cause. Rather, it is the product of intersecting social processes that result in inequalities in socioeconomic status, income, and exposure, including, for example, discrimination on the basis of gender, class, race/ethnicity, age, and (dis)ability. See Box TS.4 Figure 1. Understanding differential capacities and opportunities of individuals, households, and communities requires knowledge of these intersecting social drivers, which may be context-specific and clustered in diverse ways (e.g., class and ethnicity in one case, gender and age in another). Few studies depict the full spectrum of these intersecting social processes and the ways in which they shape multidimensional vulnerability to climate change.

Examples of inequality-driven impacts and risks of climate change and climate change responses (*medium evidence, high agreement*):

- Privileged members of society can benefit from climate change impacts and response strategies, due to their flexibility in mobilizing and accessing resources and positions of power, often to the detriment of others. [13.2-3, 22.4, 26.8]
- Differential impacts on men and women arise from distinct roles in society, the way these roles are enhanced or constrained by other dimensions of inequality, risk perceptions, and the nature of response to hazards. [8.2, 9.3, 11.3, 12.2, 13.2, 18.4, 22.4, Box CC-GC]

- Both male and female deaths are recorded after flooding, affected by socioeconomic disadvantage, occupation, and culturally imposed expectations to save lives. While women are generally more sensitive to heat stress, more male workers are reported to have died largely due to responsibilities related to outdoor and indoor work. [11.3, 13.2, Box CC-GC]
- Women often experience additional duties as laborers and caregivers as a result of extreme weather events and climate change, as well as responses (e.g., male outmigration), while facing more psychological and emotional distress, reduced food intake, adverse mental health outcomes due to displacement, and in some cases increasing incidences of domestic violence. [9.3-4, 12.4, 13.2, Box CC-GC]
- Children and the elderly are often at higher risk due to narrow mobility, susceptibility to infectious diseases, reduced caloric intake, and social isolation. While adults and older children are more severely affected by some climate-sensitive vector-borne diseases such as dengue, young children are more likely to die from or be severely compromised by diarrheal diseases and floods. The elderly face disproportional physical harm and death from heat stress, droughts, and wildfires. [8.2, 10.9, 11.1, 11.4-5, 13.2, 22.4, 23.5, 26.6]
- In most urban areas, low-income groups, including migrants, face large climate change risks because of poor-quality, insecure, and clustered housing, inadequate infrastructure, and lack of provision for health care, emergency services, flood exposure, and measures for disaster risk reduction. [8.1-2, 8.4-5, 12.4, 22.3, 26.8]
- People disadvantaged by race or ethnicity, especially in high-income countries, experience more harm from heat stress, often due to low economic status and poor health conditions, and displacement after extreme events. [11.3, 12.4, 13.2]
- Livelihoods and lifestyles of indigenous peoples, pastoralists, and fisherfolk, often dependent on natural resources, are highly sensitive to climate change and climate change policies, especially those that marginalize their knowledge, values, and activities. [9.3, 11.3, 12.3, 14.2, 22.4, 25.8, 26.8, 28.2]
- Disadvantaged groups without access to land and labor, including female-headed households, tend to benefit less from climate change response mechanisms (e.g., CDM, REDD+, large-scale land acquisition for biofuels, and planned agricultural adaptation projects). [9.3, 12.2, 12.5, 13.3, 22.4, 22.6]

[INSERT BOX TS.4 FIGURE 1 HERE
Box TS.4 Figure 1: Multidimensional vulnerability driven by intersecting dimensions of inequality. Vulnerability increases when people’s capacities and opportunities to adapt to climate change and adjust to climate change responses are diminished. [Figure 13-5]]

_____ END BOX TS.4 HERE _____

Freshwater resources

In many regions, changing precipitation or melting snow and ice are altering hydrological systems, affecting water resources and quality (*medium confidence*). Glaciers continue to shrink in many regions due to climate change (*high confidence*) (Figure TS.2B). Climate change has caused permafrost warming and thawing in high-latitude and high-elevation mountain regions. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand. [3.2, 4.3, 18.3, 18.5, 24.4, 25.5, 26.2, 28.2, Tables 3-1 and 25-1, Figures 18-2 and 26-1]

Terrestrial and freshwater ecosystems

Many terrestrial plant and animal species have shifted their ranges and seasonal activities and altered their abundance in response to past climate change, and they are doing so now in many regions (*high confidence*). Increased tree mortality, observed in many places worldwide, has been attributed to climate change in some regions (Figure TS.2C). Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind-storms, fires, and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). While recent warming contributed to the extinction of many species of Central American amphibians (*medium confidence*), most recent observed terrestrial-species extinctions have not been attributed to recent climate change, despite some speculative efforts (*high confidence*). [4.2-4, 18.3, 18.5, 22.3, 25.6, 26.4, 28.2, Figure 4-10, Boxes 4-2, 4-3, 4-4, and 25-3]

Coastal systems and low-lying areas

Coastal systems are particularly sensitive to changes in sea level and ocean temperature and to ocean acidification (*very high confidence*). Coral bleaching and species range shifts have been attributed to changes in ocean temperature. For many other coastal changes, the impacts of climate change are difficult to identify given other human-related drivers (e.g. land-use change, coastal development, pollution) (*robust evidence, high agreement*). [5.3-5, 18.3, 25.6, 26.4, Box 25-3]

Marine systems

Warming has caused and will continue to cause shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of species (*very high confidence*), paralleled by reduction in maximum body sizes in warming waters (*medium confidence*). This has resulted and will further result in changing interactions between species, including competition and predator-prey dynamics (*high confidence*). Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (*very high confidence*) and altered ecosystem composition (*high confidence*) on multidecadal time scales, tracking climate trends. Many fishes, invertebrates, and phytoplankton have shifted their distribution and/or abundance poleward and/or to deeper, cooler waters (Figure TS.2D). Some warm-water corals and their reefs have responded to warming with species replacement, bleaching, and decreased coral cover causing habitat loss. Few field observations to date demonstrate biological responses attributable to anthropogenic ocean acidification, as in many places these responses are not yet outside their natural variability and may be influenced by confounding local or regional factors. See also Box TS.7. Natural climate change at rates slower than current anthropogenic change has led to significant ecosystem shifts, including species emergences and extinctions, in the past millions of years. [5.4, 6.1, 6.3-5, 18.3, 18.5, 22.3, 25.6, 26.4, 30.4-5, Boxes 25-3, CC-OA, CC-CR, and CC-MB]

Vulnerability of most marine organisms to warming is set by their physiology which defines their limited temperature ranges and hence their thermal sensitivity (*high confidence*). See Figure TS.3. Temperature defines the geographic distribution of many species and their responses to climate change. Shifting temperature means and extremes alter habitat (e.g., sea ice and coastal habitat), and cause changes in abundance through local extinctions and latitudinal expansions or shifts of up to hundreds of kilometers per decade (*very high confidence*). Although genetic adaptation occurs (*medium confidence*), the capacity of fauna and flora to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). [6.3, 6.5]

Oxygen minimum zones are progressively expanding in the tropical Pacific, Atlantic, and Indian Oceans, due to reduced ventilation and O_2 solubilities in more stratified oceans at higher temperatures (*high confidence*). In combination with human activities that increase the productivity of coastal systems, hypoxic areas (“dead zones”) are increasing in number and size. Regional exacerbation of hypoxia causes shifts to hypoxia-tolerant biota and reduces habitat for commercially relevant species, with implications for fisheries. [6.1, 6.3, 30.3, 30.5-6; WGI AR5 3.8]

[INSERT FIGURE TS.3 HERE
Figure TS.3: Temperature specialization of species (A), which is influenced by other factors such as oxygen, causes warming-induced distribution shifts (B), for example, the northward expansion of warm-temperate species in the Northeast Atlantic (C). These distribution changes depend on species-specific physiology and ecology. Detailed introduction of each panel follows: (A) The temperature tolerance range and performance levels of an organism are described by its performance curve. Each performance (e.g., exercise, growth, reproduction) is highest at optimum temperature (T_{opt}) and lower at cooler or warmer temperatures. Surpassing temperature thresholds (T_p) means going into time-limited tolerance, and more extreme temperature changes lead to exceedance of thresholds that cause metabolic disturbances (T_c) and ultimately onset of cell damage (T_d). These thresholds for an individual can shift (horizontal arrows), within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) or low oxygen, thermal windows narrow (dashed grey curves). (B) During climate warming, a species follows its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the northern hemisphere). The polygon delineates the distribution range in space and seasonal time; the level of grey denotes abundance. (C) Long-term changes in the mean number of warm-temperate pseudo-oceanic copepod species in the Northeast Atlantic from 1958 to 2005. [Figures 6-5, 6-7, and 6-8]]

Food production systems and food security

Negative impacts of climate change on crop and terrestrial food production have been more common than positive impacts, which are evident in some high-latitude regions (*high confidence*). Production of wheat and maize globally and in many regional systems has been impacted by climate change over the past several decades (*medium confidence*). The impacts of climate change on rice and soybean have been small in major production regions and globally. See Figure TS.2E. Recent periods of rapid food and cereal price increases have indicated that current markets in key producing regions are sensitive to climate extremes (*high confidence*). Crop yields have a large negative sensitivity to extreme daytime temperatures around 30°C, throughout the growing season. CO_2 has stimulatory effects on crop yields in most cases, and elevated tropospheric ozone has damaging effects. Interactions among CO_2 and ozone, mean temperature, extremes, water, and nitrogen are non-linear and difficult to predict (*medium confidence*). [7.3, 18.4, 22.3, 24.4, 26.5, Figures 7-2, 7-3, and 7-7, Box 25-3]

Urban areas

Urban areas hold more than half the world's population and most of its built assets and economic activities. A high proportion of the population and economic activities at risk from climate change are in urban areas, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents. Cities are composed of complex inter-dependent systems that can be leveraged to support climate change adaptation via effective city governments supported by cooperative multi-level governance (*medium confidence*). This can enable synergies with infrastructure investment and maintenance, land-use management, livelihood creation, and ecosystem services protection. [8.1, 8.3-4]

Rapid urbanization and growth of large cities in low- and middle-income countries have been accompanied by expansion of highly vulnerable urban communities living in informal settlements, many of which are on land exposed to extreme weather (*medium confidence*). [8.2-3]

Rural areas

Climate change in rural areas will take place in the context of many important economic, social, and land-use trends (*very high confidence*). In different regions, absolute rural populations have peaked or will peak in the next few decades. The proportion of the rural population depending on agriculture is varied across regions, but declining everywhere. Poverty rates in rural areas are higher than overall poverty rates, but also falling more sharply, and the proportions of population in extreme poverty accounted for by rural people are also falling: in both cases with the exception of Sub-Saharan Africa, where these rates are rising. Accelerating globalization, through migration, labor linkages, regional and international trade, and new information and communication technologies, is bringing about economic transformation in rural areas of both developing and developed countries. [9.3, Figure 9-2]

For rural households and communities, access to land and natural resources, flexible local institutions, knowledge and information, and livelihood strategies can contribute to resilience to climate change (*high confidence*). **Especially in developing countries, rural people are subject to multiple non-climatic stressors, including under-investment in agriculture, problems with land and natural resource policy, and processes of environmental degradation (*very high confidence*).** In developed countries, there are important shifts towards multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors, and a change from subsidy-based to investment-based policy. [9.3, 22.4, Table 9-3]

Key economic sectors and services

Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, with a possible influence of climate change (*low confidence* in attribution to climate change). Flooding can have major economic costs, both in term of impacts (e.g., capital destruction, disruption) and adaptation (e.g., construction, defensive investment) (*robust evidence, high agreement*). Since the mid-20th century, socioeconomic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). [3.2, 3.4, 10.3, 18.4, 23.2-3, 26.7, Figure 26-2, Box 25-7]

Human health

In recent decades, climate change has *likely* contributed to human ill-health although the present world-wide burden of ill-health from climate change is relatively small compared with effects of other stressors and is not well quantified. There has been increased heat-related mortality and decreased cold-related mortality in some regions as a result of warming (*medium confidence*). Local changes in temperature and rainfall have altered distribution of some water-borne illnesses and disease vectors and have reduced food production for some vulnerable populations (*medium confidence*). [11.4-6, 18.4, 22.3, 24.4, 25.8, 26.6, 28.2]

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and in the occurrence of heat waves, floods, droughts, and fires. Health may be damaged indirectly by climate-change-related ecological disruptions, such as crop failures or shifting patterns of disease vectors, or by social responses to climate change, such as displacement of populations following prolonged drought. Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. [11.4, 28.2]

Human security

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance (*high confidence*). Violent conflict strongly influences vulnerability to climate change impacts for people living in affected places (*medium evidence, high agreement*). Large-scale violent conflict harms assets that facilitate adaptation, including infrastructure, institutions, natural capital, social capital, and livelihood opportunities. [12.5, 19.4, 19.6]

Livelihoods and poverty

Climate-related hazards constitute an additional burden to people living in poverty, acting as a threat multiplier often with negative outcomes for livelihoods (*high confidence*). Climate-related hazards affect poor people's lives directly through impacts on livelihoods, such as reductions in crop yields or destruction of homes, and indirectly through increased food prices and food insecurity. Urban and rural transient poor who face multiple deprivations can slide into chronic poverty as a result of extreme events, or a series of events, when unable to rebuild their eroded assets (*limited evidence, high agreement*). Limited positive observed impacts on poor people include isolated cases of social asset accumulation, agricultural diversification, disaster preparedness, and collective action. [9.3, 11.3, 13.1-3, 22.4, 24.4, 26.8]

Livelihoods of indigenous peoples in the Arctic have been altered by climate change, through impacts on food security and traditional and cultural values (*medium confidence*). There is emerging evidence of climate change impacts on livelihoods of indigenous people in other regions. [18.4, Table 18-9, Box 18-5]

A-2. Adaptation Experience

This section focuses on adaptive human responses to climate change and its impacts. People cope with climate variability, extremes, and change, and they manage risks through adaptation. Adaptive human responses can be motivated by observed and projected climate change impacts and by broader vulnerability-reduction and development objectives, such as reducing existing adaptation deficits to current climate.

Adaptation is already occurring and is becoming embedded in some planning processes (*high confidence*). Engineered and technological adaptation options are the most commonly implemented adaptive responses. There is increasing recognition of the value of ecosystem-based, institutional, and social measures, including provision of social protection measures, and of linkages with disaster risk reduction. Governments at various scales are starting to develop adaptation plans and policies. Selection of adaptation options continues to emphasize incremental adjustments and co-benefits and is starting to emphasize flexibility and learning (*medium evidence, medium agreement*). [4.4, 5.5, 6.4, 8.3, 9.4, 11.7, 14.1, 14.3, 15.2-4, 17.2-3, 22.3-5, 23.7, 25.4, 25.10, 26.8-9, 27.3, 30.6, Boxes 25-1, 25-2, 25-9, and CC-EA]

Most evaluations of adaptation have been restricted to impacts, vulnerability, and adaptation planning, with very few assessing the processes of implementation or actual adaptation actions (*medium evidence, high agreement*). Vulnerability indicators define, quantify, and weight aspects of vulnerability across regional units, but methods of constructing indices are subjective, often lack transparency, and can be difficult to interpret. There are conflicting views on the choice of adaptation metrics, given differing values placed on needs and outcomes, many of which cannot be captured in a comparable way by metrics. Indicators proving most useful for policy learning are those that track not just process and implementation, but also the extent to which targeted outcomes are occurring. Multi-metric evaluations including risk and uncertainty are increasingly used, an evolution from a previous focus on cost-benefit analysis and identification of "best economic adaptations" (*high confidence*). Adaptation assessments best suited to delivering effective adaptation measures often include both top-down assessments of biophysical climate changes and bottom-up assessments of vulnerability targeted towards local solutions to globally derived risks and towards particular decisions. [4.4, 14.4-5, 15.2-3, 17.2-3, 21.3, 21.5, 22.4, 25.4, 25.10, 26.8-9, Box CC-EA]

Specific examples of adaptation actions across regions and contexts include the following:

- Urban adaptation has emphasized city-based disaster risk management such as early warning systems and infrastructure investments; ecosystem-based adaptation and green roofs; enhanced storm and wastewater management; urban and peri-urban agriculture improving food security; enhanced social protection; and good-quality, affordable, and well-located housing (*high confidence*). [8.3-4, 15.4, 26.8, Boxes 25-9, CC-UR, and CC-EA]
- There is a growing body of literature on adaptation practices in both developed- and developing-country rural areas, including documentation of practical experience in agriculture, water, forestry, and biodiversity and, to a lesser extent, fisheries (*very high confidence*). Public policies supporting decision-making for adaptation in rural areas exist in developed and, increasingly, developing countries, and there are also examples of private adaptations led by individuals, companies, and NGOs (*high confidence*). Adaptation constraints, particularly pronounced in developing countries, result from lack of access to credit, land, water, technology, markets, information, and perceptions of the need to change. [9.4, 17.3, Tables 9-7 and 9-8]
- In Africa, most national governments are initiating governance systems for adaptation (*high confidence*). Progress on national and sub-national policies and strategies has initiated the mainstreaming of adaptation into sectoral planning, but evolving institutional frameworks cannot yet effectively co-ordinate the range of adaptation initiatives being implemented. Disaster risk management, social protection, adjustments in technologies and infrastructure, ecosystem-based approaches, conservation agriculture, and livelihood diversification are reducing vulnerability, but largely in isolated initiatives. [11.7, 22.4, Box CC-EA]
- In Europe, adaptation policy has been developed at international (EU), national, and local government levels, with limited systematic information on current implementation or effectiveness (*high confidence*). Some adaptation planning has been integrated into coastal and water management and into disaster risk management, but there is *limited evidence* of adaptation planning in rural development or land-use planning. [11.7, 23.7, Box 23-3]
- In Asia, community-based approaches are a means to address poverty and livelihoods as well as facilitate integration of disaster risk reduction, development, and climate change adaptation (*limited evidence, high agreement*). Adaptation practices have sometimes provided unexpected livelihood benefits, as with the introduction of traditional flood mitigation measures in China, which have led to reductions in the physical and economic vulnerabilities of communities. Adaptation has also been expedited though integrated water resource management. [11.7, 24.4]
- In Australasia, planning for sea-level rise and, in southern Australia, for reduced water availability is becoming widely adopted, although implementation of specific policies remains piecemeal, subject to political changes, and open to legal challenges (*high confidence*). Adaptive capacity is generally high in many human systems, but implementation faces major constraints especially for transformational responses at local and community levels. [25.4, 25.10, Table 25-2, Boxes 25-1, 25-2, and 25-9]
- In North America, governments are engaging in incremental adaptation assessment and planning, particularly at the municipal level, with some proactive adaptation anticipating future impacts for longer-term investments in energy and public infrastructure (*high confidence*). [26.8-9]
- In Central and South America, ecosystem-based adaptation practices, such as adaptive management and establishment of protected areas, conservation agreements, and community management of natural areas, are

increasingly common, with potential for balancing biodiversity conservation, improving livelihoods, and preserving traditional cultures (*high confidence*). [27.3]

- In the Arctic, residents have a history of adapting to change, but the rate of climate change and complex inter-linkages with societal, economic, and political factors represent unprecedented challenges for northern communities (*high confidence*). [28.2, 28.4]
- In small islands, diverse physical and human attributes and their sensitivity to climate-related drivers have been inconsistently integrated into adaptation planning (*high confidence*). [Table 29-3, Figure 29-1]
- Observed coastal adaptation includes major projects (e.g., Thames Estuary, Venice Lagoon, Delta Works) and specific practices in some countries (e.g., Netherlands, Australia, Bangladesh) (*high confidence*). [5.5, 7.3, 15.4, Box CC-EA]
- Ocean adaptation strategies beyond coastal areas are generally poorly developed (*high confidence*). [30.6]

Table TS.2 presents examples of how climate extremes and change, as well as exposure and vulnerability at the scale of risk management, shape adaptation actions and approaches to reducing vulnerability and enhancing resilience.

[INSERT TABLE TS.2 HERE
Table TS.2: Illustrative examples of adaptation experience, as well as approaches to reducing vulnerability and enhancing resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerability, exposure, and climate change come to the fore. [Table 21-4]]

A-3. The Decision-making Context

Responding to climate-related risks involves making decisions and taking actions in the face of continuing uncertainty about the extent of climate change and the severity of impacts in a changing world, with potential limits to the effectiveness of incremental approaches (*high confidence*). Iterative risk management is a useful framework for decision-making in situations characterized by large potential consequences, persistent uncertainties, long timeframes, potential for learning, and multiple influences changing over time, such as climate and non-climatic stressors. See Figure TS.4. Assessment of the full range of potential future impacts, including low-probability outcomes with large consequences, is central to understanding future risks and the benefits and tradeoffs of alternative risk management actions. The increasing complexity of adaptation actions across scales and contexts means that institutional learning and monitoring are important components of effective adaptation. [2.1-4, 3.6, 14.1-5, 15.2-3, 15.5, 16.2-4, 17.2, 20.6, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1 and 25-2]

[INSERT FIGURE TS.4 HERE
Figure TS.4: Illustration of iterative risk management. [Figure 2-1]]

The benefits of mitigation and adaptation occur over different timeframes (*high confidence*). Figure TS.5 illustrates projected climate futures under scenarios RCP2.6 and 8.5, along with observed temperature and precipitation changes. Projected global temperature increase over the next few decades is similar across emission scenarios. [WGI AR5 11.3] During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. Societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increase diverges across emission scenarios. [WGI AR5 12.4 and Table SPM.2] For this longer-term era of climate options, near-term and ongoing mitigation and adaptation, as well as development pathways, will determine the risks of climate change. Present-day choices thus affect the risks of climate change throughout the 21st century. [2.5, 21.2-3, 21.5, Box CC-RC]

[INSERT FIGURE TS.5 HERE
Figure TS.5: Observed and projected changes in annual average temperature (A) and precipitation (B). (A, top panel) Observed temperature trends from 1901-2012 determined by linear regression. [WGI AR5 Figures SPM.1 and 2.21] (B, top panel) Observed precipitation change from 1951-2010 determined by linear regression. [WGI AR5 Figure SPM.2] For observed temperature and precipitation, trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data

availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. (A, middle panel) Observed and simulated variations in past and projected future global annual average temperature relative to 1986-2005. Black lines show the GISTEMP, NCDC-MLOST, and HadCRUT4.2 estimates from observational measurements. Blue and red shading denotes the ±1.64 standard deviation range based on simulations from 32 models for RCP2.6 and 39 models for RCP8.5; blue and red lines denote the ensemble mean for each scenario. For future projections, light-gray vertical bands specify an indicative timeframe (2030-2040) for the near-term era of committed climate change and an indicative timeframe (2080-2100) for the longer-term era of climate options. [Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7] (A and B, bottom panel) CMIP5 multi-model mean projections of annual average temperature changes (A) and average percent change in annual mean precipitation (B) for 2081-2100 under RCP2.6 and 8.5, relative to 1986-2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability, although there may be significant change at shorter timescales such as seasons, months, or days. Analysis uses model data from WGI AR5 Figure SPM.8, with full description of methods in Box CC-RC. See also Annex I of WGI AR5. [Boxes 21-2 and CC-RC]]

Adaptation planning and implementation at a range of scales are contingent on values, objectives, and risk perceptions (*high confidence*). Some types of adaptation options, such as insurance or large-scale infrastructure projects, may differentially affect stakeholders. Awareness that climate change may exceed the adaptive capacity of some people and ecosystems may have ethical implications for mitigation decisions and investments. Recognition of diverse interests, values, and expectations, including local and indigenous knowledge, can benefit decision-making processes. Economic analysis of adaptation is moving away from a unique emphasis on efficiency, market solutions, and benefit/cost analysis to include consideration of non-monetary and non-market measures, risks, inequities, behavioral biases, barriers and limits, and consideration of ancillary benefits and costs. [2.2-4, 12.3, 15.2, 16.2-4, 16.6-7, 17.2-3, 21.3, 22.4, 25.4, 25.8, 26.7, 26.9, Table 15-1, Boxes 16-1, 16-4, and 25-7]

Decision support is most effective when it is sensitive to context, taking into account the diversity of different types of decisions, decision processes, and constituencies (*robust evidence, high agreement*). Organizations bridging science and policy play an important role in the communication and transfer of climate-related knowledge, such as information on risks combining physical climate science and assessments of impacts, adaptation, and vulnerability (*medium evidence, high agreement*). [2.1-4, 8.4, 14.4, 16.2-3, 16.5, 21.2-3, 21.5, 22.4, Box 9-4]

Scenarios are useful tools for characterizing possible future socioeconomic pathways, climate change and its risks, and policy implications (*high confidence*). Climate change risks vary substantially across plausible alternative development pathways, and the relative importance of development and climate change varies by sector, region, and time period. Both development and climate change are important determinants of possible outcomes. Modeled future impacts assessed in this report are generally based on climate-model projections using the Representative Concentration Pathway (RCP) and the older IPCC Special Report on Emission Scenarios (SRES) scenarios. [1.1, 1.3, 2.2-3, 19.6, 20.2, 21.3, 21.5, 26.2, Box CC-RC; WGI AR5 Box SPM.1]

Scenarios can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration) (*robust evidence, high agreement*). Adaptation approaches address uncertainties associated with future climate and socioeconomic conditions and with the diversity of specific contexts (*medium evidence, high agreement*). Although many national studies identify a variety of strategies and approaches for adaptation, they can be classified into two broad categories: 'top-down' and 'bottom-up' approaches. The top-down approach is a scenario-impact approach, consisting of downscaled climate projections, impact assessments, and formulation of strategies and options. The bottom-up approach is a vulnerability-threshold approach, starting with identification of vulnerabilities, sensitivities, and thresholds for specific sectors or communities. Iterative assessments of impacts and adaptation in the top-down approach and building adaptive capacity of local communities are typical strategies for responding to uncertainties. [2.2-3, 15.3]

Uncertainties about future vulnerability, exposure, and responses of human and natural systems can be larger than uncertainties in regional climate projections, and they are beginning to be incorporated in assessments of future risks (*high confidence*). Understanding future vulnerability, as well as exposure, of interlinked human and natural systems is challenging due to the number of relevant socioeconomic factors, which have been incompletely considered to date. These factors include wealth and its distribution across society, patterns of aging, access to technology and information, labor force participation, the quality of adaptive responses, societal values, and mechanisms and institutions to resolve conflicts. Cross-regional phenomena are also important for understanding the ramifications of climate change at regional scales. [11.3, 21.3-5, 25.3-4, 25.11, 26.2]

B) FUTURE RISKS AND OPPORTUNITIES FOR ADAPTATION

This section presents future risks and more limited potential benefits across sectors and regions, examining how they are affected by the magnitude and rate of climate change and by development choices. It also points to opportunities for reducing risks through mitigation and adaptation. The section examines the distribution of risks across populations with contrasting vulnerability and adaptive capacity, across sectors where metrics for quantifying impacts may be quite different, and across regions with varying traditions and resources. The assessment features interactions across sectors and regions and among climate change and other stressors. The section describes risks and potential benefits over the next few decades, the near-term era of committed climate change. Over this timeframe, magnitude of projected climate change is similar across high and low emission scenarios. The section also provides information on risks and potential benefits in the second half of the 21st century and beyond, the longer-term era of climate options. Over this longer term, magnitude of climate change diverges across high and low emission scenarios, and the assessment distinguishes potential outcomes for 2°C and 4°C global mean temperature increase above preindustrial levels. The section elucidates how and when choices matter in reducing future risks, highlighting the differing timeframes for mitigation and adaptation benefits.

B-1. Key Risks across Sectors and Regions

Many risks of climate change warrant consideration. Key risks, in particular, are potentially severe impacts relevant to "dangerous anthropogenic interference with the climate system," as described in Article 2 of the United Nations Framework Convention on Climate Change. Key risks can involve potentially large or irreversible consequences, high probability of consequences, and/or limited adaptive capacity. Key risks are integrated into five overarching reasons for concern (RFCs) in Box TS.5.

Key risks that span sectors and regions (*high confidence*) include the following, each of which contributes to one or more RFC. Roman numerals correspond to entries in Table TS.3, which further illustrates relevant examples and interactions. [19.2-4, 19.6, Table 19-4, Boxes 19-2 and CC-KR]

i. Risk of death, injury, and disruption to livelihoods, food supplies, and drinking water, in addition to loss of common-pool resources, sense of place, and identity, due to sea-level rise, coastal flooding, and storm surges affecting high concentrations of people, economic activity, biodiversity, and critical infrastructure in low-lying coastal zones and small island developing states. See RFC 1-5. [5.4, 8.1-2, 13.1-2, 19.2-4, 19.6-7, 24.4-5, 26.7-8, 29.3, 30.3, Tables 19-4 and 26-1, Figure 26-2, Boxes 25-1, 25-7, and CC-KR]
ii. Risk of food insecurity and breakdown of food systems linked to warming, drought, and precipitation variability, particularly in regions with poorer populations. See RFC 2-4. [3.5, 7.4-5, 11.3, 11.6, 13.2, 19.3-4, 19.6, 22.3, 24.4, 25.5, 25.7, 26.5, 26.8, 27.3, Table 19-4, Figure 7-4, Boxes CC-KR and CC-VW]
iii. Risk of severe harm due to inland flooding and limited coping and adaptive capacities of large urban populations. See RFC 2 and 3. [3.2, 3.4-5, 8.1-2, 13.2, 19.6, 25.10, 26.3, 26.7-8, 27.3, Tables 19-4 and 26-1, Boxes 25-8 and CC-KR]
iv. Risk of loss of rural livelihoods and income of rural residents due to insufficient access to drinking and irrigation water and reduced agricultural productivity, as well as risk of food insecurity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. See RFC 2 and 3. [3.2, 3.4-5, 8.2, 9.3, 12.3, 13.2, 19.3, 19.6, 24.4, 25.7, 26.8, Table 19-4, Boxes 25-5 and CC-KR]
v. Systemic risks due to multiple interacting hazards affecting infrastructure networks in combination with a high dependency of people on critical services (e.g., electricity, water supply, and health and emergency services) that may break down during extreme events. See RFC 2-4. [8.1-2, 10.2-3, 12.6, 19.6, 23.9, 25.10, 26.7-8, 28.3, Table 19-4, Boxes CC-KR and CC-HS]
vi. Risk of loss of marine ecosystems and the services they provide for coastal livelihoods. Biodiversity and coastal ecosystem services important for fishing communities in the tropics and the Arctic are especially at risk due to rising water temperature, increased stratification, and ocean acidification. See RFC 1-5. [5.4, 6.3, 7.4, 9.3, 19.5-6, 22.3, 25.6, 27.3, 28.2-3, 29.3, 30.5-7, Table 19-4, Boxes CC-OA, CC-CR, CC-KR, and CC-HS]
vii. Risk of loss of terrestrial ecosystems and the services they provide for terrestrial livelihoods. These services are at risk due to rising temperatures, changes in precipitation patterns, and extreme weather events. Risks are high for communities whose livelihoods depend on provisioning services. See RFC 1, 3, and 4. [4.3, 19.3-6, 22.3-4, 25.6, 27.3, 28.2-3, Tables 19-4 and 23-2, Boxes CC-KR and CC-WE]

viii. Risk of mortality, morbidity, and other harms during periods of extreme heat, particularly for urban populations of the elderly, infants, people with chronic ill-health, and expectant mothers. Increasing frequency and intensity of extreme heat (including exposure to the urban heat island effect and air pollution) interacts with an inability of some local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups. See RFC 2 and 3. [8.1-2, 11.3-4, 13.2, 19.3, 19.6, 23.5, 24.4, 25.8, 26.6, 26.8, Tables 19-4 and 26-1, Boxes CC-KR and CC-HS]

[INSERT TABLE TS.3 HERE
Table TS.3: A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in chapters of this report. The examples underscore the complexity of risks determined by various interacting climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities (see also Figure TS.1). Vulnerabilities identified as key arise when exposure to hazards combines with social, institutional, economic, or environmental vulnerability, as indicated by icons in the table. Emergent risks arise from complex-system interactions. Roman numerals correspond with key risks listed in section B-1. [19.6, Table 19-4]]

Mitigation of greenhouse gas emissions can substantially reduce risks of climate change in the second half of the 21st century (*high confidence*). Examples include reduced risk of negative agricultural yield impacts, of water scarcity, of major challenges to urban settlements and infrastructure from sea-level rise, and of adverse impacts from heat extremes, floods, and droughts in areas where increased occurrence of these extremes are projected. Under all assessed scenarios for mitigation and adaptation, some risk from residual damages is unavoidable (*very high confidence*). Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades, but adaptation cannot generally overcome all climate change effects. In addition to biophysical limits to adaptation for example under high temperatures, some adaptation options will be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs (*high confidence*). Some mitigation or adaptation options also pose risks. [3.4-5, 4.2, 4.4, 16.3, 16.6, 17.2, 19.7, 20.3, 22.4-5, 25.10, Tables 3-2, 8-3, and 8-5, Boxes 13-2, 16-3, and 25-1]

Large magnitudes of warming increase the likelihood of severe, pervasive, and challenging impacts. Risks associated with global temperature rise in excess of 4°C relative to preindustrial levels include potential adverse impacts on agricultural production worldwide, potentially extensive ecosystem impacts, and increasing species extinction risk (*high confidence*), as well as possible crossing of thresholds that lead to disproportionately large earth system responses (*low confidence*). The precise levels of climate change sufficient to trigger tipping points (critical thresholds) remain uncertain, but the likelihood of crossing tipping points in the earth system or interlinked human and natural systems decreases with reduced greenhouse gas emissions (*medium confidence*). [4.2-3, 11.8, 19.5, 19.7, 26.5, Box CC-HS]

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Box TS.5. Human Interference with the Climate System

Human interference with the climate system is occurring, yet determining whether this interference is dangerous, as relevant to Article 2 of the UNFCCC, involves both risk assessment and value judgments. Scientific assessment can characterize risks based on the likelihood, magnitude, and scope of potential consequences of climate change. Science can also evaluate risks varying spatially and temporally across alternative development pathways, which affect vulnerability, exposure, and level of climate change. Interpreting the potential danger of risks, however, also requires value judgments by people with differing goals and worldviews. Judgments about the risks of climate change depend on the relative importance ascribed to economic vs. ecosystem assets, to the present vs. the future, and to the distribution vs. aggregation of impacts. From some perspectives, isolated or infrequent impacts from climate change may not rise to the level of dangerous anthropogenic interference, but accumulation of the same kinds of impacts could, as they become more widespread, more frequent, or more severe. The rate of climate change can also influence risks. This report assesses risks across contexts and through time, providing a basis for value judgments about the level of climate change at which risks become dangerous.

Five integrative reasons for concern (RFCs) provide a framework for summarizing key risks across sectors and regions. First identified in the IPCC Third Assessment Report, the reasons for concern illustrate the implications of warming and of adaptation limits for people, economies, and ecosystems. They provide one starting point for evaluating dangerous anthropogenic interference with the climate system. An updated assessment of risks for each reason for concern is presented below and in Box TS.5 Figure 1. All temperature changes are given relative to 1986-2005 ("recent"). [18.6, 19.6]

(1) ***Unique and threatened systems:*** Some unique and threatened systems, including ecosystems and cultures, are at risk from climate change at recent temperatures. The number of such systems at risk of severe consequences increases at warming of 1°C. Many species and systems with limited adaptive capacity are subject to very high risks at warming of 2°C, particularly Arctic sea ice systems and coral reefs (*high confidence*).
(2) ***Extreme weather events:*** Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are moderate at recent temperatures (*high confidence*) and high at 1°C warming (*medium confidence*).
(3) ***Distribution of impacts:*** Risks for disproportionately affected people and communities are generally greatest in low-latitude, less-developed areas, and are moderate at recent temperatures because of regionally differentiated climate-change impacts on food production (*medium* to *high confidence*). Developed countries also have highly vulnerable populations. Based on risks for regional crop production and water resources in some countries, risks become high for warming above 2°C (*medium confidence*).
(4) ***Global aggregate impacts:*** Risks to the overall global economy and Earth's biodiversity become moderate for warming between 1-2°C (*medium confidence*) and high around 3°C, reflecting warming-dependent increases in risks of economic impacts (*low confidence*) and extensive biodiversity loss with concomitant loss of ecosystem services (*high confidence*).
(5) ***Large-scale singular events:*** With increasing warming, some physical systems or ecosystems may be at risk of abrupt and drastic changes. Risks of such tipping points become moderate between 0-1°C, due to early warning signs that both coral reef and Arctic systems are already experiencing irreversible regime shifts. Risks become high between 1-4°C, with a disproportionate increase in risks as temperature increases between 1-2°C, due to the potential for commitment to a large and irreversible sea-level rise from ice sheet loss (*medium confidence*).

[INSERT BOX TS.5 FIGURE 1 HERE
Box TS.5 Figure 1: (Right panel) The dependence of risks associated with reasons for concern on the level of climate change, updated based on assessment of the literature and expert judgments. Purple shading, introduced in this assessment, indicates very high risk of severe impacts and the presence of significant irreversibilities combined with limited adaptive capacity. [Figure 19-4] (Left panel) Observed and simulated variations in past and projected future global annual average temperature relative to 1986-2005, as in Figure TS.5. [Figure RC-1, Box CC-RC; WGI AR5 Figures SPM.1 and SPM.7]]

_____ END BOX TS.5 HERE _____

_____ START BOX TS.6 HERE _____

Box TS.6. Consequences of Large Temperature Increase

This box provides a selection of salient climate change impacts projected for large temperature rise. Warming levels described here (e.g., 4°C warming) refer to global mean temperature increase above preindustrial levels.

With 4°C warming, climate change is projected to become the dominant driver of impacts on ecosystems, superseding drivers such as land-use change. [4.2.4, 19.5.1, 26.3] A number of studies project large increases in water stress, groundwater supplies, and drought in a number of regions with >4°C warming, and decreases in others, generally placing already arid regions at greater water stress. [19.5.1, Box 26-1]

Risks of large-scale singular events such as ice sheet disintegration, methane release from clathrates, and onset of long-term droughts in areas such as southwest North America [Box 26-1; WGI AR5 12.4.5, 12.5.5, 13.4], as well as regime shifts in ecosystems and substantial species loss [4.3.2, 19.6.3], are higher with increased warming. Sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea-level rise of up to 7 m (*high confidence*); current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming. [WGI AR5 5.8, 13.4-5] Abrupt and irreversible ice loss from a potential instability of marine-based areas of the Antarctic ice sheet in response to climate forcing is possible, but current evidence and understanding is insufficient to make a quantitative assessment. [19.6.3; WGI AR5 5.8, 13.4-5] Sea-level rise of 0.45-0.82 m (mean 0.63m) is *likely* by 2081-2100 under RCP8.5 (*medium confidence*) [WGI AR5 Table 13.5], with sea level continuing to rise beyond 2100.

The Atlantic Meridional Overturning Circulation (AMOC) is considered *very likely* to weaken over the 21st century, with a best estimate of 34% loss (range 12-54%) under RCP8.5. [WGI AR5 12.4] The release of CO_2 or CH_4 to the atmosphere from thawing permafrost carbon stocks over the 21st century is assessed to be in the range of 180 to 910 $GtCO_2$ for RCP8.5 (*low confidence*). [WGI AR5 6.4] A nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*). [WGI AR5 11.3, 12.4-5]

For RCP8.5 by 2100, the combination of high temperatures and high humidity in some areas for parts of the year will compromise normal human activities, including growing food or working outdoors (*high confidence*). [11.8.1] Above 4°C local warming, risks for food security become very significant (*high confidence*). [7.5, Table 7-3, Figure 7-7]

Under 4°C warming, some models project large increases in fire risk in parts of the world. [4.3.3, Figure 4-6] 4°C warming implies a substantial increase in extinction risk for terrestrial and freshwater species, although there is *low agreement* concerning the fraction of species at risk. [4.3.2] Widespread coral reef mortality is expected with significant impacts on coral reef ecosystems (*high confidence*). [5.4.2, Box CC-CR] Assessments of potential ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*). [4.3.2, 4.3.4, 19.3.2, Box 25-6]

Projected large increases in exposure to water stress, fluvial and coastal flooding, negative impacts on crop yields, and disruption of ecosystem function and services would represent large, potentially compounding impacts of climate change on society generally and on the global economy. [19.4.3, 19.5.1, 19.6.3, 26.3, 26.7, 26.8, Figure 7-4]

_____ END BOX TS.6 HERE _____

B-2. Sectoral Risks and Potential for Adaptation

For the near-term era of committed climate change (the next few decades) and the longer-term era of climate options (the second half of the 21st century), climate change will amplify climate-related risks to natural and human systems, dependent on the magnitude and rate of climate change and on the vulnerability and exposure of interlinked human and natural systems. Some of these risks will be limited to a particular sector or region, and others will have cascading effects. To a lesser extent, climate change will also reduce some climate-related risks and have some potential benefits. Key sectoral risks identified with *medium* to *high confidence* are presented in Table TS.4. For extended summary of sectoral risks and the more limited potential benefits, see introductory overviews for each sector below and also Chapters 3-13.

[INSERT TABLE TS.4 HERE
Table TS.4: Key sectoral risks from climate change and the potential for reducing risks through mitigation and adaptation. Risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature, as detailed in supporting chapter sections. Each key risk is characterized as very low to very high for three timeframes: the present, near-term (here, assessed over 2030-2040), and longer-term (here, assessed over 2080-2100). Assessed risk levels integrate probability and consequence over the full range of possible outcomes, acknowledging the importance of differences in values and objectives in interpretation of the assessed risk levels. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels, illustrating the potential role of mitigation in reducing risks. For the present, risk levels are estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the future, risk levels are estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Relevant climate variables are indicated by icons. Risk levels are not necessarily comparable across sectors because the assessment considers potential impacts and adaptation across diverse physical, biological, and human systems.]

Freshwater resources

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas emissions (*robust evidence, high agreement*). By the end of the 21st century, the number of people exposed annually to a 20th-century 100-year river flood is projected to be three times greater for RCP8.5 than for RCP2.6. See Figure TS.6. In presently dry regions, drought frequency will *likely* increase by the end of this century under RCP8.5 (*medium confidence*). [3.4-5, 26.3, Tables 3-2 and 25-1, Box 25-8; WGI AR5 12.4.5]

Climate change will reduce renewable surface water and groundwater resources significantly in most dry subtropical regions, exacerbating competition for water among sectors (*robust evidence, high agreement*). In contrast, water resources will increase at high latitudes. Each degree of warming is projected to decrease renewable water resources by at least 20% for an additional 7% of the global population. Climate change is projected to reduce raw water quality and pose risks to drinking water quality, due to interacting factors: increased temperature; increased sediment, nutrient, and pollutant loadings from heavy rainfall; reduced dilution of pollutants during droughts; and disruption of treatment facilities during floods (*medium evidence, high agreement*). [3.2, 3.4-5, 22.3, 25.5, 26.3, Table 3-2, Boxes 25-10 and CC-WE]

Adaptive water management techniques, including scenario planning, learning-based approaches, and flexible and low-regret solutions, can address uncertainty due to climate change (*limited evidence, high agreement*). Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication. [3.6, Box 25-2]

[INSERT FIGURE TS.6 HERE
Figure TS.6: Projected change in river flood return period and exposure, based on one hydrological model driven by 11 CMIP5 GCMs and on global population in 2005. (A) In the 2080s under RCP8.5, multi-model median return period (years) for the 20th-century 100-year flood. (B) Global exposure to the 20th-century 100-year flood in millions of people. Left: ensemble means of historical (black line) and future simulations (colored lines) for each scenario. Shading denotes ±1 standard deviation. Right: maximum and minimum (whiskers), mean (horizontal lines within each bar), ±1 standard deviation (box), and projections of each GCM (colored symbols) averaged over the 21st century. [Figure 3-6]]

Terrestrial and freshwater ecosystems

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and 8.5 (*high confidence*). Through to 2040 globally, direct human impacts such as land-use change, pollution, and water resource development will continue to dominate threats to most freshwater ecosystems (*high confidence*) and most terrestrial ecosystems (*medium confidence*). Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-range rates of climate change (i.e., RCP4.5, 6.0, and 8.5) (*medium confidence*). See Figure TS.7. Tree mortality and associated forest dieback will occur in many regions in the next one to three decades (*medium confidence*), with forest dieback posing risks for carbon storage, biodiversity, wood production, water quality, amenity, and economic activity. Management actions can reduce, but not eliminate, risks to ecosystems and can increase ecosystem adaptability, for example through reduction of other stresses and habitat fragmentation, maintenance of genetic diversity, assisted translocation, and manipulation of disturbance regimes (*high confidence*). [4.3-4, 25.6, 26.4, Boxes 4-2, 4-3, and CC-RF]

A large fraction of terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, over-exploitation, pollution, and invasive species (*high confidence*). Extinction risk is increased under all RCP scenarios, with risk increasing with both magnitude and rate of climate change. Models project that the risk of species extinctions will increase in the future due to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic distribution of such extinctions, and the timeframe over which extinctions could occur. Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either underestimated or overestimated when based on simpler models. [4.3, 25.6]

Within this century, magnitudes and rates of climate change associated with RCP4.5, 6.0, and 8.5 pose high risk of abrupt and irreversible regional-scale change in the composition, structure, and function of terrestrial and freshwater ecosystems, for example in the boreal-tundra Arctic system and the Amazon forest, leading to substantial additional climate change (*medium confidence*). For the boreal-tundra system, continued climate change will transform the species composition, land cover, drainage, and permafrost extent of the boreal-tundra system, leading to decreased albedo and the release of greenhouse gases (*medium confidence*), with adaptation measures unable to prevent substantial change (*high confidence*). Increased severe drought together with land-use change and forest fire would cause much of the Amazon forest to transform to less-dense drought- and fire-adapted ecosystems, increasing risk for biodiversity while decreasing net carbon uptake from the atmosphere (*medium confidence*). Large reductions in deforestation, as well as wider application of effective wildfire management, will lower the risk of abrupt change in the Amazon, as well as potential negative impacts of that change (*medium confidence*). [4.2-3, Figure 4-8, Boxes 4-3 and 4-4]

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal timescale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss to the atmosphere as a result of climate change, deforestation, and ecosystem degradation. [4.2-3, Box 4-3]

[INSERT FIGURE TS.7 HERE
Figure TS.7: Rates of climate change (A), corresponding climate velocities (B), and rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention (C). Horizontal and vertical pink bands provide a guide to interpretation of the figure. Species groups with displacement rates left of each band (in C) are projected to be unable to track climate in the absence of human intervention. Extended introduction of each panel follows: (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis; all other rates are calculated based on the average of CMIP5 climate model ensembles for the historical period (grey shading indicates model uncertainty) and for the future based on the four RCPs. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one member per model. (B) Estimates of climate velocity for temperature were synthesized from historical and projected future relationships between rates of temperature change and climate velocity. The three scalars are climate velocities representative of mountainous areas (left), the global-land-area average (center), and large flat regions (right). (C) Rates of displacement for trees, plants, mammals, birds, plant-feeding insects, and freshwater mollusks. [Figure 4-5]]

Coastal systems and low-lying areas

Due to sea-level rise throughout the 21st century and beyond, coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion (*very high confidence*). The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development, and urbanization (*high confidence*). [5.3-5, 22.3, 24.4, 25.6, 26.3, 26.8, Table 26-1, Box 25-1]

By 2100, due to climate change and development patterns and without adaptation, hundreds of millions of people will be affected by coastal flooding and displaced due to land loss (*high confidence*). The majority affected will be in East, Southeast, and South Asia. The relative costs of adaptation vary strongly among and within regions and countries for the 21st century (*high confidence*). Some low-lying developing countries and small island states are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of GDP. [5.3-5, 24.4, 25.6, Box 25-1]

Marine systems

By mid 21st century, spatial shifts of marine species will cause species richness to increase at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium confidence*). Species displacements are projected to lead to high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas. Animal displacements will cause a 30-70% increase in the fisheries yield of some high-latitude regions by 2055 (relative to 2005), a redistribution at mid latitudes, and a drop of 40-60% in some of the tropics and the Antarctic, for 2°C warming above preindustrial levels (*medium confidence* for direction of fisheries' yield trends, *low confidence* for the precise magnitudes of yield change). See Figure TS.8A. Open-ocean net primary production is projected to redistribute and to fall globally by 2100 under RCP8.5 (*medium confidence*). [6.3-5, 25.6, 28.3, 30.4-6, Boxes CC-MB and CC-PP]

The progressive redistribution of species and the reduction in marine biodiversity in sensitive regions and habitats puts the sustained provision of fisheries productivity and other ecosystem services at risk, which will increase due to warming by 1°C or more by 2100 compared to the present, with limited adaptive capacity of human societies (*high confidence*). Socioeconomic vulnerability is highest in developing tropical countries, leading to risks from reduced supplies, income, and employment from marine fisheries. [6.4-5]

Ocean acidification poses risks to ecosystems, especially polar ecosystems and coral reefs, associated with impacts on the physiology, behavior, and population dynamics of individual species (*medium* to *high confidence*). See Box TS.7. Highly calcified mollusks, echinoderms, and reef-building corals are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*), with potential consequences for fisheries and livelihoods (Figure TS.8B). Ocean acidification occurs in combination with other environmental changes, both globally (e.g., warming, decreasing oxygen levels) and locally (e.g., pollution, eutrophication) (*high confidence*). Simultaneous environmental drivers, such as warming and ocean acidification, can lead to interactive, complex, and amplified impacts for species. [5.3-4, 6.3, 6.5, 22.3, 25.6, 28.2-3, 30.4-5, Boxes CC-CR and CC-OA]

Climate change adds to the threats of over-fishing and other non-climatic stressors, thus complicating marine management regimes (*high confidence*). In the short term, strategies including climate forecasting and early warning systems can reduce risks from ocean warming and acidification for some fisheries and aquaculture industries. Fisheries and aquaculture industries with high-technology and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling, and resource assessments. For smaller-scale fisheries and developing nations, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. [6.4, 7.3-4, 25.6, 29.4, 30.6-7]

[INSERT FIGURE TS.8 HERE
Figure TS.8: Climate change risks for fisheries. (A) For 2°C increase from preindustrial levels using SRES A1B (≈RCP6.0), projected global redistribution of maximum catch potential of 1000 species of exploited fishes and invertebrates, comparing the 10-year averages 2001-2010 and 2051-2060, without analysis of potential impacts of overfishing. (B) Marine mollusk and crustacean fisheries (estimated catch rates ≥0.005 tonnes per sq. km) and known locations of warm- and cold-water corals, depicted on a global map showing the distribution of ocean acidification in 2100 under RCP8.5. [WGI AR5 Figure SPM.8] The bottom panel compares sensitivity to ocean acidification across corals, mollusks, and crustaceans, vulnerable animal phyla with socioeconomic relevance (e.g., for coastal protection and fisheries). The number of species analyzed across studies is given for each category of elevated CO_2. For 2100, RCP scenarios falling within each pCO_2 category are as follows: RCP4.5 for 500-650 μatm, RCP6.0 for 651-850 μatm, and RCP8.5 for 851-1370 μatm. [6.1, 6.3, 30.5, Figures 6-10 and 6-14; WGI AR5 Box SPM.1]]

Food production systems and food security

Without adaptation, local temperature increases of 1°C or more above preindustrial levels are projected to negatively impact yields for the major crops (wheat, rice, and maize) in tropical and temperate regions, although individual locations may benefit (*medium confidence*). With or without adaptation, climate change will reduce median yields by 0 to 2% per decade for the rest of the century, as compared to a baseline without climate change. These projected impacts will occur in the context of rising crop demand, projected to increase by about 14% per decade until 2050. See Figure TS.9 for a summary of projected changes in crop yields over the 21st century. Risks are greatest for tropical countries, given projected impacts that exceed adaptive capacity and higher poverty rates compared with temperate regions. Climate change will progressively increase inter-annual variability of crop yields in many regions. [7.4, 22.3, 24.4, 25.7, 26.5, Figures 7-4, 7-5, 7-6, and 7-7]

On average, adaptation improves yields by the equivalent of ~15-18% of current yields, but the effectiveness of adaptation is highly variable (*medium confidence*). Positive and negative yield impacts projected for local temperature increases of about 2^{o}C above preindustrial levels maintain possibilities for effective adaptation in crop production (*high confidence*). For local warming of about 4^{o}C or more, differences between crop production and population-driven demand will become increasingly large in many regions, posing significant risks to food security even with adaptation. [7.5, 22.3, 25.7, 26.5, Table 7-2, Figures 7-4, 7-5, 7-7, and 7-8]

[INSERT FIGURE TS.9 HERE
Figure TS.9: Summary of projected changes in crop yield as a function of time with and without adaptation, across studies for all regions. Data (n=1090) are plotted in the 20-year period on the horizontal axis that includes the midpoint of each future projection period. [Figure 7-5]]

Urban areas

Rising sea levels and storm surges, heat stress, extreme precipitation, inland and coastal flooding, drought and water scarcity, and air pollution pose widespread negative risks for people, health, livelihoods, assets, local and national economies, and ecosystems (*very high confidence*). These risks are amplified for those who lack essential infrastructure and services or who live in exposed areas. [3.5, 8.2-3, 22.3, 24.4, 24.5, 26.8, Box CC-HS]

Reducing basic service deficits and building resilient infrastructure systems (e.g., for water supply, sanitation, storm and waste water drains, electricity, transportation and telecommunication, health care, education, and emergency response) could significantly reduce hazard exposure and vulnerability to climate change, especially for those who are most at risk or vulnerable (*very high confidence*). Urban adaptation provides opportunities for incremental and transformational adjustments towards resilience and sustainable development via effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector, or appropriate financing and institutional development (*medium confidence*). Enabling the capacity of low-income groups and vulnerable communities and their partnerships with local governments can also be an effective urban adaptation strategy. [8.3-4, 24.4, 24.5, 26.8, Table 11-3, Box 25-9]

Rural areas

Major future rural impacts will be felt in the near-term and beyond through impacts on water supply, food security, and agricultural incomes, including shifts in production of food and non-food crops in many areas of the world (*high confidence*). Price rises, which may be induced by climate shocks as well as other factors, have a disproportionate impact on the welfare of the poor in rural areas, such as female-headed households and those with limited access to modern agricultural inputs, infrastructure, and education. Climate change will increase international agricultural trade volumes in both physical and value terms (*limited evidence, medium agreement*). Importing food can help countries adjust to climate-change-induced domestic productivity shocks while short-term food deficits in low-income countries may have to be met through food aid. Valuation of non-marketed ecosystem services and limitations of economic valuation models that aggregate across contexts pose challenges for valuing rural impacts. [9.3, 26.8, Box 25-5]

Options exist for adaptations within international agricultural trade (*medium confidence*). Deepening agricultural markets and improving the predictability and the reliability of the world trading system through trade reform could result in reduced market volatility and manage food supply shortages caused by climate change. Investing in the production of small-scale farms in developing countries also provides benefits. [9.3, 25.9]

Key economic sectors and services

For most economic sectors, the impacts of drivers such as changes in population, age structure, income, technology, relative prices, lifestyle, regulation, and governance will be large relative to the impacts of climate change (*medium evidence, high agreement*). Climate change will reduce energy demand for heating and increase energy demand for cooling in the residential and commercial sectors (*robust evidence, high agreement*). Climate change will affect energy sources and technologies differently, depending on resources (e.g., water flow, wind, insolation), technological processes (e.g., cooling), or locations (e.g., coastal regions, floodplains) involved. More frequent and/or severe weather disasters for some regions and/or hazards will increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. [3.5, 10.2, 10.7, 10.10, 25.7, 26.7, Box 25-7]

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium evidence, medium agreement*). Climate change may require changes in design standards for the construction and operation of pipelines and of power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids. Climate change may negatively affect transport infrastructure (*limited evidence, high agreement*). All infrastructure is vulnerable to freeze-thaw cycles; paved roads are particularly vulnerable to temperature extremes, unpaved roads and bridges to precipitation extremes. Transport infrastructure on ice or permafrost is especially vulnerable. [10.2, 10.4, 25.7, 26.7]

Climate change will affect tourism resorts, particularly ski resorts, beach resorts, and nature resorts (*robust evidence, high agreement*), and tourists may spend their holidays at higher altitudes and latitudes (*medium evidence, high agreement*). The economic implications of climate-change-induced changes in tourism demand and supply entail gains for countries closer to the poles and countries with higher elevations and losses for other countries. [10.6, 25.7]

Global mean temperature increase of 2.5°C above preindustrial levels may lead to global aggregate economic losses between 0.2 and 2.0% of income (*medium evidence, medium agreement*). Losses increase with greater warming, but little is known about aggregate economic impacts above 3°C. Impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable, and aggregate impacts hide large differences between and within countries. The incremental economic impact of emitting a tonne of carbon dioxide lies between a few dollars and several hundreds of dollars per tonne of carbon (*robust evidence, medium agreement*). Estimates vary strongly with the assumed discount rate, with larger ranges for lower discount rates. [10.9]

Human health

Until mid-century, climate change will impact human health mainly by exacerbating health problems that already exist (*very high confidence*), and climate change throughout the 21st century will lead to increases in ill-health in many regions, as compared to a baseline without climate change (*high confidence*). Examples include greater likelihood of injury, disease, and death due to more intense heat waves and fires; increased likelihood of under-nutrition resulting from diminished food production in poor regions; risks from lost work capacity and reduced labor productivity in vulnerable populations; and increased risks from food- and water-borne diseases. Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development, particularly among the poorest and least healthy groups. Climate change will increase demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies for treatment (*medium evidence, high agreement*). Positive effects will include modest improvements in cold-related mortality and morbidity in some areas due to fewer cold extremes, shifts in food production, and reduced capacity of disease-carrying vectors (*medium confidence*). Globally, positive impacts will be outweighed by the magnitude and severity of negative impacts (*high confidence*). The most effective adaptation measures for health in the near-term are programs that implement basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty (*very high confidence*). For RCP8.5 by 2100, the combination of high temperature and humidity in some areas for parts of the year will compromise normal human activities, including growing food or working outdoors (*high confidence*). See Figure TS.10. [8.2, 10.8, 11.3-8, 19.3, 22.3, 25.8, 26.6, Box CC-HS]

[INSERT FIGURE TS.10
Figure TS.10: Conceptual presentation of health risks from climate change and the potential for risk reduction through adaptation. Risks are identified in eight health-related categories based on assessment of the literature and

expert judgments by authors of Chapter 11.The width of the slices indicates in a qualitative way relative importance in terms of burden of ill-health globally at present. Risk levels are assessed for the present and for the near-term era of committed climate change (here, for 2030-2040). For some categories, e.g., vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Risks levels are also presented for the longer-term era of climate options (here, for 2080-2100) for global mean temperature increase of 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors. [Figure 11-6]]

Human security

Human security will be progressively threatened as the climate changes (*robust evidence, high agreement*). Human insecurity almost never has single causes, but instead emerges from the interaction of multiple factors. Climate change is an important factor in threats to human security through (i) undermining livelihoods, (ii) compromising culture and identity, (iii) increasing migration that people would rather have avoided, and (iv) challenging the ability of states to provide the conditions necessary for human security. See Figure TS.11. [12.1-4, 12.6]

Climate change will compromise the cultural values that are important for community and individual well-being (*medium evidence, high agreement*). The effect of climate change on culture will vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge. Changing weather and climatic conditions threaten cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion, and sense of place. Loss of land and displacement, for example on small islands and coastal communities, have well documented negative cultural and well-being impacts. [12.3, 12.4]

Climate change over the 21st century will have significant impacts on forms of migration that compromise human security (*medium evidence, high agreement*). Coastal inundation and loss of permafrost can lead to migration and resettlement. Mobility is a widely used strategy to maintain livelihoods in response to social and environmental changes. Populations that lack the resources for mobility and migration often experience higher exposure to weather-related extremes, in both rural and urban areas, particularly in low-income countries. Expanding opportunities for mobility can reduce vulnerability, but altered migration flows can also create risks as well as potential benefits for migrants and for sending and receiving regions and states. [9.3, 12.4, 19.4, 22.3, 22.6, 25.9]

Climate change indirectly increases risks from violent conflict in the form of civil war, inter-group violence, and violent protests by exacerbating well-established drivers of these conflicts such as poverty and economic shocks (*medium confidence*). Statistical studies show that climate variability is significantly related to these forms of conflict. Poorly designed adaptation and mitigation strategies can increase risks from violent conflict. [12.5, 13.2, 19.4]

Climate change over the 21st century will lead to new challenges to states and will increasingly shape national security policies (*medium evidence, medium agreement*). Small-island states and other states highly vulnerable to sea-level rise face major challenges to their territorial integrity. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and migration of fish stocks, have the potential to increase rivalry among states. The presence of robust institutions can manage many of these rivalries to reduce conflict risks. [12.5-6, 23.9, 25.9]

[INSERT FIGURE TS.11 HERE
Figure TS.11: Schematic of climate change risks for human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies are indicated by the difference between initial conditions (solid black circles) and the outcome of intervention (white circles). Some interventions (blue arrows) show net increase in human security while others (red arrows) lead to net decrease in human security. [Figure 12-3]]

Livelihoods and poverty

Throughout the 21st century, climate change impacts will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger (*medium confidence*). Climate change will exacerbate poverty in low and lower-middle income countries, including high mountain states, countries at risk from sea-level rise, and countries with indigenous peoples, and create new poverty pockets in upper-middle- to high-income countries in which inequality is increasing. In urban and rural areas, wage-labor-dependent poor households that are net buyers of food will be particularly affected due to food price increases, including in regions with high food insecurity and high inequality (particularly Africa), although the agricultural self-employed could benefit. Insurance programs, social protection measures, and disaster risk reduction may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty. [8.1, 8.4, 9.3, 10.9, 13.2-4, 22.3, 26.8]

_____ START BOX TS.7 HERE _____

Box TS.7. Ocean Acidification

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Box TS.7 Figure 1A). [WGI AR5 2.2] Eutrophication, upwelling, and deposition of atmospheric nitrogen and sulfur contribute to ocean acidification locally. [5.3, 6.1, 30.3] The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). [30.3; WGI AR5 3.8, 6.4] It has been more difficult to understand and project changes within the more complex coastal systems. [5.3, 30.3]

Ocean acidification occurs on a backdrop of other environmental changes, both globally (e.g., warming, decreasing oxygen levels) and locally (e.g., pollution, eutrophication), yet their combined impacts remain poorly understood. A pattern of positive and negative impacts of ocean acidification emerges for processes and organisms (*high confidence*; Box TS.7 Figure 1B), but key uncertainties remain from organismal to ecosystem levels. A wide range of sensitivities exists within and across organisms, with higher sensitivity in early life stages. [6.3] Lower pH decreases the rate of calcification of most, but not all, sea-floor calcifiers, reducing their competitiveness with non-calcifiers (*robust evidence, medium agreement*). [5.4, 6.3] Ocean acidification stimulates dissolution of calcium carbonate (*very high confidence*). Growth and primary production are stimulated in seagrasses and some phytoplankton (*high confidence*), and harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Serious behavioral disturbances have been reported in fishes (*high confidence*). [6.3] Natural analogues at CO_2 vents indicate decreased species diversity, biomass, and trophic complexity. Shifts in organisms' performance and distribution will change both predator-prey and competitive interactions, which could impact food webs and higher trophic levels (*limited evidence, high agreement*). [6.3]

A few studies provide *limited evidence* for adaptation in phytoplankton and mollusks. However, mass extinctions in Earth history occurred during much slower rates of change in ocean acidification, combined with other drivers, suggesting that evolutionary rates may be too slow for sensitive and long-lived species to adapt to the projected rates of future change (*medium confidence*). [6.1]

The biological, ecological, and biogeochemical changes driven by ocean acidification will affect key ecosystem services. The oceans will become less efficient at absorbing CO_2 and hence moderating climate (*very high confidence*). [WGI AR5 Figure 6.26] The impacts of ocean acidification on coral reefs, together with those of thermal stress (driving mass coral bleaching and mortality) and sea-level rise, will diminish their role in shoreline protection as well as their direct and indirect benefits to fishing and tourism industries (*limited evidence, high agreement*). [Box CC-CR] The global cost of production loss of mollusks could be over 100 billion US$ by 2100 (*low confidence*). The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and complex additive, antagonistic, and/or synergistic interactions will occur with disruptive ramifications for ecosystems as well as for important ecosystem goods and services.

[INSERT BOX TS.7 FIGURE 1 HERE
Box TS.7 Figure 1: (A) Overview of the chemical, biological, and socioeconomic impacts of ocean acidification and of policy options. (B) Effect of near-future acidification (seawater pH reduction of 0.5 unit reduction or less) on

major response variables estimated using weighted random effects meta-analyses, with the exception of survival, which is not weighted. The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification, but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. '*' denotes a statistically significant effect. [Figure OA-1, Box CC-OA]]

_____ END BOX TS.7 HERE _____

B-3. Regional Risks and Potential for Adaptation

Climate change will amplify climate-related risks to natural and human systems in most parts of the world. Key regional risks identified with *medium* to *high confidence* are presented in Table TS.5. Projected changes in climate and increasing atmospheric CO_2 will have positive effects for some sectors in some locations. For extended summary of regional risks and the more limited potential benefits, see introductory overviews for each region below and also Chapters 21-30.

[INSERT TABLE TS.5 HERE
Table TS.5: Key regional risks from climate change and the potential for reducing risks through mitigation and adaptation. Risks have been identified based on assessment of the relevant scientific, technical, and socioeconomic literature, as detailed in supporting chapter sections. Each key risk is characterized as very low to very high for three timeframes: the present, near-term (here, assessed over 2030-2040), and longer-term (here, assessed over 2080-2100). Assessed risk levels integrate probability and consequence over the full range of possible outcomes, acknowledging the importance of differences in values and objectives in interpretation of the assessed risk levels. For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels, illustrating the potential role of mitigation in reducing risks. For the present, risk levels are estimated for current adaptation and a hypothetical highly adapted state, identifying where current adaptation deficits exist. For the future, risk levels are estimated for a continuation of current adaptation and for a highly adapted state, representing the potential for and limits to adaptation. Relevant climate variables are indicated by icons. Risk levels are not necessarily comparable, especially across regions, because the assessment considers potential impacts and adaptation in different physical, biological, and human systems across diverse regional contexts.]

***Africa.* Climate change will amplify existing stress on water availability and on agricultural systems particularly in semi-arid environments (*high confidence*).** Increasing temperatures and changes in precipitation are *very likely* to reduce cereal crop productivity with strong adverse effects on food security (*high confidence*). Progress has been achieved on managing risks to food production from current climate variability and near-term climate change, but these will not be sufficient to address long-term impacts of climate change. Adaptive agricultural processes such as collaborative, participatory research that includes scientists and farmers, strengthened communication systems for anticipating and responding to climate risks, and increased flexibility in livelihood options provide potential pathways for strengthening adaptive capacities. Climate change is a multiplier of existing health vulnerabilities including insufficient access to safe water and improved sanitation, food insecurity, and limited access to health care and education. Strategies that integrate consideration of climate change risks with land and water management and disaster risk reduction bolster resilient development. [22.3-4, 22.6]

***Europe.* Climate change will increase the likelihood of systemic failures across European countries caused by extreme climate events affecting multiple sectors (*medium confidence*).** Sea-level rise and increases in extreme rainfall are projected to further increase coastal and river flood risks and without adaptive measures will substantially increase flood damages (i.e., people affected and economic losses); adaptation can prevent most of the projected damages (*high confidence*). Heat-related deaths and injuries are *likely* to increase, particularly in southern Europe (*medium confidence*). Climate change is *likely* to increase cereal crop yields in northern Europe (*medium confidence*) but decrease yields in southern Europe (*high confidence*). Climate change will increase irrigation needs in Europe, and future irrigation will be constrained by reduced runoff, demand from other sectors, and economic costs, with integrated water management a strategy for addressing competing demands. Hydropower production is *likely* to decrease in all sub-regions except Scandinavia. Climate change is *very likely* to cause changes in habitats and species, with local extinctions (*high confidence*), continental-scale shifts in species distributions (*medium confidence*), and significantly reduced alpine-plant habitat (*high confidence*). Climate change is *likely* to entail the loss or displacement of coastal wetlands. The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe is *likely* to increase with climate change (*medium confidence*). [23.2-9]

Asia. **Climate change will cause declines in agricultural productivity in many subregions of Asia, for crops such as rice (*medium confidence*).** In Central Asia, cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters, and slight increase in winter precipitation, while droughts in western Turkmenistan and Uzbekistan could negatively affect cotton production, increase water demand for irrigation, and exacerbate desertification. The effectiveness of potential and practiced agricultural adaptation strategies is not well understood. Future projections of precipitation at subregional scales and thus of freshwater availability in most parts of Asia are uncertain (*low confidence* in projections), but increased water demand from population growth, increased water consumption per capita, and lack of good management will increase water scarcity challenges for most of the region (*medium confidence*). Adaptive responses include integrated water management strategies, such as development of water saving technologies, increased water productivity, and water reuse. Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia (*high confidence*). In many parts of Asia, observed terrestrial impacts, such as permafrost degradation and shifts in plant species' distributions, growth rates, and timing of seasonal activities, will increase due to climate change projected during the 21st century. Coastal and marine systems in Asia, such as mangroves, seagrass beds, salt marshes, and coral reefs, are under increasing stress from climatic and non-climatic drivers. In the Asian Arctic, sea-level rise interacting with projected changes in permafrost and the length of the ice-free season will increase rates of coastal erosion (*medium evidence, high agreement*). [24.4, 30.5]

Australasia. **Without adaptation, further changes in climate, atmospheric CO_2, and ocean acidity are projected to have substantial impacts on water resources, coastal ecosystems, infrastructure, health, agriculture, and biodiversity (*high confidence*).** Freshwater resources are projected to decline in far south-west and far south-east mainland Australia (*high confidence*) and for some rivers in New Zealand (*medium confidence*). Rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure, and housing (*high confidence*); increasing heat waves will increase risks to human health; rainfall changes and rising temperatures will shift agricultural production zones; and many native species will suffer from range contractions and some may face local or even global extinction. Uncertainty in projected rainfall changes remains large for many parts of Australia and New Zealand, which creates significant challenges for adaptation. Some sectors in some locations have the potential to benefit from projected changes in climate and increasing atmospheric CO_2, for example due to reduced energy demand for winter heating in New Zealand and southern parts of Australia, and due to forest growth in cooler regions except where soil nutrients or rainfall are limiting. Indigenous peoples in both Australia and New Zealand have higher than average exposure to climate change due to a heavy reliance on climate-sensitive primary industries and strong social connections to the natural environment, and face additional constraints to adaptation (*medium confidence*). [25.2-3, 25.5-8, Boxes 25-1, 25-2, 25-5, and 25-8]

North America. **Many climate-related hazards that carry risk, particularly related to severe heat, heavy precipitation, and declining snowpack, will increase in frequency and/or severity in North America in the next decades (*very high confidence*).** Climate change will amplify risks to water resources already affected by non-climatic stressors, with potential impacts associated with decreased snowpack, decreased water quality, urban flooding, and decreased water supplies for urban areas and irrigation (*high confidence*). More adaptation options are available to address water supply deficits than flooding and water quality concerns (*medium confidence*). Ecosystems are under increasing stress from rising temperatures, CO_2 concentrations, and sea levels, with particular vulnerability to climate extremes (*very high confidence*). In many cases, climate stresses exacerbate other anthropogenic influences on ecosystems, including land-use changes, non-native species, and pollution. Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st century without adaptation, although some regions, particularly in the north, may benefit. Adaptation, often with mitigation co-benefits, could offset projected negative yield impacts for many crops at 2°C global mean temperature increase above preindustrial, with reduced effectiveness of adaptation at 4°C (*high confidence*). Although larger urban centers would have higher adaptive capacities, high population density, inadequate infrastructures, lack of institutional capacity, and degraded natural environments increase future climate risks from heat waves, droughts, storms, and sea-level rise (*medium evidence*, *high agreement*). Future risks from climate extremes can be reduced, for example through targeted and sustainable air conditioning, more effective warning and response systems, enhanced pollution controls, urban planning strategies, and resilient health infrastructure (*high confidence*). [26.3-6, 26.8]

Central and South America. **Despite improvements, high and persistent levels of poverty in most countries result in high vulnerability to climate variability and change (*high confidence*).** Climate change impacts on agricultural productivity are expected to exhibit large spatial variability, for example with sustained or increased productivity through mid-century in southeast South America and decreases in productivity in the near-term (by 2030) in Central America, threatening food security of the poorest populations (*medium confidence*). Reduced precipitation and increased evapotranspiration in semi-arid regions will increase risks from water-supply shortages, affecting cities, hydropower generation, and agriculture (*high confidence*). Ongoing adaptation strategies include reduced mismatch between water supply and demand, and water-management and coordination reforms (*medium confidence*). Conversion of natural ecosystems, a driver of anthropogenic climate change, is the main cause of biodiversity and ecosystem loss (*high confidence*). Climate change is expected to increase rates of species extinction (*medium confidence*). In coastal and marine systems, sea-level rise and human stressors increase risks for fish stocks, corals, mangroves, recreation and tourism, and control of diseases (*high confidence*). Climate change will exacerbate future health risks given regional population growth rates and vulnerabilities due to pollution, food insecurity in poor regions, and existing health, water, sanitation, and waste collection systems (*medium confidence*). [27.2-3]

Polar Regions. **In the Arctic, climate change and often-interconnected non-climate-related drivers, including environmental changes, demography, culture, and economic development, interact to determine physical, biological, and socioeconomic risks, with rates of change that may be faster than social systems can adapt (*high confidence*).** Thawing permafrost and changing precipitation patterns have the potential to affect infrastructure and related services, with particular risks for residential buildings, for example in Arctic cities and small rural settlements. Climate change will especially impact Arctic communities that have narrowly based economies limiting adaptive choices. Increased Arctic navigability and expanded land- and freshwater-based transportation networks will increase economic opportunities. Impacts on the informal, subsistence-based economy will include changing sea-ice conditions that increase the difficulty of hunting marine mammals. Polar bears have been and will be affected by loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness. Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea-level rise, and increased intensity of weather extremes are forcing relocation of some indigenous communities in Alaska (*high confidence*). In the Arctic and Antarctic, some marine species will shift their ranges in response to changing ocean and sea ice conditions (*medium confidence*). Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species, the majority expected to arrive through direct human assistance (*high confidence*). [6.3, 6.5, 28.2-4]

Small Islands. **Small islands have high vulnerability to climatic and non-climatic stressors (*high confidence*).** Diverse physical and human attributes and their sensitivity to climate-related drivers lead to variable climate change risk profiles and adaptation from one island region to another and among countries in the same region. Risks can originate from transboundary interactions, for example associated with existing and future invasive species and human health challenges. Sea-level rise poses one of the most widely recognized climate change threats to low-lying coastal areas on islands and atolls. Projected sea-level rise at the end of the 21st century, superimposed on extreme sea-level events, presents severe coastal-flooding and erosion risks for low-lying coastal areas and atoll islands. Wave over-wash will degrade groundwater resources. Coral reef ecosystem degradation associated with increasing sea surface temperature and ocean acidification will negatively impact island communities and livelihoods, given the dependence of island communities on coral reef ecosystems for coastal protection, subsistence fisheries, and tourism. [29.3-5, 29.9, 30.5, Figure 29-1, Table 29-3, Box CC-CR]

The Ocean. **Warming will increase risks to ocean ecosystems (*high confidence*).** Coral reefs within coastal boundary systems, semi-enclosed seas, and sub-tropical gyres are rapidly declining as a result of local non-climatic stressors (i.e., coastal pollution, overexploitation) and climate change. Projected increases in mass coral bleaching and mortality will alter or eliminate ecosystems, increasing risks to coastal livelihoods and food security (*medium* to *high confidence*). An analysis of the CMIP5 ensemble projects loss of coral reefs from most sites globally to be *very likely* by 2050 under mid to high rates of ocean warming. Reducing non-climatic stressors represents an opportunity to strengthen ecological resilience. The highly productive high-latitude spring bloom systems in the Northeastern Atlantic are responding to warming (*medium evidence, high agreement*), with the greatest changes being observed since the late 1970s in the phenology, distribution, and abundance of plankton assemblages, and the reorganization of fish assemblages, with a range of consequences for fisheries (*high confidence*). Projected warming increases the likelihood of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and encourage the formation of hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). Changing surface winds and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy, and mineral extraction. New opportunities as well as international issues over access to resources and vulnerability may accompany warming waters particularly at high latitudes. [5.3-4, 6.4, 28.2-3, 30.3, 30.5-6, Table 30-1, Figures 30-4 and 30-10, Boxes 6-1, CC-CR, and CC-MB]

Understanding of extreme events and their interactions with climate change is particularly important for managing risks in a regional context. Table TS.6 provides a summary of observed and projected trends in some types of temperature and precipitation extremes.

[INSERT TABLE TS.6
Table TS.6: Observed and projected future changes in some types of temperature and precipitation extremes over 26 sub-continental regions as defined in SREX. Confidence levels are indicated by symbol color. Likelihood terms are given only for *high* or *very high confidence* statements. Observed trends in temperature and precipitation extremes, including dryness and drought, are generally calculated from 1950, using 1961-1990 as the reference period, unless otherwise indicated. Future changes are derived from global and regional climate model projections for 2071-2100 compared with 1961-1990 or for 2080-2100 compared with 1980-2000. Table entries are summaries of information in SREX Tables 3.2 and 3.3 supplemented with or superseded by material from WGI AR5 2.6, 14.4, and Table 2.13 and WGII AR5 Table 25-1. The source(s) of information for each entry are indicated by superscripts: (a) SREX Table 3.2; (b) SREX Table 3.3; (c) WGI AR5 2.6 and Table 2.13; (d) WGI AR5 14.4; (e) WGII AR5 Table 25-1. [Tables 21-7 and SM21-2, Figure 21-4]]

C) MANAGING FUTURE RISKS AND BUILDING RESILIENCE

Managing the risks of climate change involves decisions with implications for future societies, economies, environment, and climate. Figure TS.12 provides an overview of entry points, approaches, and core considerations in addressing climate change.

Starting with principles for effective adaptation, this section evaluates the ways that interlinked human and natural systems can build resilience through adaptation, mitigation, and sustainable development. It describes understanding of climate-resilient pathways, of incremental versus transformational changes, and of limits to adaptation, and it considers co-benefits, synergies, and tradeoffs among mitigation, adaptation, and development.

[INSERT FIGURE TS.12 HERE
Figure TS.12: An overview of overlapping entry points and approaches, as well as core considerations, in responding to climate change, as assessed in the WGII AR5. Bracketed references indicate sections of this summary with corresponding assessment findings.]

C-1. Principles for Effective Adaptation

The report assesses a wide variety of approaches for managing risks and building resilience. Strategies and approaches to climate change adaptation include efforts to decrease vulnerability or exposure and/or increase resilience or adaptive capacity. Mitigation is assessed in the WGIII AR5. An overview of types of responses to climate change is presented in Table TS.7.

[INSERT TABLE TS.7 HERE
Table TS.7: Managing the risks of climate change: entry points, strategies, and adaptation options. These approaches should be considered overlapping rather than discrete, and they are often pursued simultaneously. Examples given can be relevant to more than one category.]

Adaptation is highly regionally and context specific, with no single approach for reducing risk appropriate across all settings (*medium confidence*). Effective risk reduction and adaptation strategies consider the dynamics of vulnerability and exposure and their linkages with development and climate change (*high confidence*). [2.1, 8.3-4, 13.1, 13.3-4, 15.2-3, 15.5, 16.2-3, 16.5, 17.2, 17.5, 19.6, 21.3, 22.4, 25.4, 26.8-9, 29.6, 29.8]

From individuals to governments, actors across scales and regions have complementary roles in enabling adaptation planning and implementation (*high confidence*), for example through increasing awareness of climate change risks, learning from experience with climate variability, and achieving synergies with disaster risk reduction. Local government and the private sector are increasingly recognized as critical to progress in adaptation, given their roles in scaling up adaptation of communities and households and in managing risk information and financing (*medium evidence, high agreement*). National governments can coordinate adaptation by local and subnational governments, creating legal frameworks, protecting vulnerable groups, and providing information, policy frameworks, and financial support (*robust evidence, high agreement*). Public action can influence the degree to which private parties undertake adaptation actions. [2.1-4, 3.6, 8.3-4, 9.3-4, 14.2, 15.2-3, 15.5, 16.2-5, 17.2-3, 22.4, 24.4, 25.4, 26.8-9, 30.7, Tables 21-1, 21-5, and 21-6, Boxes 16-1, 16-2, and 25-7]

In many cases, a first step towards adaptation to future climate change is reducing vulnerability and exposure to present climate through low-regrets measures and actions emphasizing co-benefits (*high confidence*). Available strategies and actions can increase resilience across a range of possible future climates while helping to improve human livelihoods, social and economic well-being, and environmental quality. Integration of adaptation into planning and decision-making can promote synergies with development. Adaptation strategies that also strengthen livelihoods, enhance development, and reduce poverty include improved social protection, improved water and land governance, enhanced water storage and services, greater involvement in planning, and elevated attention to urban and peri-urban areas heavily affected by migration of poor people. See Table TS.7. [3.6, 9.4, 11.2, 14.2, 15.2-3, 15.5, 17.2, 20.4, 20.6, 22.4, 24.4, 25.10, 27.3-5, Boxes 25-2, 25-6, 25-8, and 25-9]

Integration of adaptation into planning and decision-making can promote synergies with development and reduce the possibility of maladaptive actions (*robust evidence, high agreement*). Such mainstreaming embeds climate-sensitive thinking in existing and new institutions and organizations**.** Adaptation can generate larger benefits when connected with development activities and disaster risk reduction (*medium confidence*). [8.3, 9.3, 14.2, 14.6, 15.3-4, 17.2, 20.2-3, 22.4, 24.5, 29.6, Box CC-UR]

Multiple simultaneous constraints can interact to impede adaptation planning and implementation (*high confidence*). Common constraints on implementation arise from the following: uncertainty about projected impacts; limited financial and human resources; limited integration or coordination of different levels of governance; different perceptions of risks; inadequate responses from political institutions; competing values; absence of adaptation leaders and champions; and limited tools to monitor adaptation effectiveness. Underestimating the complexity of adaptation as a social process can create unrealistic expectations. [3.6, 4.4, 8.4, 9.4, 13.2-3, 14.2, 15.2-3, 15.5, 16.2-3, 16.5, 17.2, 22.3-5, 23.6-7, 24.5, 25.4, 25.10, 26.8-9, 30.6, Table 25-2, Boxes 16-1, 16-3, and CC-EA]

Poor planning, overemphasizing short-term outcomes, or discounting or failing to consider all consequences can result in maladaptation (*medium evidence, high agreement*). Narrow focus on quantifiable costs and benefits can bias decisions against the poor, against ecosystems, and against those in the future whose values can be excluded or are understated. Maladaptation can increase the vulnerability or exposure of the target group in the future, or the vulnerability of other locations or sectors. [14.6, 15.5, 17.2-3, 22.4, 25.9]

Existing and emerging economic instruments can foster adaptation by providing incentives for anticipating and reducing impacts (*medium confidence*). Instruments include risk sharing and transfer mechanisms, loans, public-private finance partnerships, payments for environmental services, improved resource pricing (e.g., water markets), charges and subsidies including taxes, norms and regulations, and behavioral approaches. Risk financing mechanisms across scales contribute to increasing resilience to climate extremes and climate variability, but can also provide disincentives, cause market failure, and decrease equity. Mechanisms include insurance, reinsurance, micro insurance, and national, regional, and global risk pools. The public sector often plays a key role as regulator, provider, or insurer of last resort. [10.7, 10.9, 13.3, 17.4-5, 22.4, Box 25-7]

Indigenous, local, and traditional forms of knowledge are a major resource for adapting to climate change (*robust evidence, high agreement*). Natural resource dependent communities, including indigenous peoples, have a long history of adapting to highly variable and changing social and ecological conditions. But the salience of indigenous, local, and traditional knowledge will be challenged by climate change impacts. Such forms of knowledge are often neglected in policy and research, and their mutual recognition and integration with scientific knowledge will increase the effectiveness of adaptation. [9.4, 12.3, 15.2, 22.4, 24.4, 24.6, 25.8, Table 15-1]

Global adaptation cost estimates are substantially greater than current adaptation funding and investment, particularly in developing countries, suggesting a funding gap and a growing adaptation deficit (*medium confidence*). The most recent global adaptation cost estimates suggest a range from 70 to 100 US$ billion per year in developing countries from 2010 to 2050 (*low confidence*). Important omissions and shortcomings in data and methods render these estimates highly preliminary (*high confidence*). [17.4]

C-2. Climate-resilient Pathways and Transformation

Climate-resilient pathways are development trajectories that combine adaptation and mitigation to realize the goal of sustainable development. They can be seen as iterative, continually evolving processes for managing change within complex systems.

Climate-resilient pathways include strategies, choices, and actions that reduce climate change and its impacts. They also include actions to ensure that effective risk management and adaptation can be implemented and sustained (*high confidence*). Delaying actions may reduce options for climate-resilient pathways in the future. See Figure TS.13. Prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation. Climate-resilient development pathways will have only marginal effects on poverty reduction, unless structural inequalities are addressed and needs for equity among poor and non-poor people are met (*medium confidence*). [1.1, 2.5, 13.4, 20.2-4, 20.6, Figure 1-5]

[INSERT FIGURE TS.13 HERE

Figure TS.13: Multiple stressors and climate-resilient pathways. The literature assessed in this report shows that climate change is just one of the many stressors that influence resilience. Climate-related risks interact with other biophysical stressors (such as biodiversity loss, soil erosion, and water contamination) and with social stressors (such as inequalities, poverty, gender discrimination, and lack of institutions). Rapid advances in knowledge about climate change and its risks along with experience and other factors provide policy relevant information for decision-making that can lead to climate-resilient development pathways. The decisions that societies make within this opportunity space can increase resilience and lower risks. Such decisions and choices are core elements of an iterative risk management process. [Figure 1-5]]

Greater rates and magnitude of climate change increase the likelihood of exceeding adaptation limits that emerge from the interaction among climate change and biophysical and socioeconomic constraints (*high confidence*). See Box TS.8. Adaptation and greenhouse gas mitigation are complementary risk management strategies, but residual loss and damage will occur from climate change despite adaptive and mitigative action. Opportunities to take advantage of positive synergies between adaptation and mitigation may decrease with time, particularly if limits to adaptation are exceeded. In some parts of the world, current failures to address emerging impacts are already eroding the basis for sustainable development. [1.1, 11.8, 16.2-7, 17.2, 20.2-4, 20.5-6, 25.10, 26.5, 26.9, Boxes 16-1, 16-3, and 16-4]

Transformations in political, economic, and technological systems resulting from changes in paradigms and goals can facilitate adaptation and mitigation and promote sustainable development (*high confidence*). Transformational adaptation is an important consideration for decisions involving long life- or lead-times, and it can be a response to adaptation limits. It includes adaptation at greater scale or magnitude, introduction of new technologies or practices, formation of new structures or systems of governance, or shifts in the location of activities. Societal debates over risks from forced and reactive transformations as opposed to deliberate transitions to sustainability may place new and increased demands on governance structures to reconcile conflicting goals and visions for the future. [1.1, 2.1, 2.5, 8.4, 14.1, 14.3, 16.2-7, 17.3, 20.5, 22.4, 25.4, 25.10, Figure 1-5, Boxes 16-1 and 16-4]

Examples of co-benefits, synergies, and tradeoffs among adaptation, mitigation, and sustainable development

Significant co-benefits, synergies, and tradeoffs exist between mitigation and adaptation and between alternative adaptation responses; interactions occur both within and across regions (*very high confidence*). Illustrative examples include the following.

- Increasing efforts to mitigate and adapt to climate change imply an increasing complexity of interactions, particularly at the intersections among water, energy, land use, and biodiversity, but tools to understand and manage these interactions remain limited (*very high confidence*). See Box TS.9. Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, will lead to negative impacts on ecosystems and biodiversity (*high confidence*). [3.7, 4.2-4, 22.6, 24.6, 25.7, 25.9, 27.3, Boxes 25-10 and CC-WE]
- Climate policies such as increasing energy supply from renewable resources, encouraging bioenergy crop cultivation, or facilitating payments under REDD+ will affect some rural areas both positively (e.g., increasing employment opportunities) and negatively (e.g., land use changes, increasing scarcity of natural capital) (*medium confidence*). These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including benefits of promoting participation of rural stakeholders. Mitigation policies with social co-benefits expected in their design, such as CDM and REDD+, have had limited or no effect in terms of poverty alleviation and sustainable development (*medium confidence*). Mitigation efforts focused on land acquisition for biofuel production show preliminary negative impacts for the poor in many low and middle-income countries, and particularly for indigenous people and (women) smallholders. [9.3, 13.3, 22.6]
- Mangrove, sea grass, and salt marsh ecosystems offer important carbon storage and sequestration opportunities (*limited evidence*, *medium agreement*), in addition to ecosystem services such as protection against coastal erosion and storm damage and maintenance of habitats for fisheries species. For ocean-related mitigation and adaptation in the context of anthropogenic ocean warming and acidification, international frameworks offer opportunities to solve problems collectively, for example managing fisheries across national borders and responding to extreme events. [5.4, 25.6, 30.6-7]

- Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Alternative methods focusing on solar radiation management (SRM) leave ocean acidification unabated as they cannot mitigate rising atmospheric CO_2 emissions. [6.4]
- Some agricultural practices can reduce emissions and also increase resilience of crops to temperature and rainfall variability (*high confidence*). [23.8, Table 25-7]
- Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g., greening cities and recycling water) are already being implemented (*high confidence*). Transport systems promoting active transport and reduced motorized-vehicle use can improve air quality and increase physical activity (*medium confidence*). [11.9, 23.8, 24.4, 26.3, 26.8, Boxes 25-2 and 25-9]
- Improved energy efficiency and a shift to cleaner energy sources can reduce local emissions of health-damaging climate-altering air pollutants (*very high confidence*). [11.9, 23.8]
- In Africa, experience in implementing integrated adaptation–mitigation responses that leverage developmental benefits encompasses some participation of farmers and local communities in carbon offset systems and increased use of agroforestry and farmer-assisted tree regeneration (*high confidence*). [22.4, 22.6]
- In Asia, development of sustainable cities with fewer fossil-fuel-driven vehicles and with more trees and greenery would have a number of co-benefits, including improved public health (*high confidence*). [24.4-7]
- In Australasia, transboundary effects from climate change impacts and responses outside Australasia have the potential to outweigh some of the direct impacts within the region, particularly economic impacts on trade-intensive sectors such as agriculture (*medium confidence*) and tourism (*limited evidence, high agreement*), but they remain among the least-explored issues. [25.7, 25.9, Box 25-10]
- In North America, policies addressing local concerns (e.g., air pollution, housing for the poor, declines in agricultural production) can be adapted at low or no cost to fulfill adaptation, mitigation, and sustainability goals (*medium confidence*). [26.9]
- In Central and South America, biomass-based renewable energy can impact land use change and deforestation, and could be affected by climate change (*medium confidence*). The expansion of sugarcane, soy, and oil palm may have some effect on land use, leading to deforestation in parts of the Amazon and Central America, among other subregions, and to loss of employment in some countries. [27.3]
- For small islands, energy supply and use, tourism infrastructure and activities, and coastal wetlands offer opportunities for adaptation-mitigation synergies (*medium confidence*). [29.6-8]

Table TS.8 provides further specific examples of interactions among adaptation, mitigation, and sustainable development to complement the assessment findings above.

[INSERT TABLE TS.8 HERE
Table TS.8: Illustrative examples of intra-regional interactions among adaptation, mitigation, and sustainable development.]

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Box TS.8. Adaptation Limits and Transformation

Adaptation can expand the capacity of natural and human systems to cope with a changing climate. Risk-based decision-making can be used to assess potential limits to adaptation. Such limits to adaptation may be signaled by the inability to prevent intolerable risks to an actor's objectives and/or to the needs of an ecosystem. Limits to adaptation are context-specific and closely linked to cultural norms and societal values. Judgments of what constitutes an intolerable risk may differ among actors, but understandings of limits to adaptation can be informed by historical experiences, or by anticipation of impacts, vulnerability, and adaptation associated with different scenarios of climate change. The greater the magnitude of climate change, the greater the likelihood that adaptation will encounter limits. [16.2-4, 20.5, 20.6, 22.4, 25.4, 25.10, Box 16-2]

Limits to adaptation may be influenced by the subjective values of societal actors, which can affect both the perceived need for adaptation and the perceived appropriateness of specific policies and measures. While limits imply that intolerable risks and the increased potential for losses and damages can no longer be avoided, the dynamics of social and ecological systems mean that there are both “soft” and “hard” limits to adaptation. For “soft” limits, there are opportunities in the future to alter limits and reduce risks, for example through the emergence of new technologies or changes in laws, institutions, or values. In contrast, “hard” limits are those where there are no reasonable prospects for avoiding intolerable risks. Recent studies on tipping points, key vulnerabilities, and planetary boundaries provide some insights on the behavior of complex systems. [16.2-7, 25.10]

In cases where the limits to adaptation have been surpassed, losses and damage may increase and the objectives of some actors may no longer be achievable. There may be a need for transformational adaptation to change fundamental attributes of a system in response to actual or expected impacts of climate change. It may involve adaptations at a greater scale or intensity than previously experienced, adaptations that are new to a region or system, or adaptations that transform places or lead to a shift in the location of activities. [16.2-4, 20.3, 20.5, 22.4, 25.10, Boxes 25-1 and 25-9]

The existence of limits to adaptation suggests transformational change may be a requirement for sustainable development in a changing climate; i.e., not only for adapting to the impacts of climate change, but for altering the systems and structures, economic and social relations, and beliefs and behaviors that contribute to climate change and social vulnerability. However, just as there are ethical implications associated with some adaptation options, there are also legitimate concerns about the equity and ethical dimensions of transformation. Societal debates over risks from forced and reactive transformations as opposed to deliberate transitions to sustainability may place new and increased demands on governance structures at multiple levels to reconcile conflicting goals and visions for the future. [1.1, 16.2-7, 20.5, 25.10]

_____ END BOX TS.8 HERE _____

_____ START BOX TS.9 HERE _____

Box TS.9. The Water-Energy-Food Nexus

Water, energy, and food/feed/fiber are linked through numerous interactive pathways affected by a changing climate (Box TS.9 Figure 1). [Box CC-WE] The depth and intensity of those linkages vary enormously among countries, regions, and production systems. Many energy sources require significant amounts of water and produce a large quantity of waste water that requires energy for treatment. [3.7, 7.3, 10.2-3, 22.3, 25.7, Box CC-WE] Food production, refrigeration, transport, and processing also require both energy and water. A major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water, and the sensitivity of precipitation, temperature, and crop yields to climate change (*robust evidence, high agreement*). [7.3, Boxes 25-10 and CC-WE]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (*robust evidence, high agreement*). [10.2-3, 25.7, Box CC-WE] Water is required for mining, processing, and residue disposal of fossil fuels or their byproducts. [25.7] Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country. [Box CC-WE] Future water requirements will depend on electric demand growth, the portfolio of generation technologies, and water management options. Future water availability for energy production will change due to climate change (*robust evidence, high agreement*). [3.4-5]

Energy is also required to supply and treat water. Water may require significant amounts of energy for lifting (especially as aquifers continue to be depleted), transport, and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. [Table 25-7, Box 25-2] Energy intensities per m^3 of water vary by about a factor of 10 among different sources, e.g., locally produced potable water from ground/surface water sources vs. desalinated seawater. [Boxes 25-2 and CC-WE] Groundwater is generally more energy intensive than surface water. [Box CC-WE]

Linkages among water, energy, food/feed/fiber, and climate are strongly related to land use and management, such as afforestation, which can affect water as well as other ecosystem services, climate, and water cycles (*robust* *evidence*, *high agreement*). [4.4, Box 25-10] Land degradation often reduces efficiency of water and energy use (e.g., resulting in higher fertilizer demand and surface runoff), and many of these interactions can compromise food security. [3.7, 4.4] On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat, but may reduce renewable water resources. [Box 25-10]

Consideration of the interlinkages of energy, food/feed/fiber, water, land use, and climate change has implications for security of supplies of energy, food, and water; adaptation and mitigation pathways; air pollution reduction; and health and economic impacts. This nexus is increasingly recognized as critical to effective climate-resilient-pathway decision-making (*medium evidence*, *high agreement*), although tools to support local- and regional-scale assessments and decision-support remain very limited.

[INSERT BOX TS.9 FIGURE 1 HERE
Box TS.9 Figure 1: The water-energy-food nexus as related to climate change, with implications for both adaptation and mitigation strategies. [Figure WE-1, Box CC-WE]]

_____ END BOX TS.9 HERE _____

Table TS.1.

REGION	Snow & Ice, Rivers & Lakes, Floods & Drought	Terrestrial Ecosystems	Coastal Erosion & Marine Ecosystems	Food Production & Livelihoods
Africa	Retreat of tropical highland glaciers in East Africa (H,C) Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba (H,C) Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990 (M,C) [22.2.2-3, 22.3.2, Tables 18-5, 18-6, and 22-3]	Tree density decreases in Sahel & semi-arid Morocco, beyond changes due to land use (M,C) Range shifts of several southern plants & animals, beyond changes due to land use (M,C) [22.3.2, Tables 18-7 and 22-3]		
Europe	Retreat of Alpine, Scandinavian, and Icelandic glaciers (H,C) Increase in rock slope failures in Western Alps (M,C) [18.3.1, 23.3.1, Table 18-5; WGI AR5 4.3.3]	Earlier greening, leaf emergence, & fruiting in temperate & boreal trees (H,C) Increased colonization of alien plant species in Europe, beyond a baseline of some invasion (M,C) Earlier arrival of migratory birds in Europe since 1970 (M,C) Increasing burnt forest areas during recent decades in Portugal and Greece, beyond some increase due to land use (H,C) [4.3.2-3, Tables 18-7 and 23-6]	Northward distributional shifts of zooplankton, fishes, seabirds, & benthic invertebrates in Northeast Atlantic (H,C) Northward and depth shift in distribution of many fish species across European seas (M,C) Plankton phenology changes in Northeast Atlantic (M,C) Spread of warm water species into the Mediterranean, beyond changes due to invasive species and human impacts (M,C) [6.3.1, 23.6.4-5, 30.5.1, 30.5.3, Tables 6-2 and 18-8, Boxes 6-1 and CC-MB]	Impacts on livelihoods of Sámi people in northern Europe, beyond effects of economic and sociopolitical changes (M,C) Stagnation of wheat yields in some countries in recent decades, despite improved technology (M,c) Positive yield impacts for some crops mainly in northern Europe, beyond increase due to improved technology (M,c) Spread of bluetongue virus in sheep, and of ticks across parts of Europe (M,c) [23.4.1, 23.4.2, Table 18-9, Figure 7-2]
Asia	Permafrost degradation in Siberia, Central Asia, & Tibetan Plateau (H,C) Shrinking mountain glaciers across Asia (M,C) Increased flow in many rivers due to shrinking glaciers in the Himalayas & Central Asia (H,C) Earlier timing of maximum spring flood in Russian rivers (M,C) Reduced soil moisture in North Central and Northeast China (1950-2006) (M,C) Surface water degradation in parts of Asia beyond changes due to land use (M,c) [24.4.1-2, 28.2.1, Tables 18-5 and 18-6, Boxes 3-1 and 3-2; WGI AR5 4.3.2-3, 10.5.3]	Changes in plant phenology & growth in many parts of Asia (earlier greening), particularly in the north & east (M,C) Distribution shifts of many plant & animal species upwards in elevation or polewards, particularly in the north of Asia (M,C) Advance of shrubs into the Siberian tundra (H,C) [4.3.2-3, 24.4.2, 28.2.3, Table 18-7, Figure 4-4]	Decline in coral reefs & large seaweeds in tropical Asian waters & coastal waters of western Japan, beyond decline due to human impacts (H,C) Northward range extension of coral reefs and predatory fish in Sea of Japan (M,C) [24.4.3, 30.5.1, Table 18-8]	Negative impacts on aggregate wheat yields in South Asia, against a baseline of increase due to improved technology (M,c) [7.2.1, Table 18-9, Figure 7-2]
Australasia	Significant decline in late-season snow depth at 3 of 4 alpine sites in Australia (1957-2002) (M,C) Substantial reduction in ice and glacier ice volume in New Zealand (M,C) Reduced inflow in river systems in southwestern Australia (since the mid-1970s) (H,C) [25.5.1, Tables 18-5, 18-6, and 25-1; WGI AR5 4.3.3]	Changes in genetics, growth, distribution, & phenology of many species, in particular birds, butterflies, & plants in Australia, beyond fluctuations due to variable local climates, land use, pollution, & invasive species (H,C) Expansion of monsoon rainforest at expense of savannah and grasslands in northern Australia (M,C) [Tables 18-7 and 25-3]	Southward shifts in the distribution of marine species near Australia, beyond changes due to short-term environmental fluctuations, fishing, and pollution (M,C) Increased coral bleaching in Great Barrier Reef and Western Australian Reefs, beyond effects from pollution & physical disturbance (H,C) Changed coral disease patterns at Great Barrier Reef, beyond effects from pollution (M,C) [6.3.1, 25.6.2, Tables 18-8 and 25-3]	Advanced timing of wine-grape maturation in recent decades, beyond advance due to improved management (M,C) [Tables 18-9 and 25-3]

REGION	Snow & Ice, Rivers & Lakes, Floods & Drought	Terrestrial Ecosystems	Coastal Erosion & Marine Ecosystems	Food Production & Livelihoods
North America	Shrinkage of glaciers across western and northern North America (H,C) Decreasing amount of water in spring snowpack in western North America (1960-2002) (H,C) Shift to earlier peak flow in snow dominated rivers in western North America (H,C) [Tables 18-5 and 18-6; WGI AR5 2.6.2, 4.3.3]	Phenology changes & species distribution shifts upward in elevation & northward across multiple taxa (M,C) Increased wildfire frequency in subarctic conifer forests and tundra (M,C) Increase in wildfire activity, fire frequency & duration, & burnt area in boreal forest of North America, beyond changes due to land use & fire management (M,c) [26.4.1, 28.2.3, Table 18-7, Box 26-2]	Northward distributional shifts of Northwest Atlantic fish species (H,C) Changes in musselbeds along the west coast of US (H,C) Changed migration and survival of salmon in northeast Pacific (H,C) Increased coastal erosion in Alaska and Canada (M,C) [18.3.1, 18.3.3, 30.5.1, Tables 6-2 and 18-8]	Impacts on livelihoods of indigenous groups in the Canadian Arctic, beyond effects of economic and sociopolitical changes (M,C) [18.4.6, Tables 18-4 and 18-9, 28.2.4]
Central & South America	Shrinkage of Andean glaciers (H,C) Changes in extreme flows in Amazon River (M,C) Changing discharge patterns in rivers in the Western Andes (M,c) Increased streamflow in sub-basins of the La Plata River, beyond increase due to land use change (H,C) [27.3.1, Tables 18-5, 18-6, and 27-3; WGI AR5 4.3.3]		Increased coral bleaching in western Caribbean, beyond effects from pollution & physical disturbance (H,C) [27.3.3, Table 18-8]	More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia due to water shortage, beyond effects of increasing social and economic stress (M,C) Increase in agricultural yields and expansion of agricultural areas in southeastern South America, beyond increase due to improved technology (M,C) [13.1.4, 27.3.4, Table 18-9]
Polar Regions	Decreasing Arctic sea ice cover in summer (H,C) Reduction in ice volume in Arctic glaciers (H,C) Decreasing snow cover extent across the Arctic (M,C) Widespread permafrost degradation, especially in the southern Arctic (H,C) Ice mass loss along coastal Antarctica (M,C) Increased winter minimum river flow in most sectors of the Arctic (M,C) Increased lake water temperatures 1985–2009 and prolonged ice-free seasons (M,C) Disappearance of thermokarst lakes due to permafrost degradation in the low Arctic. New lakes created in areas of formerly frozen peat (H,C) [28.2.1, 28.2.3, Tables 18-5 and 18-6; WGI AR5 4.2.2-3, 4.3.3, 4.4, 4.6, 10.5.2-3]	Increased shrub cover in tundra in North America & Eurasia (H,C). Advance of Arctic tree-line in latitude & altitude (M,C). Changed breeding area & population size of subarctic birds, due to snowbed reduction &/or tundra shrub encroachment (M,C) Loss of snow-bed ecosystems & tussock tundra (H,C). Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events (M,C) Increased plant species ranges in the West Antarctic Peninsula & nearby islands over the past 50 years (H,C) [28.2.3, Table 18-7]	Increased coastal erosion across Arctic (M,C) Negative effects on non-migratory Arctic species (H,C) Decreased reproductive success in Arctic seabirds (M,C) Decline in Southern Ocean seals & seabirds (M,C) Reduced thickness of foraminiferal shells in southern oceans (M,C) Reduced krill density in Scotia Sea (M,C) [6.3.2, 18.3.1, 18.3.3, 24.4.3, 28.2.2, 28.2.4, 28.3.4, Table 18-8]	Impact on livelihoods of Arctic indigenous peoples, beyond effects of economic and sociopolitical changes (M,C) Increased shipping traffic across the Bering Strait (M,C) [18.4.6, 28.2.4, 28.2.6, Tables 18-4 and 18-9, Figure 28-4]
Small Islands		Tropical bird population changes in Mauritius (M,C) Decline of an endemic plant in Hawai'i (M,C) [29.3.2, Table 18-7]	Increased coral bleaching near many tropical small islands, beyond effects of degradation due to fishing and pollution (H,C) [29.3.1, Table 18-8]	

Table TS.2.

Early warning systems for heat
EXPOSURE AND VULNERABILITY : Factors affecting exposure and vulnerability include age, pre-existing health status, level of outdoor activity, socioeconomic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, urban heat island effects, and urban infrastructure. [8.2.3-4, 11.3.3-4, 11.4.1, 11.7, 13.2.1, 19.3.2, 23.5.1, 25.3, 25.8.1, SREX Table SPM.1]
CLIMATE INFORMATION AT THE GLOBAL SCALE: **Observed:** *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] **Projected:** *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 12.4.3]
CLIMATE INFORMATION AT THE REGIONAL SCALE: **Observed:** *Likely* that heat wave frequency has increased since 1950 in large parts of Europe, Asia, and Australia. [WGI AR5 2.6.1] *Medium confidence* in overall increase in heat waves and warm spells in North America since 1960. Insufficient evidence for assessment or spatially varying trends in heat waves or warm spells for South America and most of Africa. [SREX Table 3-2; WGI AR5 2.6.1] **Projected:** *Likely* that, by the end of the 21st century under RCP8.5 in most land regions, a current 20-year high temperature event will at least double its frequency and in many regions occur every two years or annually, while a current 20-year low temperature event will become exceedingly rare. [WGI AR5 12.4.3] *Very likely* more frequent and/or longer heat waves or warm spells over most land areas. [WGI AR5 12.4.3]
DESCRIPTION: Heat-health early warning systems are instruments to prevent negative health impacts during heat waves. Weather forecasts are used to predict situations associated with increased mortality or morbidity. Components of effective heatwave and health warning systems include identifying weather situations that adversely affect human health, monitoring weather forecasts, communicating heatwave and prevention responses, targeting notifications to vulnerable populations, and evaluating and revising the system to increase effectiveness in a changing climate. Warning systems for heat waves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia. [11.7.3, 24.4.6, 25.8.1, 26.6, Box 25-6]
BROADER CONTEXT: •Heat health warning systems can be combined with other elements of a health protection plan, for example building capacity to support communities most at risk, supporting and funding health services, and distributing public health information. •In Africa, Asia, and elsewhere, early warning systems have been used to provide warning of and reduce a variety of risks, related to famine and food insecurity; flooding and other weather-related hazards; exposure to air pollution from fire; and vector-borne and food-borne disease outbreaks. [7.5.1, 11.7,15.4.2, 22.4.5, 24.4.6, 25.8.1, 26.6.3, Box 25-6]
Mangrove restoration to reduce flood risks and protect shorelines from storm surge
EXPOSURE AND VULNERABILITY : Loss of mangroves increases exposure of coastlines to storm surge, coastal erosion, saline intrusion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, can be particularly vulnerable. [5.4.3, 5.5.6, 29.7.2, Box CC-EA]
CLIMATE INFORMATION AT THE GLOBAL SCALE: **Observed:** *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5] *Low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3] **Projected:** *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2] In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]
CLIMATE INFORMATION AT THE REGIONAL SCALE: **Observed:** Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3] **Projected:** *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2] Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5] *More likely than not* substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]
DESCRIPTION: Mangrove restoration and rehabilitation has occurred in a number of locations (e.g., Vietnam, Djibouti, and Brazil) to reduce coastal flooding risks and protect shorelines from storm surge. Restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion. [2.4.3, 5.5.4, 8.3.3, 22.4.5, 27.3.3]

BROADER CONTEXT:
•Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, saline intrusion, wave damage, and erosion. Restoration and rehabilitation of mangroves, as well as of wetlands or deltas, is ecosystem-based adaptation that enhances ecosystem services.
•Synergies with mitigation given that mangrove forests represent large stores of carbon.
•Well-integrated ecosystem-based adaptation can be more cost effective and sustainable than non-integrated physical engineering approaches.
[5.5, 8.4.2, 14.3.1, 24.6, 29.3.1, 29.7.2, 30.6.1-2, Table 5-4, Box CC-EA]

Community-based adaptation and traditional practices in small island contexts

EXPOSURE AND VULNERABILITY:
With small land area, often low elevation coasts, and concentration of human communities and infrastructure in coastal zones, small islands are particularly vulnerable to rising sea levels and impacts such as inundation, saltwater intrusion, and shoreline change. [29.3.1, 29.3.3, 29.6.1-2, 29.7.2]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5]
Low confidence in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3]
Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]
Projected: *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2]
In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged. *Likely* increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]
Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3]
Projected: *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2]
Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5]
More likely than not substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]

DESCRIPTION:
Traditional technologies and skills can be relevant for climate adaptation in small island contexts. In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. [29.6.2]

BROADER CONTEXT:
• Perceptions of self-efficacy and adaptive capacity in addressing climate stress can be important in determining resilience and identifying useful solutions.
•The relevance of community-based adaptation principles to island communities, as a facilitating factor in adaptation planning and implementation, has been highlighted, for example with focus on empowerment and learning-by-doing, while addressing local priorities and building on local knowledge and capacity. Community-based adaptation can include measures that cut across sectors and technological, social, and institutional processes, recognizing that technology by itself is only one component of successful adaptation.
[5.5.4, 29.6.2]

Adaptive approaches to flood defense in Europe

EXPOSURE AND VULNERABILITY :
Increased exposure of persons and property in flood risk areas has contributed to increased damages from flood events over recent decades. [5.4.3-4, 5.5.5, 23.3.1, Box 5-1]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5]
Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]
Projected: *Very likely* that the time-mean rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971-2010 for all RCP scenarios. [WGI AR5 13.5.1]
Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: *Likely* increase in the frequency or intensity of heavy precipitation in Europe, with some seasonal and/or regional variations. [WGI AR5 2.6.2] Increase in heavy precipitation in winter since the 1950s in some areas of northern Europe (*medium confidence*). Increase in heavy

precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*). [SREX Table 3-2]
Increasing mean sea level with regional variations, except in the Baltic sea where the relative sea level is decreasing due to vertical crustal motion. [5.3.2, 23.2.2]
Projected: Over most of the mid-latitude land-masses, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world. [WGI AR5 12.4.5]
Overall precipitation increase in northern Europe and decrease in southern Europe (*medium confidence*). [23.2.2]
Increased extreme precipitation in northern Europe during all seasons, particularly winter, and in central Europe except in summer (*high confidence*). [23.2.2; SREX Table 3.3]

DESCRIPTION:
Several governments have made ambitious efforts to address flood risk and sea level rise over the coming century. In the Netherlands, government recommendations include "soft" measures preserving land from development to accommodate increased river inundation, maintaining coastal protection through beach nourishment, and ensuring necessary political-administrative, legal, and financial resources. Through a multi-stage process, the British government has also developed extensive adaptation plans to adjust and improve flood defenses in order to protect London from future storm surges and river flooding. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions. [5.5.4, 23.7.1, Box 5-1]

BROADER CONTEXT:
•The Dutch plan is considered a paradigm shift, addressing coastal protection by "working with nature" and providing "room for river."
•The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise with numerous and diverse measures possible over the next 50-100 years to reduce risk to acceptable levels.
• In cities in Europe and elsewhere, the importance of strong political leadership or government champions in driving successful adaptation action has been noted.
[5.5.3-4, 8.4.3, 23.7.1-2, 23.7.4, Boxes 5-1 and 26-3]

Index-based insurance for agriculture in Africa

EXPOSURE AND VULNERABILITY:
Susceptibility to food insecurity and depletion of farmers' productive assets following crop failure. Low prevalence of insurance due to absent or poorly developed insurance markets or to amount of premium payments. The most marginalized and resource-poor especially may have limited ability to afford insurance premiums. [10.7.6, 13.3.2, Box 22-1]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1]
Medium confidence that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1]
Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]
Low confidence in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2]
Projected: *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 12.4.3]
Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5]
Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: *Medium confidence* in increase in frequency of warm days and decrease in frequency of cold days and nights in southern Africa. [SREX Table 3-2]
Medium confidence in increase in frequency of warm nights in northern and southern Africa. [SREX Table 3-2]
Projected: *Likely* surface drying in southern Africa by the end of this century under RCP8.5 (*high confidence*). [WGI AR5 12.4.5]
Likely increase in warm days and nights and decrease in cold days and nights in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*). [Table SREX 3-3]
Likely more frequent and/or longer heat waves and warm spells in Africa (*high confidence*). [Table SREX 3-3]

DESCRIPTION:
A recently introduced mechanism that has been piloted in a number of rural locations, including in Malawi, Sudan, and Ethiopia, as well as in India. When physical conditions reach a particular predetermined threshold where significant losses are expected to occur--weather conditions such as excessively high or low cumulative rainfall or temperature peaks--the insurance pays out. [9.4.2, 13.3.2, 15.4.4, Box 22-1]

BROADER CONTEXT:
•Index-based weather insurance is considered well-suited to the agricultural sector in developing countries.
•The mechanism allows risk to be shared across communities, with costs spread over time, while overcoming obstacles to traditional agricultural and disaster insurance markets. It can be integrated with other strategies such as micro-finance and social protection programs.
•Risk-based premiums can help encourage adaptive responses and foster risk awareness and risk reduction by providing financial incentives to policyholders to reduce their risk profile.
•Challenges can be associated with limited availability of accurate weather data and difficulties in establishing which weather conditions cause losses. Basis risk (i.e., farmers suffer losses but no payout is triggered based on weather data) can promote distrust. There can also be difficulty in scaling up pilot schemes.

•Insurance for work programs can enable cash-poor farmers to work for insurance premiums by engaging in community-identified disaster risk reduction projects.
[10.7.4-6, 13.3.2, 15.4.4, Table 10-7, Box 22-1, Box 25-7]

Relocation of agricultural industries in Australia

EXPOSURE AND VULNERABILITY :
Crops sensitive to changing patterns of temperature, rainfall, and water availability. [7.3, 7.5.2]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1]
Medium confidence that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1]
Medium confidence in precipitation change over global land areas since 1950. [WGI AR5 2.5.1]
Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]
Low confidence in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2]
Projected: *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 12.4.3]
Virtually certain increase in global precipitation as global mean surface temperature increases. [WGI AR5 12.4.1]
Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5]
Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand, since 1950 (*high confidence*). [Table 25-1]
Likely increase in heat wave frequency since 1950 in large parts of Australia. [WGI AR5 2.6.1]
Late autumn/winter decreases in precipitation in Southwestern Australia since the 1970s and Southeastern Australia since the mid-1990s, and annual increases in precipitation in Northwestern Australia since the 1950s (*very high confidence*). [Table 25-1]
Mixed or insignificant trends in annual daily precipitation extremes, but a tendency to significant increase in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). [Table 25-1]
Projected: Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). [Table 25-1]
Annual decline in precipitation over southwestern Australia (*high confidence*) and elsewhere in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). [Table 25-1]
Increase in most regions in the intensity of rare daily rainfall extremes and in sub-daily extremes (*medium confidence*) in Australia and New Zealand. [Table 25-1]
Drought occurrence to increase in Southern Australia (*medium confidence*). [Table 25-1]
Snow depth and snow area to decline in Australia (*very high confidence*). [Table 25-1]
Freshwater resources projected to decline in far southeastern and far southwest Australia (*high confidence*). [25.5.2]

DESCRIPTION:
Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use in situ in response to recent climate change or expectations of future change. For example, there has been some switching from grazing to cropping in South Australia. Adaptive movement of crops has also occurred elsewhere. [7.5.1, 25.7.2, Table 9-7, Box 25-5]

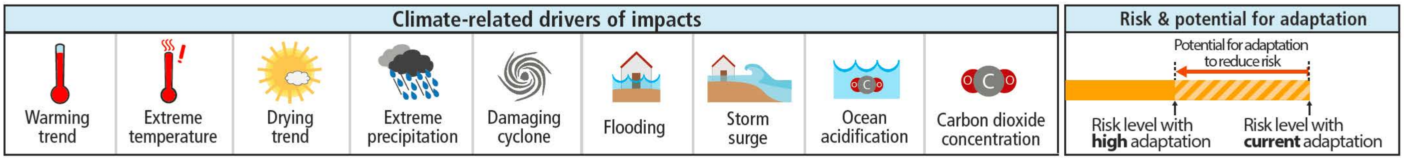
BROADER CONTEXT:
•Considered transformational adaptation in response to impacts of climate change.
•Positive or negative implications for the wider communities in origin and destination regions.
[25.7.2, Box 25-5]

Table TS.3.

#	Hazard	Key vulnerabilities		Key risks	Emergent risks
i	Sea level rise and coastal flooding including storm surges. [5.4.3, 8.1.4, 8.2.3-4, 13.1.4, 13.2.2, 24.4-5, 26.7-8, 29.3, 30.3.1, Figure 26-2, Boxes 25-1 and 25-7; WGI AR5 3.7, 13.5, Table 13-5]	High exposure of people, economic activity, and infrastructure in low-lying coastal zones and Small Island Developing States (SIDS). Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods. Inadequate local governmental attention to disaster risk reduction.	exposure social vulnerability institutional vulnerability	Death, injury, and disruption to livelihoods, food supplies, and drinking water. Loss of common-pool resources, sense of place, and identity, especially among indigenous populations in rural coastal zones.	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality.
ii	Warming, drought, and precipitation variability. [7.4-5, 11.3, 11.6.1, 13.2, 19.3.2, 19.4.1, 22.3.4, 24.4.4, 26.8, 27.3.4; WGI AR5 11.3.2]	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households.	social vulnerability institutional vulnerability	Risk of harm and loss of life due to reversal of progress in reducing malnutrition.	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality, and ongoing food insecurity for the poor increases malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.
iii	Extreme precipitation and inland flooding. [3.2.7, 3.4.8, 8.2.3-4, 13.2.1, 25.10, 26.3, 26.7-8, 27.3.5, Box 25-8; WGI AR5 11.3.2]	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements. Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, and culturally imposed gender roles. Inadequate governmental attention to disaster risk reduction.	exposure social vulnerability institutional vulnerability	Death, injury, and disruption of human security, especially among children, elderly, and disabled.	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high risk/high poverty spatial traps.
iv	Drought. [3.2.7, 3.4.8, 3.5.1, 8.2.3-4, 9.3.3, 9.3.5, 13.2.1, 19.3.2, 24.4; WGI AR5 12.4.1, 12.4.5]	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural-urban linkages.	social vulnerability institutional vulnerability	Insufficient water supply for people and industry yielding severe harm and economic impacts.	Interaction of urbanization, infrastructure insufficiency, groundwater depletion.
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water. Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources.	exposure	Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods particularly for those depending on water-intensive agriculture. Risk of food insecurity.	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in low- and middle-income countries. Potential tipping point in rain-

		Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods.	social vulnerability institutional vulnerability		fed farming system and/or pastoralism.
v	Novel hazards yielding systemic risks. [8.1.4, 8.2.4, 10.2-3, 12.6, 23.9, 25.10, 26.7-8; WGI AR5 11.3.2]	Populations and infrastructure exposed and lacking historical experience with these hazards. Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability.	exposure institutional vulnerability	Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on telecommunications. Collapse of health and emergency services in extreme events.	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
vi	Rising ocean temperature, stratification, ocean acidification, and loss of Arctic sea ice. [5.4.2, 6.3.1-2, 7.4.2, 9.3.5, 22.3.2, 25.6, 27.3.3, 28.2-3, 29.3.1, 30.5-6, Boxes CC-OA and CC-CR; WGI AR5 11.3.3]	High susceptibility of warm-water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species. Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture.	environmental vulnerability economic vulnerability environmental vulnerability	Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms.	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk.
vii	Rising land temperatures, and changes in precipitation patterns and in frequency and intensity of extreme heat. [4.3.4, 19.3.2, 22.4.5, 27.3, Table 23-2, Box CC-WE; WGI AR5 11.3.2]	Susceptibility of human systems, agro-ecosystems and natural ecosystems to (i) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate (ii) loss of provision of food, livestock, fiber, bioenergy (iii) loss of recreation, tourism, aesthetic and heritage values, and biodiversity.	economic vulnerability environmental vulnerability	Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms.	Interaction of social-ecological systems with loss of ecosystem services upon which they depend.
viii	Increasing frequency and intensity of extreme heat, including urban heat island effect. [8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8, Box CC-HS; WGI AR5 11.3.2]	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures. Inability of local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups.	social vulnerability institutional vulnerability	Increased mortality and morbidity during periods of extreme heat.	Interaction of demographic shifts with changes in regional temperature extremes, local heat island, and air pollution. Overloading of health and emergency services. Mortality, morbidity, and productivity loss among manual workers in hot climates.

Table TS.4.



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Global Risks					
Reduction in terrestrial carbon sink: Carbon stored in terrestrial ecosystems is vulnerable to loss back into the atmosphere, resulting from increased fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (*medium confidence*)	• Adaptation options include managing land use (including deforestation), fire and other disturbances, and non-climatic stressors.		4.2-3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost, spread of shrubs in tundra, and increase in pests and fires in boreal forests (*medium confidence*)	• There are few adaptation options in the Arctic.		4.3, Box 4-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Amazon tipping point: Moist Amazon forests could change abruptly to less-carbon-dense, drought- and fire-adapted ecosystems (*medium confidence*)	• Policy and market measures can reduce deforestation and fire.		4.3, Box 4-3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of species extinction: A large fraction of the species assessed is vulnerable to extinction due to climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountaintops, islands, or small protected areas are especially at risk. Cascading effects through organism interactions, especially those vulnerable to phenological changes, amplify risk (*high confidence*)	• Adaptation options include reduction of habitat modification and fragmentation, pollution, over-exploitation, and invasive species; protected area expansion; assisted dispersal; and *ex situ* conservation.		4.3-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Reduced growth and survival of commercially valuable shellfish and other calcifiers (e.g., reef building corals, calcareous red algae) due to ocean acidification (*high confidence*)	• Evidence for differential resistance and evolutionary adaptation of some species exists but is *likely* to be limited at higher CO_2 concentrations and temperatures. • Adaptation options include exploiting more resilient species or protecting habitats with low natural CO_2 levels, as well as reducing other stresses, mainly pollution, and limiting pressures from tourism and fishing.		5.3, 6.1, 6.3-4, 30.3, Box CC-OA	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Marine biodiversity loss with high rate of climate change (*medium confidence*)	• Adaptation options are limited to reducing other stresses, mainly pollution, and limiting pressures from coastal human activities such as tourism and fishing.		6.3-4, Table 30-4, Box CC-MB	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Negative impacts on average crop yields and increases in yield variability due to climate change (*high confidence*)	• With or without adaptation, negative impacts on average yields become *likely* from the 2030s with median yield impacts of 0 to -2% per decade projected for the rest of the century, and after 2050 the risk of more severe impacts increases.		7.2-5, Box 7-1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high

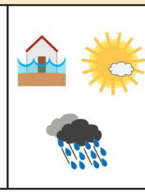
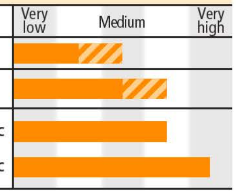
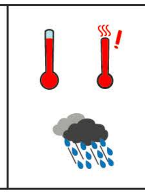
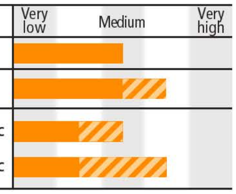
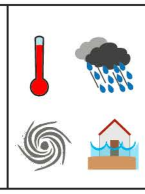
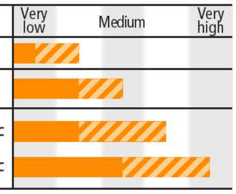
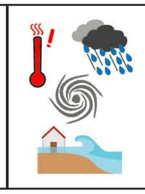
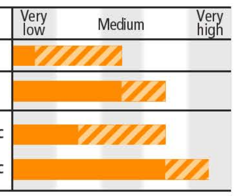
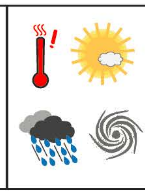
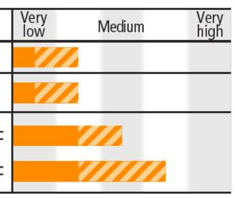
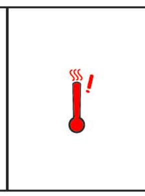
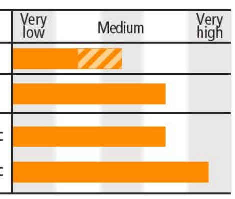
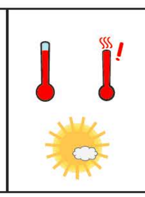
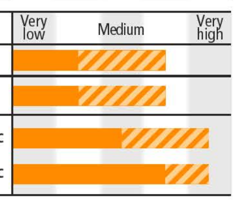
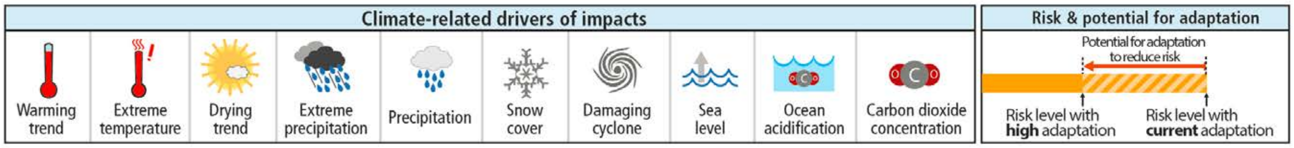
Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Global Risks					
Urban risks associated with water supply systems (*high confidence*)	• Adaptation options include changes to network infrastructure as well as demand-side management to ensure sufficient water supplies and quality, increased capacities to manage reduced freshwater availability, and flood risk reduction.		8.2-3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Urban risks associated with energy systems (*high confidence*)	• Most urban centers are energy intensive, with energy-related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is potential for non-adapted, centralized energy systems to magnify impacts, leading to national and transboundary consequences from localized extreme events.		8.2, 8.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Urban risks associated with housing (*high confidence*)	• Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation, and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have opportunities to increase resilience, but this is rarely realized. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Displacement associated with extreme events (*high confidence*)	• Adaptation to extreme events is well understood, but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		12.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Voilent conflict arising from deterioration in resource-dependent livelihoods such as agriculture and pastoralism (*high confidence*)	Adaptation options: • Buffering rural incomes against climate shocks, for example through livelihood diversification, income transfers, and social safety net provision • Early warning mechanisms to promote effective risk reduction • Well-established strategies for managing violent conflict that are effective but require significant resources, investment, and political will		12.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Declining work productivity, morbidity (e.g., dehydration, heat stroke, and heat exhaustion), and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*)	• Adaptation options are limited for people who are dependent on agriculture and cannot afford agricultural machinery. • Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. • Adaptation limits may be exceeded in certain areas in a +4°C world.		13.2, Box 13-1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*)	• Adaptation through reducing water use is not an option for the many people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalized water users are unable to compete with water extraction by industries, large-scale agriculture, and other powerful users.		13.2, Box 13-1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Table TS.5.



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Africa					
Compounded stress on water resources facing significant strain from overexploitation and degradation at present and increased demand in the future (*high confidence*)	• Reducing non-climate stressors on water resources • Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning, and integrated land and water governance		22.3-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Reduced crop productivity with strong adverse effects on regional, national, and household food security, also given increased pest and disease damage and flood impacts on food system infrastructure (*high confidence*)	• Technological adaptation responses (e.g., stress-tolerant crop varieties, irrigation) • Enhancing smallholder access to credit and other critical production resources and diversifying livelihoods • Strengthening institutions at local to regional levels to support agriculture and gender-oriented policy support		22.3-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*)	• Achieving development goals, particularly improved access to safe water and improved sanitation, and enhancement of public health functions such as surveillance • Vulnerability mapping and early warning systems • Coordination across sectors		22.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Europe					
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanization and by increasing sea levels and peak river discharges (*high confidence*)	Adaptation can prevent most of the projected damages (*high confidence*). • Significant experience in hard flood-protection technologies • High costs for increasing flood protection • Potential barriers to implementation: demand for land in Europe and environmental and landscape concerns		23.2-3, 23.7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined with increased water demand (e.g., for irrigation, energy and industry, domestic use) and with reduced water drainage and runoff as a result of increased evaporative demand (*high confidence*)	• Proven adaptation potential from adoption of more water-efficient technologies and of water-saving strategies (e.g., for irrigation, crop species, land cover, industries, domestic use) • Further adaptation possible through solar desalinization with mitigation co-benefits		23.4, 23.7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Increased economic losses and people affected by extreme heat events: impacts on health and well-being, labor productivity, crop production, and air quality (*medium confidence*)	• Implementation of warning systems • Adaptation of dwellings and workplaces and of transport and energy infratructure • Reductions in emissions to improve air quality • Improved wildfire management		23.3, 23.5-7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Asia					
Increased flooding leading to widespread damage to infrastructure and settlements in Asia (*medium confidence*)	• Exposure reduction via effective land-use planning, selective relocation, and structural measures • Reduction in the vulnerability of lifeline infrastructure and services (e.g., water, energy, waste management, food, biomass, mobility, local ecosystems, telecommunications) • Assistance to vulnerable sectors and households		24.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Asia (continued)					
Increased risk of heat-related mortality (*high confidence*)	• Heat health warning systems • Urban planning to reduce heat islands • Improvement of the built environment		24.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*)	• Disaster preparedness including early-warning systems and local response strategies		24.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Australasia					
Significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia (*high confidence*)	• Ability to adapt naturally is limited especially for species that occupy narrow climatic ranges and fragmented habitats. • Main human adaptation options are to reduce other pressures (e.g., pollution, runoff, fishing, tourism, introduced predators and pests) and improve early warning systems. Assisted colonization and other direct interventions such as shading of reefs have been proposed but remain untested at scale.		25.6, 25.10	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*)	• Significant adaptation deficit in some regions to current flood risk. • Effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		Table 25-1, Boxes 25-8 and 25-9	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damage towards the upper end of projected sea-level-rise ranges (*high confidence*)	• Adaptation deficit in some locations to current coastal erosion and flood risk. Successive building and protection cycles constrain flexible responses. • Effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		25.6, 25.10, Box 25-1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
North America					
Loss of ecosystem integrity, property loss, human morbidity, and mortality due to wildfires (*high confidence*)	• Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. • Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity.		26.4, 26.8, Box 26-2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Heat-related human mortality (*high confidence*)	• Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is often limited among the most vulnerable individuals and is subject to complete loss during power failures. Vulnerable populations include athletes and outdoor workers for whom A/C is not available. • Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via family support, heat warnings, cooling centers, greening, and high albedo surfaces.		26.6, 26.8	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Property and infrastructure damage; supply chain, ecosystem, and social system disruption; public health impacts; and water quality impairment from river and coastal urban floods (*high confidence*)	• Implementing management of urban drainage is expensive and disruptive to urban areas. • Low-regret strategies with co-benefits include less impervious surfaces leading to more groundwater recharge, green infrastructure, and rooftop gardens. • Sea-level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used that need to be updated to reflect current climate conditions.		26.2-4, 26.8	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Central and South America					
Water availability in semi-arid and glacier-melt-dependent regions and flooding in urban areas due to extreme precipitation (*high confidence*)	• Water-supply deficit replacement and improved land use • Urban flood management (including infrastructure), early warning systems, better weather and runoff forecasts, and infectious disease control		27.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Decreased food production and food quality (*medium confidence*)	• Development of new crop varieties more adapted to changes in CO_2, temperature, and drought • Offsetting of human and animal health impacts of reduced food quality • Offsetting of economic impacts of land use change		27.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Small Islands					
Loss of livelihoods, coastal settlements, and infrastructure in small islands (*high confidence*)	• Significant potential exists for adaptation in islands, but additional external resources and technologies will enhance response. • Efficacy of traditional community coping strategies is expected to be substantially reduced in the future.		Figure 29-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
The interaction of rising global mean sea level in the 21st century with high-water-level events will threaten low-lying coastal areas in small islands (*high confidence*)	• High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. • Adaptation options include maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, and appropriate building codes and settlement patterns.		29.4, Table 29-1; WGI AR5 13.5, Table 13.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
The Ocean					
Distributional shift in fish and invertebrate species, and decrease in fishery catch potential at low latitudes, e.g., in equatorial upwelling and coastal boundary systems and sub-tropical gyres (*high confidence*)	• Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their ongoing latitudinal shifts. • Human adaptation options: Large-scale translocation of industrial fishing activities following the regional decreases (low latitude) vs. possibly transient increases (high latitude) in catch potential; Flexible management that can react to variability and change; Improvement of fish resilience to thermal stress by reducing other stressors such as pollution and eutrophication; Expansion of aquaculture.		6.3, Box CC-MB	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Reduced biodiversity, fisheries abundance, and coastal protection by coral reefs due to heat-induced mass coral bleaching and mortality increases, e.g., in coastal boundary systems and sub-tropical gyres (*high confidence*)	• Evidence of rapid evolution by corals is very limited. Some corals may migrate to higher latitudes, but entire reef systems are not expected to be able to track the high rates of temperature shifts. • Human adaptation options are limited to reducing other stresses, mainly by enhancing water quality, and limiting pressures from tourism and fishing. These options will delay human impacts of climate change by a few decades, but their efficacy will be severely reduced as thermal stress increases.		5.4, 6.4, 30.3, 30.5, Box CC-CR	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Coastal inundation and habitat loss due to sea-level rise and intensified precipitation events, e.g., in coastal boundary systems and sub-tropical gyres (*medium* to *high confidence*)	• Human adaptation options are limited to reducing other stresses, mainly by reducing pollution and limiting pressures from tourism, fishing, and aquaculture. • Loss of ecosystems such as sea grass, mangroves, and coral reefs can be reduced by reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients.		5.5, 30.5-6, Box CC-CR	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Table TS.6.

Key

Symbols

- Increasing trend or signal
- Decreasing trend or signal
- Both increasing and decreasing trends or signals
- Inconsistent trend or signal or insufficient evidence
- No or only slight change

Level of confidence in findings

- Low confidence
- Medium confidence
- High confidence

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
West North America WNA, 3	*Very likely* large increases in hot days (large decreases in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends. General increase, decrease in some areas[a]	Increase in 20-year return value of annual maximum daily precipitation and other metrics over northern part of the region (Canada)[b] Less confidence in Southern part of the region, due to inconsistent signal in these other metrics[b]	No or overall slight decrease in dryness[a]	Inconsistent signal[b]
Central North America CNA, 4	Spatially varying trends: small increases in hot days in the north, decreases in the south[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation[b] Inconsistent signal in other heavy precipitation days metrics[b]	*Likely* decrease[a, c]	Increase in consecutive dry days and soil moisture in southern part of Central North America[b] Inconsistent signal in the rest of the region[b]
East North America ENA, 5	Spatially varying trends. Overall increases in hot days (decreases in cool days), opposite or insignificant signal in a few areas[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation over northern part of the region[b] No signal or inconsistent signal in these other metrics in the southern part of the region[b]	Slight decrease in dryness since 1950[a]	Inconsistent signal in consecutive dry days, some consistent decrease in soil moisture[b]
Alaska/ Northwest Canada ALA, 1	*Very likely* large increases in warm days (decreases in cold days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Slight tendency for increase[a] No significant trend in southern Alaska[a]	*Likely* increase in heavy precipitation[b]	Inconsistent trends[a] Increases in dryness in part of the region[a]	Inconsistent signal[b]
East Canada, Greenland, Iceland CGI, 2	*Likely* increases in hot days (decreases in cool days) in some areas, decrease in hot days (increase in cool days) in others[a]	*Very likely* increase in warm days (decrease in cold days)[b]	Increase in a few areas[a]	*Likely* increase in heavy precipitation[b]	Insufficient evidence[a]	Inconsistent signal[b]
Northern Europe NEU, 11	Increase in hot days (decrease in cool days), but generally not significant at the local scale[a]	*Very likely* increase in hot days (decrease in cool days) [but smaller trends than in central and southern Europe][b]	Increase in winter in some areas, but often insignificant or inconsistent trends at subregional scale, particularly in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. *Very likely* increases in heavy preciptation intensity and frequency in winter in the north[b]	Spatially varying trends. Overall only slight or no increase in dryness, slight decrease in dryness in part of the region[a]	No major changes in dryness[b]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
Central Europe CEU, 12	*Likely* overall increase in hot days (decrease in cool days) since 1950 in most regions. *Very likely* increase in hot days (likely decrease in cool days) in west Central Europe[a] Lower confidence in trends in east Central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Increase in part of the region, in particular central Western Europe and European Russia, especially in winter[a] Insignificant or inconsistent trends elsewhere, in particular in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation in large part of the region over winter[b] Less confidence in summer, due to inconsistent evidence[b]	Spatially varying trends. Increase in dryness in part of the region but some regional variation in dryness trends and dependence of trends on studies considered (index, time period)[a]	Increase in dryness in central Europe and increase in short-term droughts[b]
Southern Europe and Mediterra-nean MED, 13	*Likely* increase in hot days (decrease in cool days) in most of the region. Some regional and temporal variations in the significance of the trends. Likely strongest and most significant trends in Iberian peninsula and southern France[a] Smaller or less significant trends in southeastern Europe and Italy due to change point in trends, strongest increase in hot days since 1976[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Inconsistent trends across the region and across studies[a]	Inconsistent changes and/or regional variations[b]	Overall increase in dryness, *likely* increase in the Mediterranean[a,c]	Increase in dryness. Consistent increase in area of drought[b,d]
West Africa WAF, 15	Significant increase in temperature of hottest day and coolest day in some parts[a] Insufficient evidence in other parts[a]	*Likely* increase in hot days (decrease in cool days)[b]	Rainfall intensity increased[a]	Slight or no change in heavy precipitation indicators in most areas[b] Low model agreement in northern areas[b]	*Likely* increase but 1970s Sahel drought dominates the trend; greater inter- annual variation in recent years[a,c]	Inconsistent signal[b]
East Africa EAF, 16	Lack of evidence due to lack of literature and spatially non-uniform trends[a] Increases in hot days in Southern tip (decrease in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	*Likely* increase in heavy precipitation[b]	Spatially varying trends in dryness[a]	Decreasing dryness in large areas[b]
Southern Africa SAF, 17	*Likely* increase in hot days (decrease in cool days)[a,c]	*Likely* increase in hot days (decrease in cool days)[b]	Increases in more regions than decreases but spatially varying trends[a]	Lack of agreement in signal for region as a whole[b] Some evidence of increase in heavy precipitation in southeast regions[b]	General increase in dryness[a]	Increase in dryness, except eastern part[b,d] Consistent increase in area of drought[b]
Sahara SAH, 14	Lack of literature[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	Low agreement[b]	Limited data, spatial variation of the trends[a]	Inconsistent signal of change[b]
Central America and Mexico CAM, 6	Increases in the number of hot days, decreases in the number of cool days[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends. Increase in many areas, decrease in a few others[a]	Inconsistent trends[b]	Varying and inconsistent trends[a]	Increase in dryness in Central America and Mexico, with less confidence in trend in extreme South of region[b]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
Amazon AMZ, 7	Insufficient evidence to identify trends[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increases in many areas, decreases in a few[a]	Tendency for increases in heavy precipitation events in some metrics[b]	Decrease in dryness for much of the region. Some opposite trends and inconsistencies[a]	Inconsistent signals[b]
Northeastern Brazil NEB, 8	Increases in the number of hot days[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increases in many areas, decreases in a few[a]	Slight or no change[b]	Varying and inconsistent trends[a]	Increase in dryness[b]
Southeast-ern South America SSA, 10	Spatially varying trends (increases in some areas decreases in others)[a]	Hot days *likely* to increase (cool days *likely* decrease)[b]	Increases in northern areas[a] Insufficient evidence in southern areas[a]	Increases in northern areas[b] Insufficient evidence in southern areas[b]	Varying and inconsistent trends[a]	Inconsistent signals[b]
West Coast South America WSA, 9	Spatially varying trends (increases in some areas decreases in others)[a]	Hot days *likely* to increase (cool days *likely* decrease)[b]	Increases in many areas, decrease in a few areas[a]	Increases in tropics[b] Low confidence in extratropics[b]	Varying and inconsistent trends[a]	Decrease in consecutive dry days in the tropics, and increase in the extratropics[b] Increase in consecutive dry days and soil moisture in southwest South America[b]
North Asia NAS, 18	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in some regions, but spatial variation[a]	*Likely* increase in heavy precipitation for most regions[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
Central Asia CAS, 20	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends[a]	Inconsistent signal in models[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
East Asia EAS, 22	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends[a]	Increase in heavy precipitation across the region[b]	Tendency for increased dryness[a]	Inconsistent signal of change[b]
Southeast Asia SEA, 24	Increase in hot days (decrease cool days) for northern areas[a] Insufficient evidence for Malay Archipelago[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends, partial lack of evidence[a]	Increases in most metrics over most (especially non-continental) regions. One metric shows inconsistent signals of change[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
South Asia SAS, 23	Increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Mixed signal in India[a]	More frequent and intense heavy precipitation days over parts of S. Asia. Either no change or some consistent increases in other metrics[b]	Inconsistent signal for different studies and indices[a]	Inconsistent signal of change[b]
West Asia WAS, 19	*Very likely* increase in hot days (decrease in cool days *more likely than not*)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Decrease in heavy precipitation events[a]	Inconsistent signal of change[b]	Lack of studies, mixed results[a]	Inconsistent signal of change[b]
Tibetan Plateau TIB, 21	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Insufficient evidence[a]	Increase in heavy precipitation[b]	Insufficient evidence. Tendency to decreased dryness[a]	Inconsistent signal of change[b]
North Australia NAU, 25	*Likely* increase in hot days (decrease in cool days). Weaker trends in northwest[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends, which mostly reflect changes in mean rainfall[a]	Increase in most regions in the intensity of extreme (i.e. current 20 year return period) heavy rainfall events[a]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[a]	Inconsistent signal[b]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected
South Australia/ New Zealand SAU, 26	*Very likely* increase in hot days (decrease in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends in S Australia, which mostly reflect changes in mean rainfall[e] Spatially varying trends in NZ, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e. current 20 year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e] No trend in drought occurrence over New Zealand (defined using a soil water balance model) since 1972[e]	Increase in drought frequency in southern Australia, and in many regions of New Zealand[e]

Table TS.7.

Overlapping Entry Points	Category	Examples	Chapter Reference(s)
Vulnerability reduction through development & planning *Including many low-regrets measures*	Human development	Improved access to education, nutrition, health facilities, energy, safe settlement structures, & social support structures; Reduced gender inequality & marginalization in other forms.	8.3, 9.3, 13.1-3, 14.2-3, 22.4
	Poverty alleviation	Insurance schemes; Social safety nets & social protection; Disaster risk reduction; Improved access to & control of local resources, land tenure, & storage facilities.	8.3, 9.3, 13.1-3, Box 8-4
	Livelihood security	Income, asset, & livelihood diversification; Improved infrastructure; Access to technology & decision-making fora; Enhanced agency; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	7.5, 13.1-3, 22.3-4, 23.4, 26.5, 27.3, 29.6, Table 24-7
	Disaster risk management	Early warning systems; Hazard & vulnerability mapping; Improved drainage; Flood & cyclone shelters; Building codes; Storm & wastewater management; Transport & road infrastructure improvements.	8.2-4, 11.7, 14.3, 15.3-4, 22.4, 24.4, 25.4, 26.6, 28.4
	Ecosystem management	Maintaining wetlands & urban green spaces; Coastal afforestation; Dam management; Reduction of other stressors on ecosystems & of habitat fragmentation; Maintenance of genetic diversity; Assisted translocation; Manipulation of disturbance regimes; Community-based natural resource management.	4.3-4, 8.3, 22.4, Table 3-3, Boxes 4-2, 4-3, 8-2, 15-1, 25-8, 25-9, & CC-EA
	Spatial or land-use planning	Provisioning of adequate housing, infrastructure, & services; Managing development in flood prone & other high risk areas; Urban upgrading programs; Land zoning laws; Easements; Protected areas.	4.4, 8.1, 8.3-4, 22.4, 23.7-8, 27.3, Box 25-8
Adaptation *Including incremental & transformational adjustments*	Structural/ physical	***Engineered & built-environment options:*** Sea walls & coastal protection structures; Flood levees; Water storage; Improved drainage; Flood & cyclone shelters; Building codes; Storm & wastewater management; Transport & road infrastructure improvements; Floating houses; Power plant & electricity grid adjustments.	3.5-6, 5.5, 8.2-3, 10.2, 11.7, 23.3, 24.4, 25.7, 26.3, 26.8, Boxes 15-1, 25-1, 25-2, & 25-8
		Technological options: New crop & animal varieties; Traditional technologies & methods; Efficient irrigation; Water-saving technologies; Conservation agriculture; Food storage & preservation facilities; Hazard mapping & monitoring; Early warning systems; Building insulation; Mechanical & passive cooling.	7.5, 8.3, 9.4, 10.3, 15.3-4, 22.4, 24.4, 26.3, 26.5, 27.3, 28.2, 28.4, 29.6-7, Table 25-2, Boxes 20-5 & 25-2
		Ecosystem-based options: Ecological restoration; Afforestation & reforestation; Mangrove conservation & replanting; Green infrastructure (e.g., shade trees, green roofs); Controlling overfishing; Fisheries co-management; Assisted migration or managed translocation; Ecological corridors; Ex situ conservation & seed banks; Community-based natural resource management.	4.4, 5.5, 8.3, 9.4, 11.7, 15.3-4, 22.4, 23.6-7, 24.4, 25.6, 26.4, 27.3, 28.2, 29.7, 30.6, Boxes 15-1, 22-2, 25-9, 26-2, & CC-EA
		Services: Social safety nets & social protection; Food banks & distribution of food surplus; Municipal services including water & sanitation; Vaccination programs; Essential public health services; Enhanced emergency medical services.	3.5-6, 8.3, 9.3-4, 11.7, 11.9, 22.4, 29.6, Box 13-2
	Institutional	***Economic options:*** Financial incentives including taxes & subsidies; Insurance; Catastrophe bonds; Payments for ecosystem services; Water tariffs; Microfinance; Disaster contingency funds; Cash transfers.	8.3-4, 9.4, 10.7, 11.7, 13.3, 15.4, 17.5, 22.4, 26.7, 27.6, 29.6, Box 25-7
		Laws & regulations: Land zoning laws; Building standards; Easements; Water regulations & agreements; Laws to support disaster risk reduction; Laws to encourage insurance purchasing; Defined property rights & land tenure security; Protected areas; Fishing quotas; Patent pools & technology transfer.	4.4, 8.3, 9.3, 10.5, 10.7, 15.2, 15.4, 17.5, 22.4, 23.4, 23.7-8, 24.4, 25.4, 26.3, 27.3, Table 25-2, Box CC-CR
		Government policies & programs: National & regional adaptation plans including mainstreaming; Sub-national & local adaptation plans; Urban upgrading programs; Municipal water management programs; Disaster planning & preparedness; Integrated water resource management; Integrated coastal zone management; Ecosystem-based management; Community-based adaptation.	2.2-4, 3.6, 4.4, 5.5, 6.4, 7.5, 8.3, 11.7, 15.2-4, 22.4, 23.7, 25.4, 25.8, 26.8-9, 27.3-4, 29.6, 30.6, Boxes 25-1, 25-2, & 25-9
	Social	***Educational options:*** Awareness raising & integrating into education; Gender equity in education; Extension services; Sharing local & traditional knowledge; Participatory action research & social learning; Knowledge-sharing & learning platforms.	8.3-4, 9.4, 11.7, 12.3, 15.2-4, 22.4, 25.4, 28.4, 29.6, Table 25-2
		Informational options: Hazard & vulnerability mapping; Early warning & response systems; Systematic monitoring & remote sensing; Climate services; Use of indigenous climate observations; Participatory scenario development.	2.4, 5.5, 8.3-4, 9.4, 11.7, 15.2-4, 22.4, 23.5, 24.4, 25.8, 26.6, 26.8, 27.3, 28.2, 28.5, Table 25-2, Box 26-3
		Behavioral options: Household preparation & evacuation planning; Migration; Soil & water conservation; Storm drain clearance; Livelihood diversification; Changed cropping, livestock, & aquaculture practices; Reliance on social networks.	5.5, 7.5, 9.4, 11.7, 12.4, 22.3-4, 23.4, 23.7, 25.7, 26.5, 27.3, 29.6, Table SM24-7, Box 25-5
Transformation	Spheres of change	***Practical:*** Social & technical innovations, behavioral shifts, or institutional & managerial changes that produce substantial shifts in outcomes.	8.3, 20.5, Box 25-5
		Political: Changes in the political, social, cultural, & ecological systems or structures that currently contribute to risk & vulnerability or impede practical transformations.	14.2-3, 20.5, 25.4, Table 14-1
		Personal: Changes in individual & collective assumptions, beliefs, values, & worldviews that influence climate change responses.	14.2-3, 20.5, 25.4, Table 14-1
Mitigation		See WGIII AR5.	

Table TS.8.

Green infrastructure and green roofs
Objectives: Storm water management, adaptation to increasing temperatures, reduced energy use, urban regeneration
Relevant Sectors: Infrastructure, energy use, water management
Overview: Benefits of green infrastructure and roofs can include reduction of storm water runoff and the urban heat island effect, improved energy performance of buildings, reduced noise and air pollution, health improvements, better amenity value, increased property values, improved biodiversity, and inward investment. Trade-offs can result between higher urban density to improve energy efficiency and open space for green infrastructure. [8.3.3, 11.7.4, 23.7.4, 24.6, Tables 11-3 and 25-5]
EXAMPLES WITH INTERACTIONS: **London:** The Green Grid for East London seeks to create interlinked and multi-purpose open spaces to support regeneration of the area. It aims to connect people and places, to absorb and store water, to cool the vicinity, and to provide a diverse mosaic of habitats for wildlife. [8.3.3] **New York**: In preparation for more intense storms, New York is using green infrastructure to capture rainwater before it can flood the combined sewer system, implementing green roofs, and elevating boilers and other equipment above ground. [8.3.3, 26.3.3, 26.8.4] **Singapore**: Singapore has used several anticipatory plans and projects to enhance green infrastructure, including its Streetscape Greenery Master Plan, constructed wetlands or drains, and community gardens. Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives. [8.3.3] **Durban**: Ecosystem-based adaptation is part of Durban's climate change adaptation strategy. The approach seeks a more detailed understanding of the ecology of indigenous ecosystems and ways in which biodiversity and ecosystem services can reduce vulnerability of ecosystems and people. Examples include the Community Reforestation Programme, in which communities produce indigenous seedlings used in the planting and managing of restored forest areas. Development of ecosystem-based adaptation in Durban has demonstrated needs for local knowledge and data and the benefits of enhancing existing protected areas, land-use practices, and local initiatives contributing to jobs, business, and skill development. [8.3.3, Box 8-2]
Water management
Primary Objective: Water resource management given multiple stressors in a changing climate
Relevant Sectors: Water use, energy production and use, biodiversity, carbon sequestration, biofuel production, food production
Overview: Water management in the context of climate change can encompass ecosystem-based approaches (e.g., watershed management or restoration, flood regulation services, and reduction of erosion or siltation), supply-side approaches (e.g., dams, reservoirs, groundwater pumping and recharge, and water capture), and demand-side approaches (e.g., increased use efficiency through water recycling, infrastructure upgrades, water-sensitive design, or more efficient allocation). Water may require significant amounts of energy for lifting, transport, distribution, and treatment. [3.7.2, 26.3, Tables 9-8 and 25-5, Boxes CC-EA and CC-WE]
EXAMPLES WITH INTERACTIONS: **New York**: New York has a well-established program to protect and enhance its water supply through watershed protection. The Watershed Protection Program includes city ownership of land that remains undeveloped and coordination with landowners and communities to balance water-quality protection, local economic development, and improved wastewater treatment. The city government indicates it is the most cost-effective choice for New York given the costs and environmental impacts of a filtration plant. [8.3.3, Box 26-3] **Cape Town:** Facing challenges in ensuring future supplies, Cape Town responded by commissioning water management studies, which identified the need to incorporate climate change, as well as population and economic growth, in planning. During the 2005 drought, local authorities increased water tariffs to promote efficient water usage. Additional measures may include water restrictions, reuse of grey water, consumer education, or technological solutions such as low-flow systems or dual flush toilets. [8.3.3] **Capital cities in Australia:** Many Australian capital cities are reducing reliance on catchment runoff and groundwater—water resources most sensitive to climate change and drought—and are diversifying supplies through desalination plants, water reuse including sewage and storm water recycling, and integrated water cycle management that considers climate change impacts. Demand is being reduced through water conservation and water-sensitive urban design and, during severe shortfalls, through implementation of restrictions. The water augmentation program in Melbourne includes a desalination plant. Trade-offs beyond energy intensiveness have been noted, such as damage to sites significant to aboriginal communities and higher water costs that will disproportionately affect poorer households. [14.6.2, Table 25-7, Box 25-2]
Payment for environmental services and green fiscal policies
Primary Objective: Management incorporating the costs of environmental externalities and the benefits of ecosystem services
Relevant Sectors: Biodiversity, ecosystem services
Overview: Payment for environmental services (PES) is a market-based approach that aims to protect natural areas, and associated livelihoods and environmental services, by developing financial incentives for preservation. Mitigation-focused PES schemes are common, and there is emerging evidence of adaptation-focused PES schemes. Successful PES approaches can be difficult to design for services that are hard to define or quantify. [17.5.2, 27.6.2]
EXAMPLES WITH INTERACTIONS: **Central and South America**: A variety of PES schemes have been implemented in Central and South America. For example, national-level

programs have operated in Costa Rica and Guatemala since 1997 and in Ecuador since 2008. Examples to date have shown that PES can finance conservation, ecosystem restoration and reforestation, better land-use practices, mitigation, and more recently adaptation. Uniform payments for beneficiaries can be inefficient if, for example, recipients that promote greater environmental gains receive only the prevailing payment. [17.5.2, 27.3.2, 27.6.2, Table 27-8]

Brazil: Municipal funding in Brazil tied to ecosystem-management quality is a form of revenue transfer important to funding local adaptation actions. State governments collect a value-added tax redistributed among municipalities, and some states allocate revenues in part based on municipality area set aside for protection. This mechanism has helped improve environmental management and increased creation of protected areas. It benefits relations between protected areas and surrounding inhabitants, as the areas can be perceived as opportunities for revenue generation rather than as obstacles to development. The approach builds on existing institutions and administrative procedures and thus has low transaction costs. [8.4.3, Box 8-4]

Renewable Energy

Primary Objective: Renewable energy production and reduction of emissions

Relevant Sectors: Biodiversity, agriculture, food security

Overview: Renewable energy production can require significant land areas and water resources, creating the potential for both positive and negative interactions between mitigation policies and land management. [4.4.4, 13.3.1, 19.3.2, 19.4.1, Box CC-WE]

EXAMPLES WITH INTERACTIONS:

Central and South America: Renewable resources, especially hydroelectric power and biofuels, account for substantial fractions of energy production in countries such as Brazil. Where bioenergy crops compete for land with food crops, substantial trade-offs can exist. Land-use change to produce bioenergy can affect food crops, biodiversity, and ecosystem services. Lignocellulosic feedstocks, such as sugarcane second-generation technologies, do not compete with food. [19.3.2, 27.3.6, 27.6.1, Table 27-6]

Australia & New Zealand: Mandatory renewable energy targets and incentives to increase carbon storage support increased biofuel production and increased biological carbon sequestration, with impacts on biodiversity depending on implementation. Benefits can include reduced erosion, additional habitat, and enhanced connectivity, with risks or lost opportunities associated with large-scale monocultures especially if replacing more diverse landscapes. Large-scale land-cover changes can affect catchment yields and regional climate in complex ways. New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services. [Table 25-7, Box 25-10]

Disaster risk reduction and adaptation to climate extremes

Primary Objective: Increasing resilience to extreme weather events in a changing climate

Relevant Sectors: Infrastructure, energy use, spatial planning

Overview: Synergies and tradeoffs among sustainable development, adaptation, and mitigation occur in preparing for and responding to climate extremes and disasters. [13.2-4, 20.3-4]

EXAMPLES WITH INTERACTIONS:

Philippines: The Homeless People's Federation of the Philippines developed responses following disasters, including: community-rooted data gathering (e.g., assessing destruction and victims' immediate needs); trust and contact building; savings support; community-organization registration; and identification of needed interventions (e.g., building-materials loans). Community surveys mapped inhabitants especially at risk in informal settlements, raising risk-awareness among the inhabitants and increasing community engagement in planning risk reduction and early warning systems. [8.3.2, 8.4.2]

London: Within London, built form and other dwelling characteristics can have a stronger influence on indoor temperatures during heat waves than the urban heat island effect, and utilizing shade, thermal mass, ventilation control, and other passive-design features are effective adaptation options. Passive housing designs enhance natural ventilation and improve insulation, while also reducing household emissions. For example, in London the Beddington Zero Energy Development was designed to reduce or eliminate energy demand for heating, cooling, and ventilation for much of the year. [8.3.3, 11.7.4]

United States: In the United States, post-disaster funds for loss reduction are added to funds provided for disaster recovery. They can be used, for instance, to buy out properties that have experienced repetitive flood losses and relocate residents to safer locations, to elevate structures, to assist communities with purchasing property and altering land-use patterns in flood-prone areas, and to undertake other activities designed to lessen the impacts of future disasters. [14.3.3]

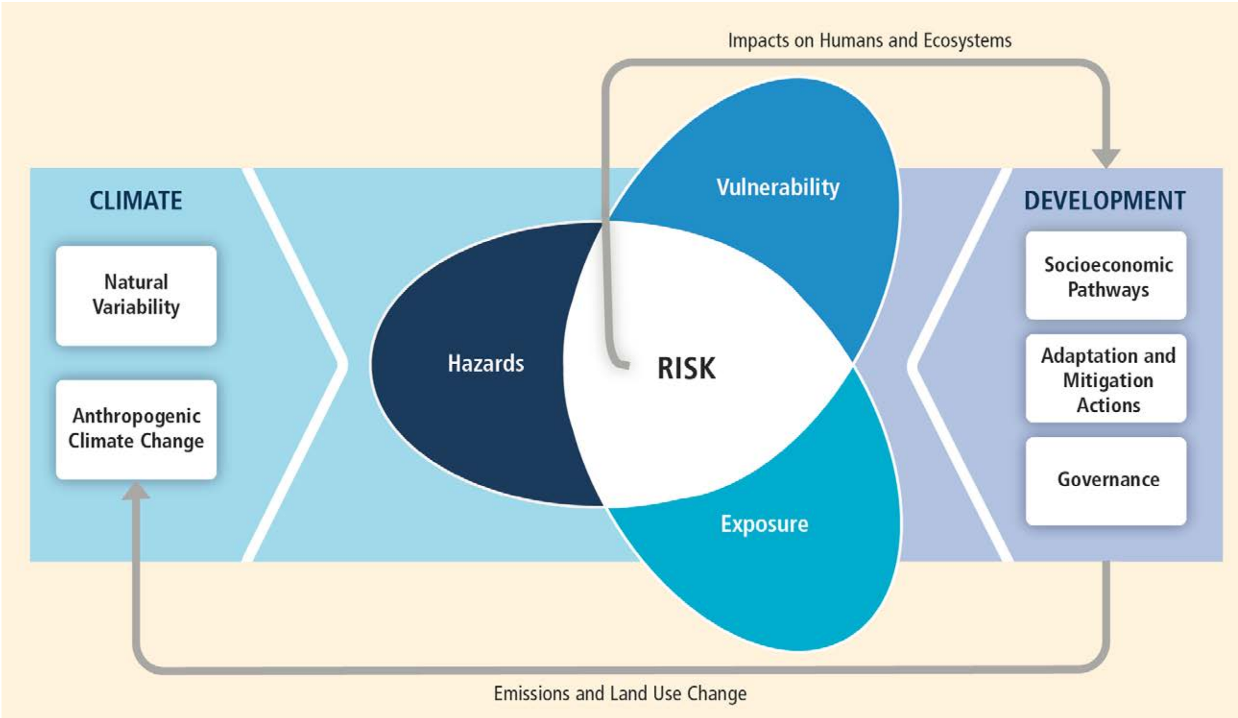
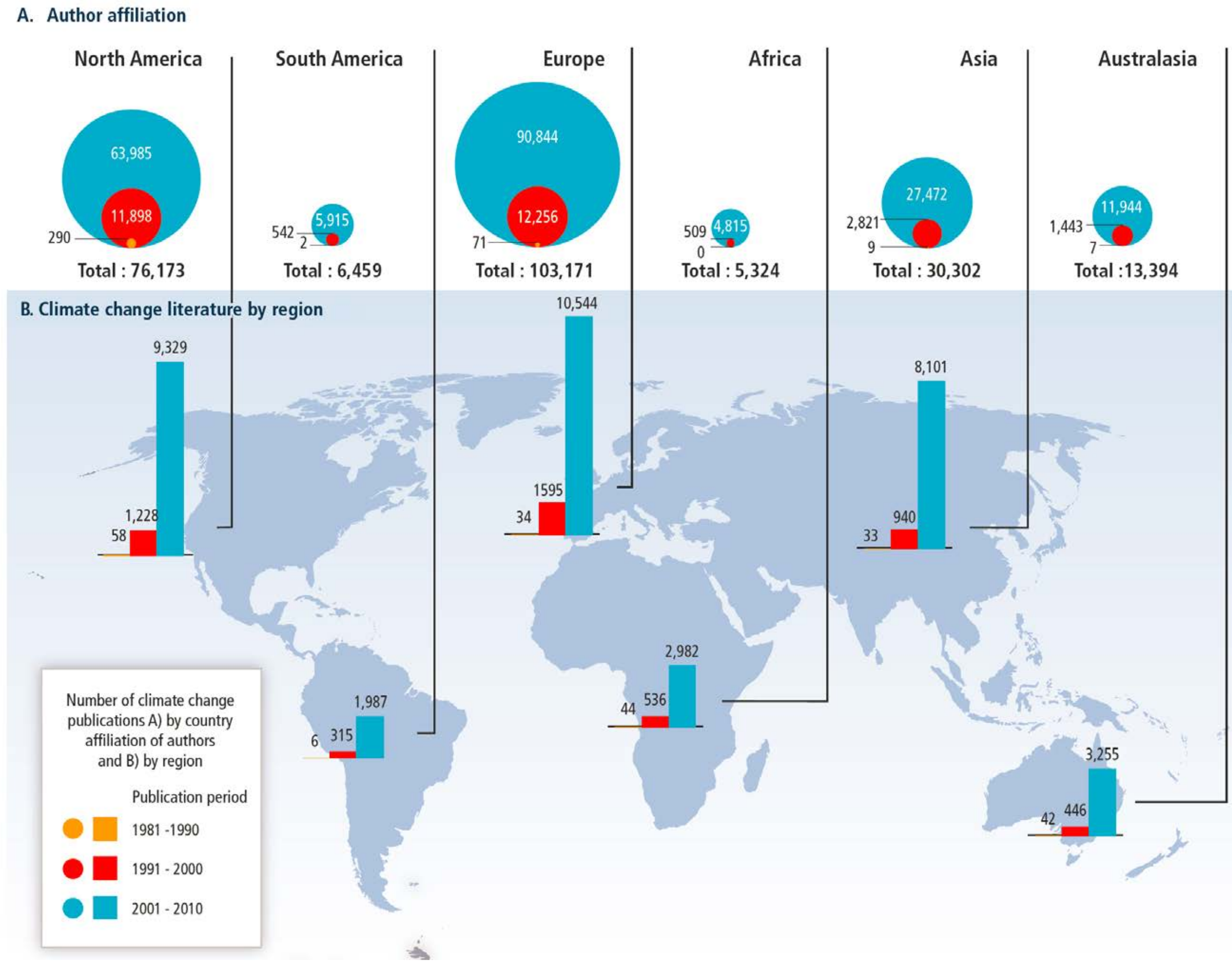
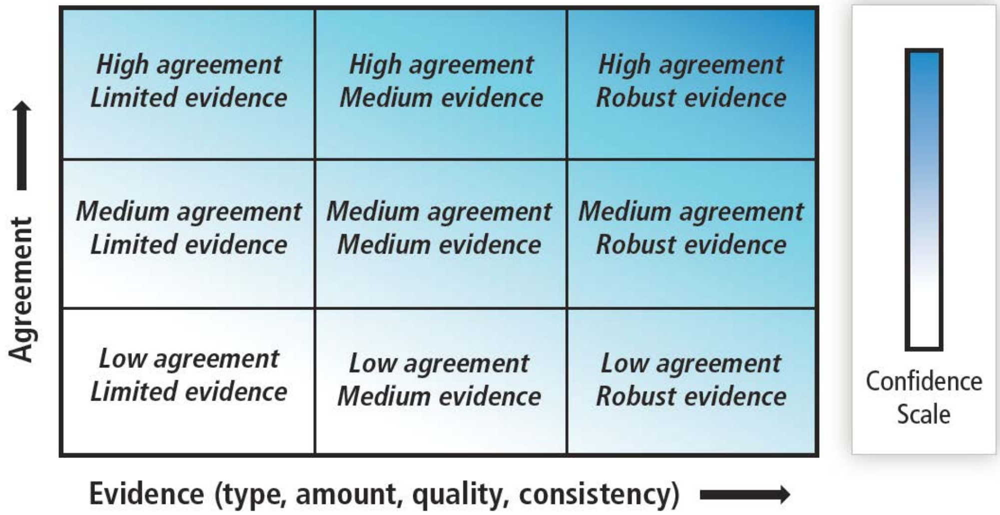

Impacts on Humans and Ecosystems
CLIMATE
Natural Variability
Anthropogenic Climate Change
Vulnerability
Hazards
RISK
Exposure
DEVELOPMENT
Socioeconomic Pathways
Adaptation and Mitigation Actions
Governance
Emissions and Land Use Change

Figure TS.1.



Box TS.1 Figure 1.



Box TS.3 Figure 1.

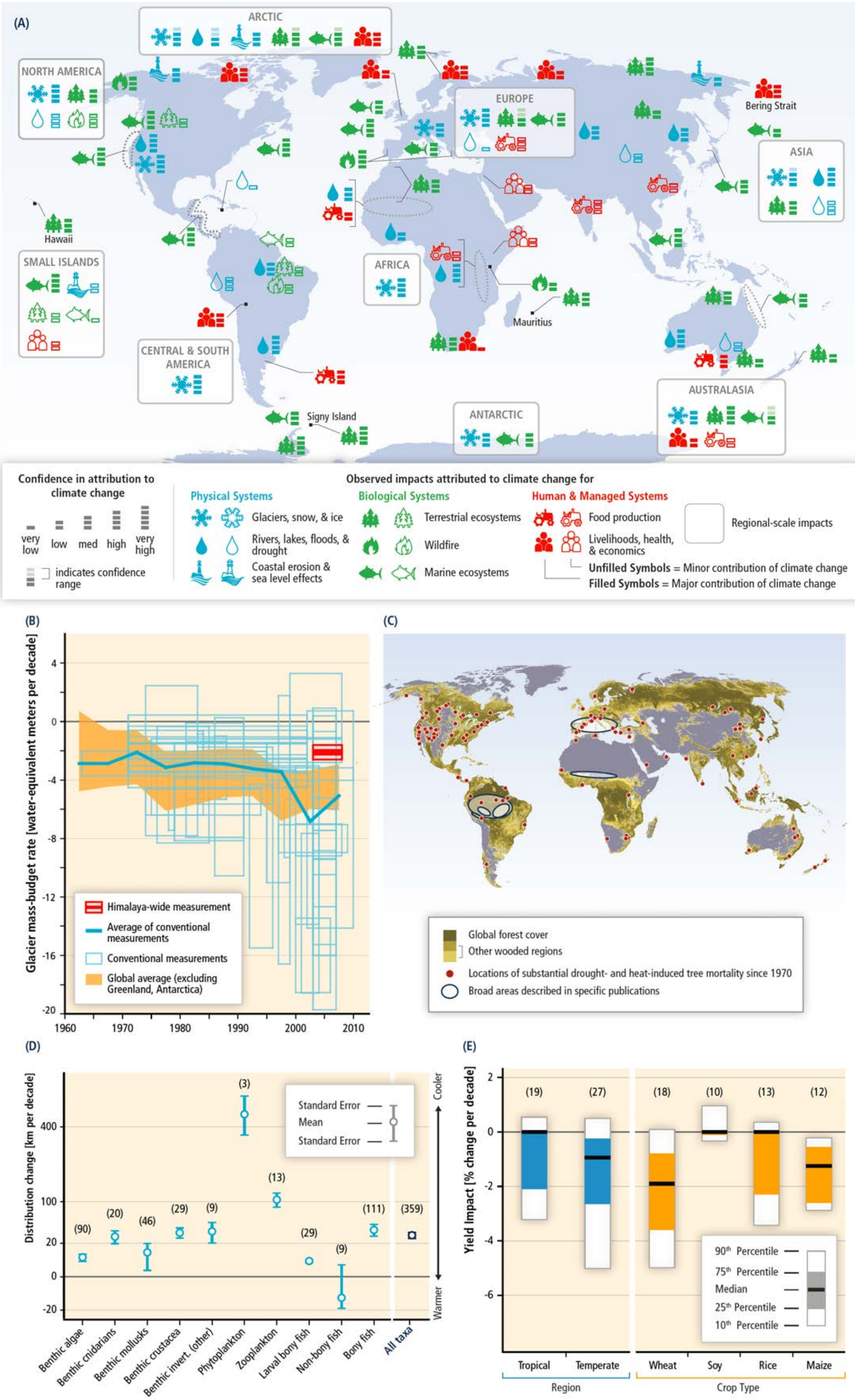
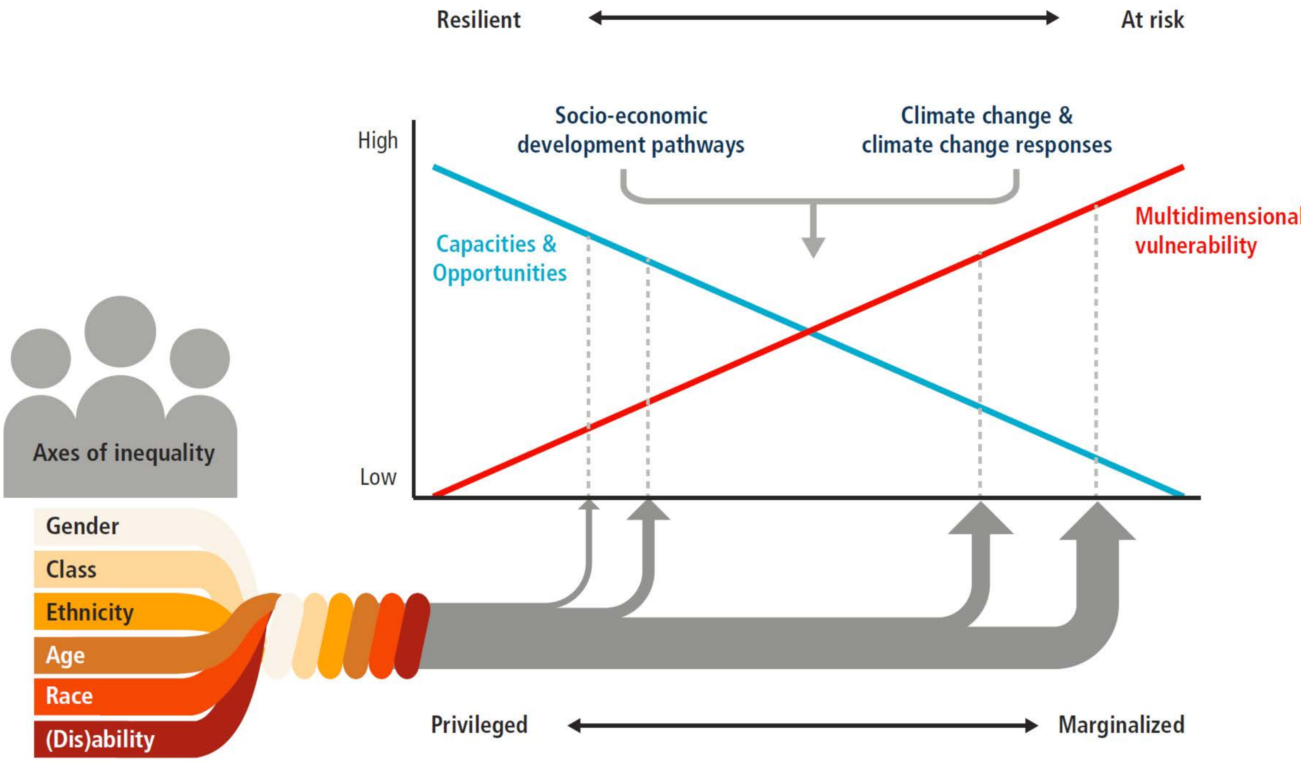

(A)
ARCTIC
NORTH AMERICA
EUROPE
ASIA
Bering Strait
Hawaii
SMALL ISLANDS
AFRICA
CENTRAL & SOUTH AMERICA
Mauritius
Signy Island
ANTARCTIC
AUSTRALASIA
Confidence in attribution to climate change
very low
low
med
high
very high
indicates confidence range
Observed impacts attributed to climate change for
Physical Systems
Glaciers, snow, & ice
Rivers, lakes, floods, & drought
Coastal erosion & sea level effects
Biological Systems
Terrestrial ecosystems
Wildfire
Marine ecosystems
Human & Managed Systems
Food production
Livelihoods, health, & economics
Regional-scale impacts
Unfilled Symbols = Minor contribution of climate change
Filled Symbols = Major contribution of climate change
(B)
Glacier mass-budget rate [water-equivalent meters per decade]
Himalaya-wide measurement
Average of conventional measurements
Conventional measurements
Global average (excluding Greenland, Antarctica)
4
0
-4
-8
-12
-16
-20
1960
1970
1980
1990
2000
2010
(C)
Global forest cover
Other wooded regions
Locations of substantial drought- and heat-induced tree mortality since 1970
Broad areas described in specific publications
(D)
Distribution change [km per decade]
400
100
20
0
-20
(90)
(20)
(46)
(29)
(9)
(3)
(13)
(29)
(9)
(111)
(359)
Standard Error
Mean
Standard Error
Cooler
Warmer
Benthic algae
Benthic cnidarians
Benthic mollusks
Benthic crustacea
Benthic invert. (other)
Phytoplankton
Zooplankton
Larval bony fish
Non-bony fish
Bony fish
All taxa
(E)
Yield impact [% change per decade]
2
0
-2
-4
-6
(19)
(27)
(18)
(10)
(13)
(12)
90th Percentile
75th Percentile
Median
25th Percentile
10th Percentile
Tropical
Temperate
Region
Wheat
Soy
Rice
Maize
Crop Type

Figure TS.2.



Box TS.4 Figure 1.

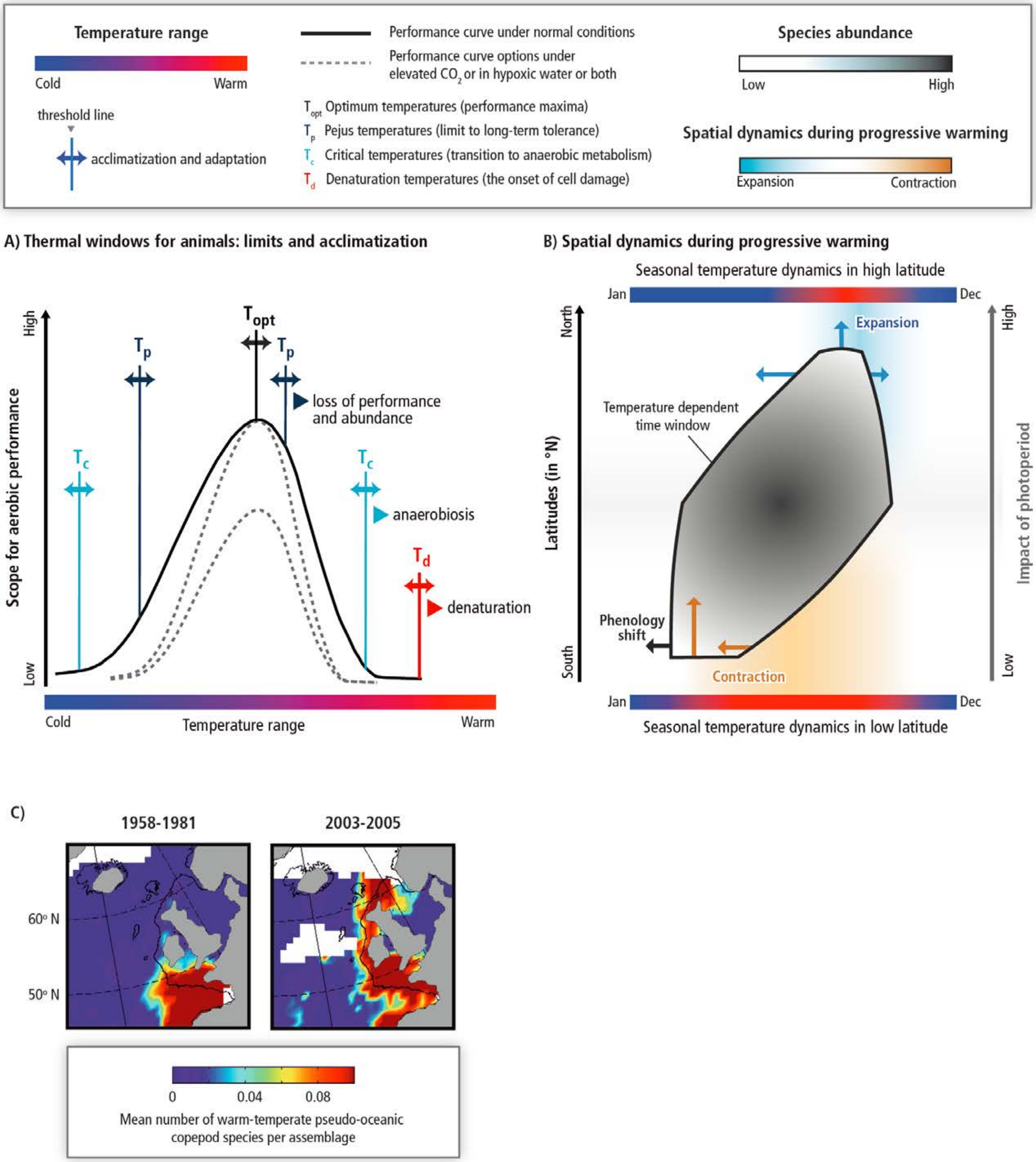

Temperature range
Cold
Warm
threshold line
acclimatization and adaptation
Performance curve under normal conditions
Performance curve options under elevated CO2 or in hypoxic water or both
Topt Optimum temperatures (performance maxima)
Tp Pejus temperatures (limit to long-term tolerance)
Tc Critical temperatures (transition to anaerobic metabolism)
Td Denaturation temperatures (the onset of cell damage)
Species abundance
Low
High
Spatial dynamics during progressive warming
Expansion
Contraction
A) Thermal windows for animals: limits and acclimatization
Scope for aerobic performance
High
Low
Topt
Tp
Tc
Td
loss of performance and abundance
anaerobiosis
denaturation
Cold
Temperature range
Warm
B) Spatial dynamics during progressive warming
Seasonal temperature dynamics in high latitude
Jan
Dec
North
South
Latitudes (in °N)
Expansion
Temperature dependent time window
Phenology shift
Contraction
Impact of photoperiod
High
Low
Seasonal temperature dynamics in low latitude
C)
1958-1981
2003-2005
60° N
50° N
0
0.04
0.08
Mean number of warm-temperate pseudo-oceanic copepod species per assemblage

Figure TS.3.

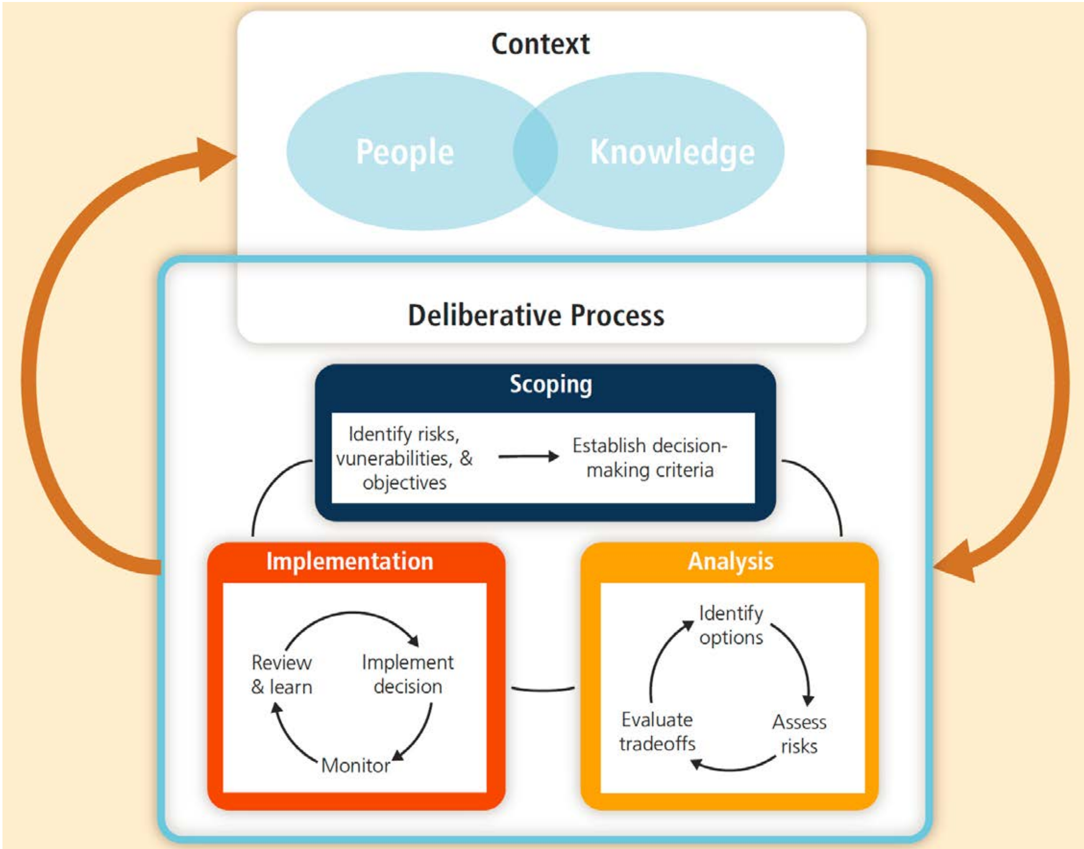

Context
People
Knowledge
Deliberative Process
Scoping
Identify risks, vunerabilities, & objectives
Establish decision-making criteria
Implementation
Review & learn
Implement decision
Monitor
Analysis
Identify options
Assess risks
Evaluate tradeoffs

Figure TS.4.

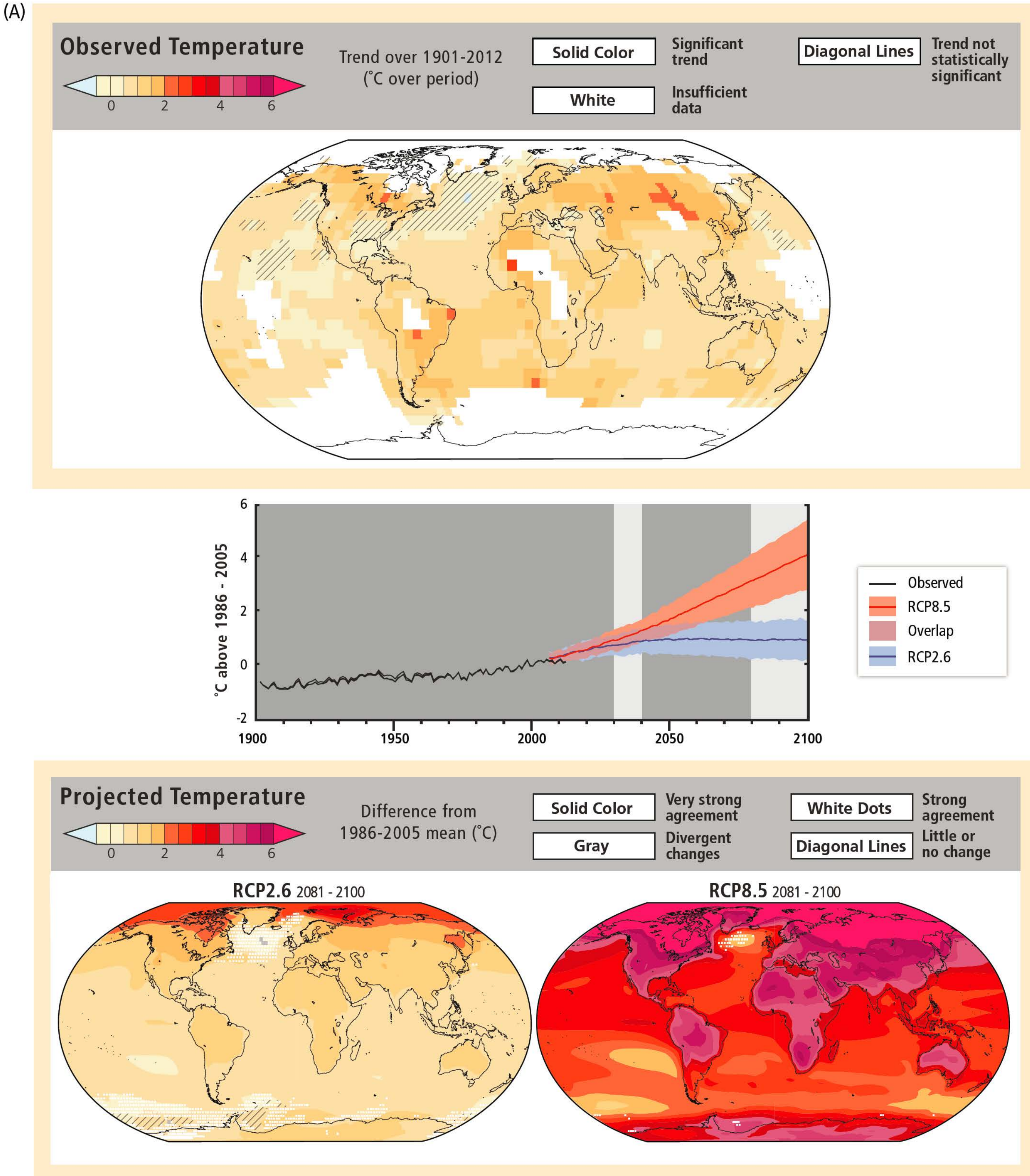

(A)
Observed Temperature
Trend over 1901-2012
(˚C over period)
0
2
4
6
Solid Color
Significant trend
White
Insufficient data
Diagonal Lines
Trend not statistically significant
°C above 1986 - 2005
6
4
2
0
-2
1900
1950
2000
2050
2100
Observed
RCP8.5
Overlap
RCP2.6
Projected Temperature
Difference from
1986-2005 mean (˚C)
Solid Color
Very strong agreement
Gray
Divergent changes
White Dots
Strong agreement
Diagonal Lines
Little or no change
RCP2.6 2081 - 2100
RCP8.5 2081 - 2100

Figure TS.5.

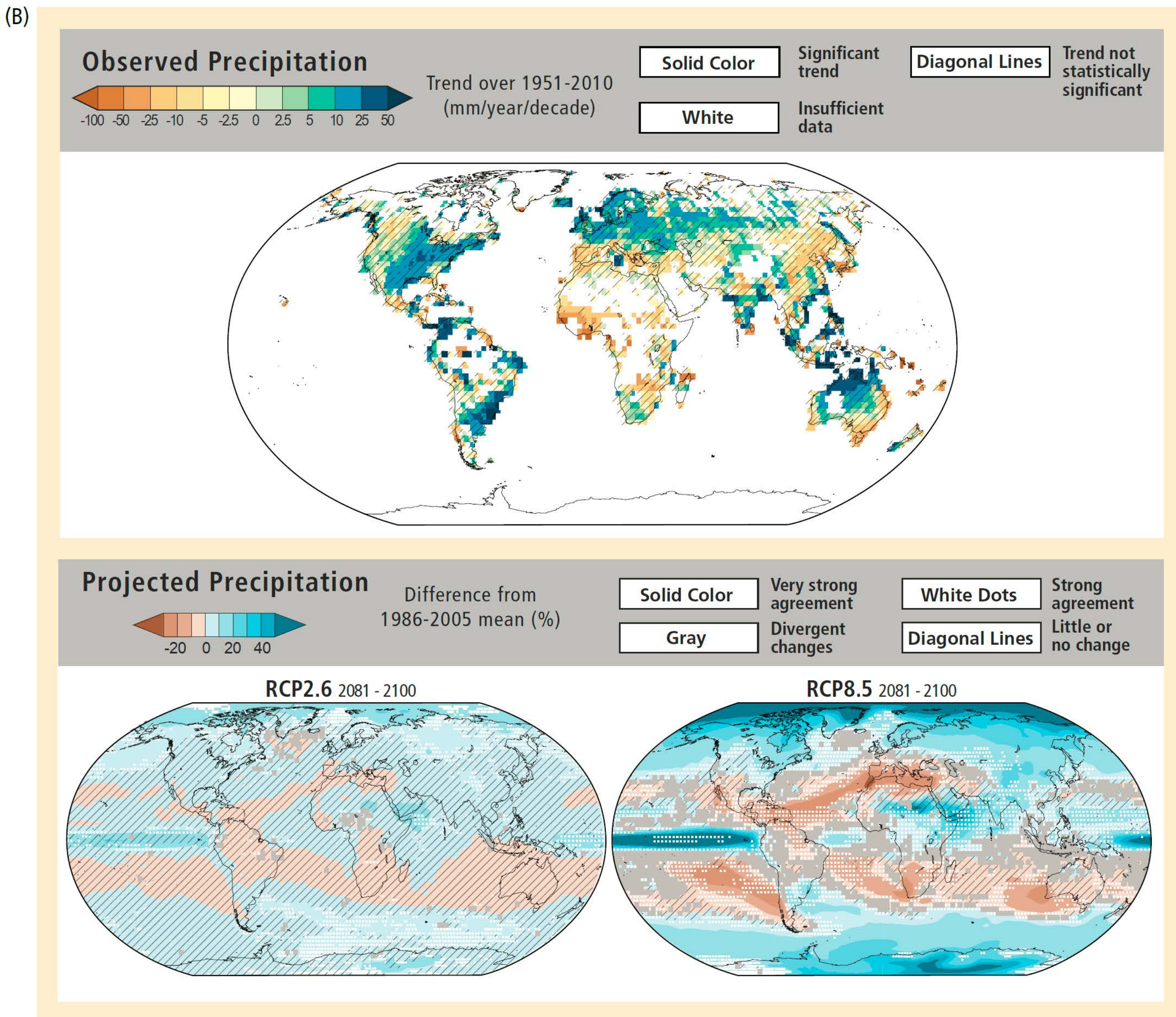
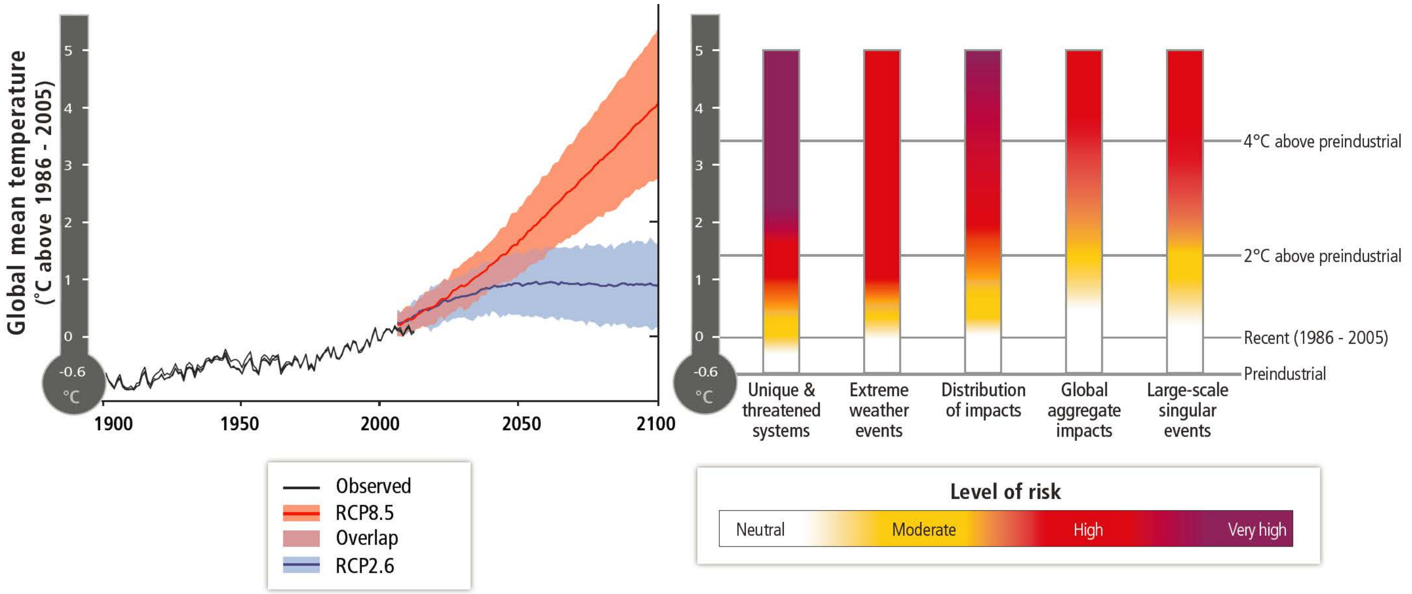

(B)
Observed Precipitation
-100 -50 -25 -10 -5 -2.5 0 2.5 5 10 25 50
Trend over 1951-2010
(mm/year/decade)
Solid Color
Significant trend
White
Insufficient data
Diagonal Lines
Trend not statistically significant
Projected Precipitation
-20 0 20 40
Difference from
1986-2005 mean (%)
Solid Color
Very strong agreement
Gray
Divergent changes
White Dots
Strong agreement
Diagonal Lines
Little or no change
RCP2.6 2081 - 2100
RCP8.5 2081 - 2100

Figure TS.5.



Box TS.5 Figure 1.

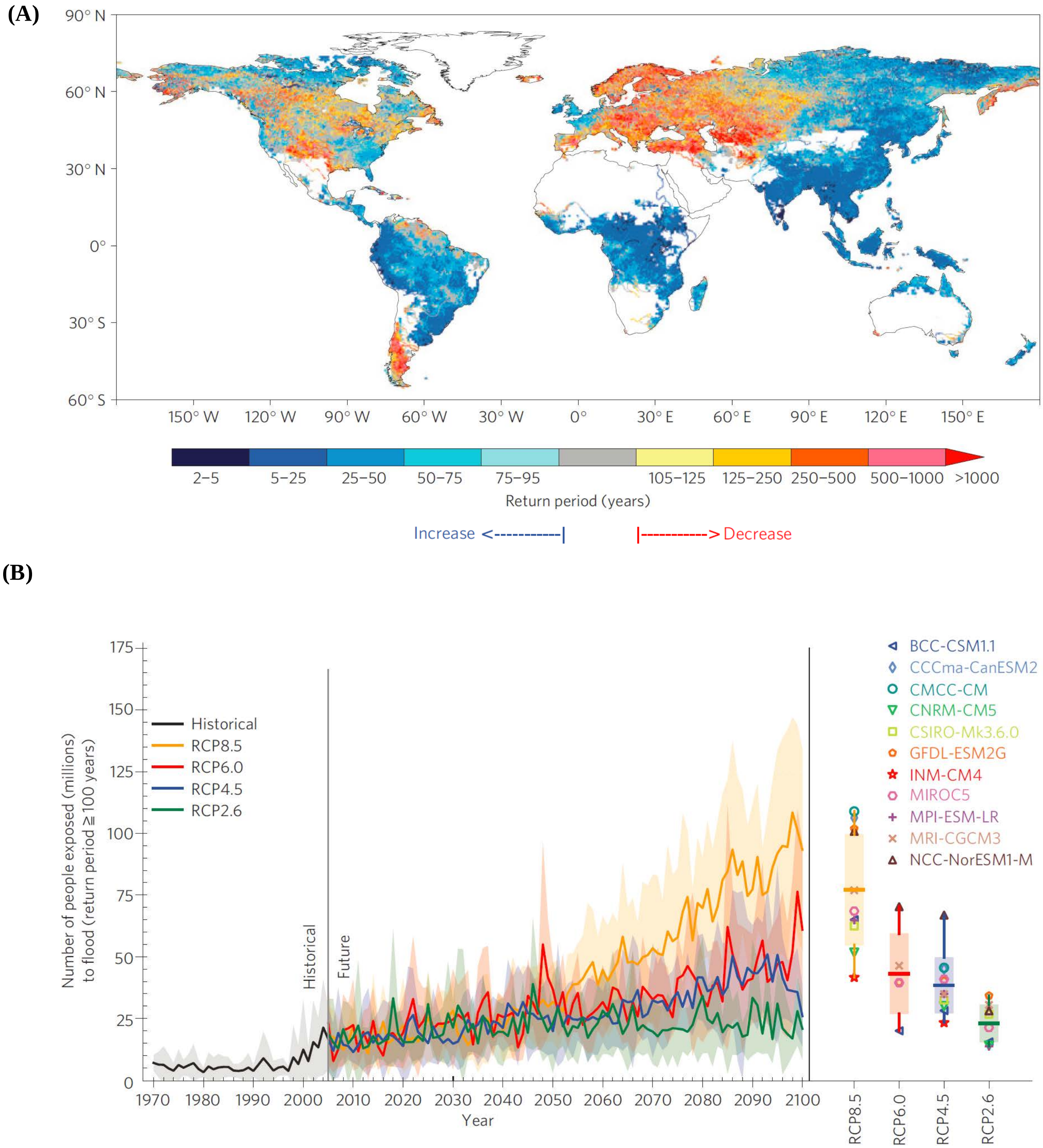

(A)
90° N
60° N
30° N
0°
30° S
60° S
150° W
120° W
90° W
60° W
30° W
0°
30° E
60° E
90° E
120° E
150° E
2–5
5–25
25–50
50–75
75–95
105–125
125–250
250–500
500–1000
>1000
Return period (years)
Increase
Decrease
(B)
Number of people exposed (millions) to flood (return period ≥ 100 years)
Historical
RCP8.5
RCP6.0
RCP4.5
RCP2.6
Historical
Future
Year
BCC-CSM1.1
CCCma-CanESM2
CMCC-CM
CNRM-CM5
CSIRO-Mk3.6.0
GFDL-ESM2G
INM-CM4
MIROC5
MPI-ESM-LR
MRI-CGCM3
NCC-NorESM1-M
RCP8.5
RCP6.0
RCP4.5
RCP2.6

Figure TS.6.

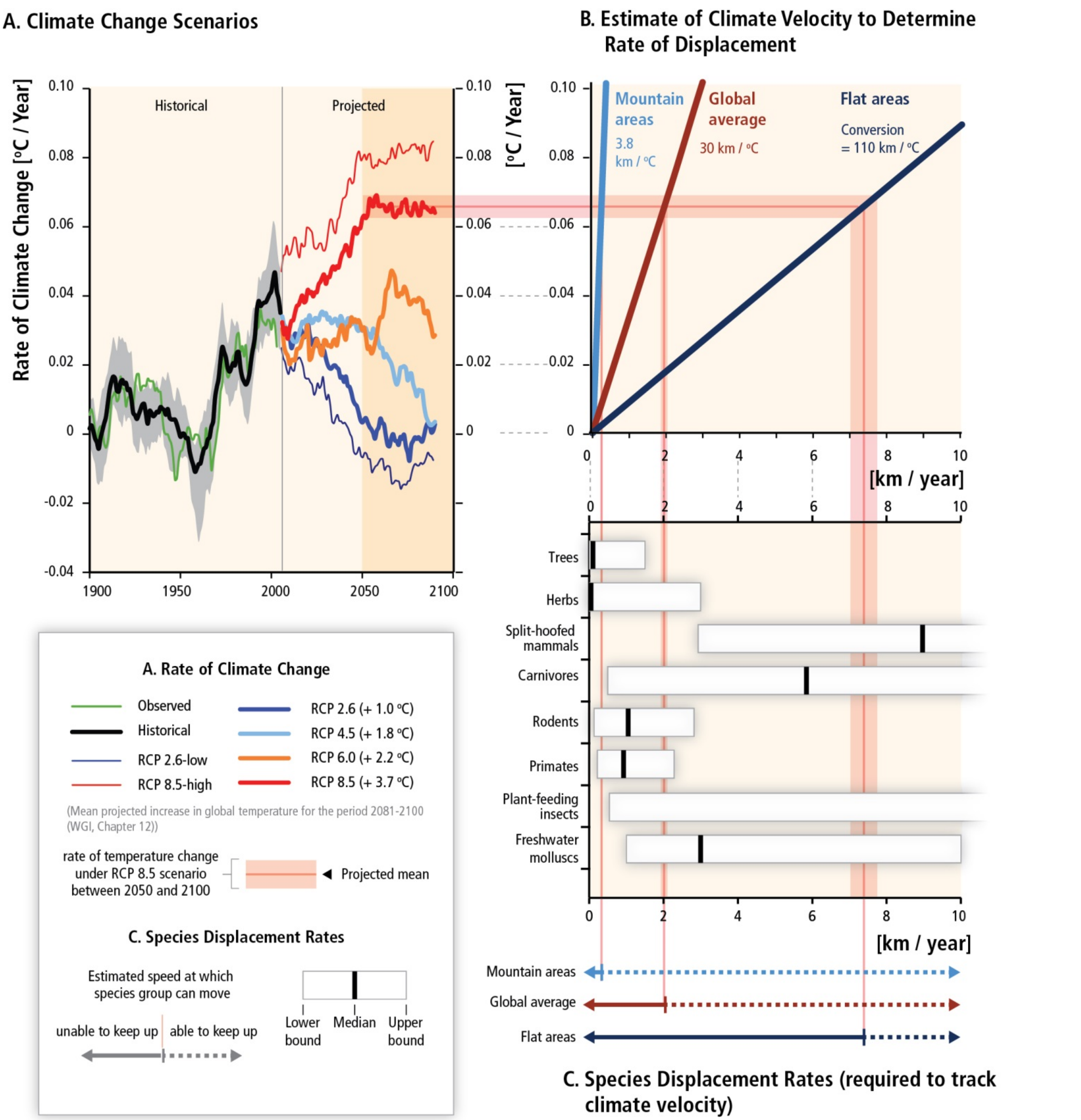

A. Climate Change Scenarios
B. Estimate of Climate Velocity to Determine Rate of Displacement
Rate of Climate Change [°C / Year]
[°C / Year]
Historical
Projected
Mountain areas
3.8 km / °C
Global average
30 km / °C
Flat areas
Conversion = 110 km / °C
[km / year]
Trees
Herbs
Split-hoofed mammals
Carnivores
Rodents
Primates
Plant-feeding insects
Freshwater molluscs
Mountain areas
Global average
Flat areas
C. Species Displacement Rates (required to track climate velocity)
A. Rate of Climate Change
Observed
Historical
RCP 2.6-low
RCP 8.5-high
RCP 2.6 (+ 1.0 °C)
RCP 4.5 (+ 1.8 °C)
RCP 6.0 (+ 2.2 °C)
RCP 8.5 (+ 3.7 °C)
(Mean projected increase in global temperature for the period 2081-2100 (WGI, Chapter 12))
rate of temperature change under RCP 8.5 scenario between 2050 and 2100
Projected mean
C. Species Displacement Rates
Estimated speed at which species group can move
unable to keep up
able to keep up
Lower bound
Median
Upper bound

Figure TS.7.

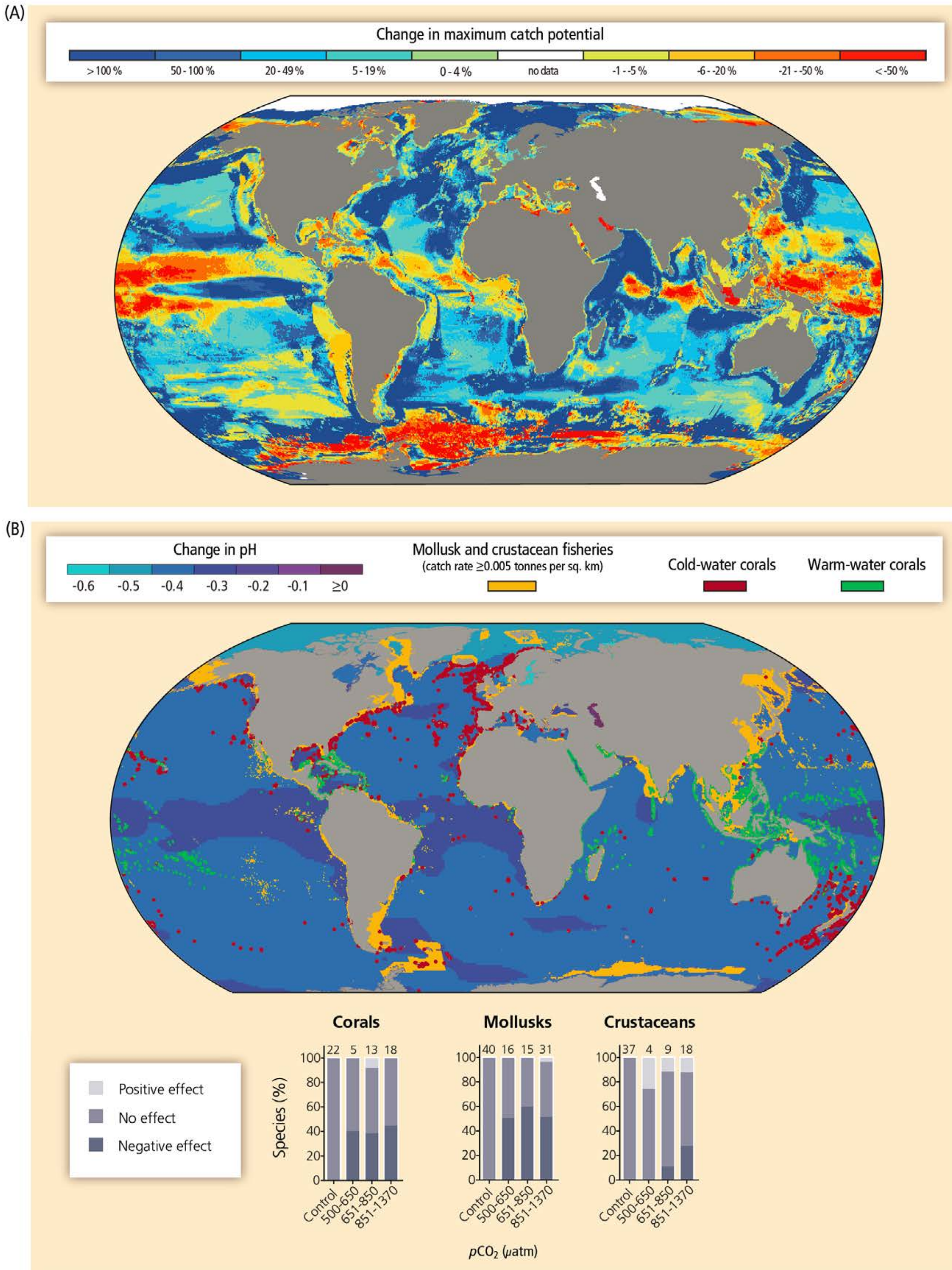

(A)
Change in maximum catch potential
> 100 %
50 - 100 %
20 - 49 %
5 - 19 %
0 - 4 %
no data
-1 - -5 %
-6 - -20 %
-21 - -50 %
< -50 %
(B)
Change in pH
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
≥0
Mollusk and crustacean fisheries
(catch rate ≥0.005 tonnes per sq. km)
Cold-water corals
Warm-water corals
Corals
Mollusks
Crustaceans
Positive effect
No effect
Negative effect
Species (%)
22 5 13 18
40 16 15 31
37 4 9 18
Control
500-650
651-850
851-1370
pCO2 (µatm)

Figure TS.8.

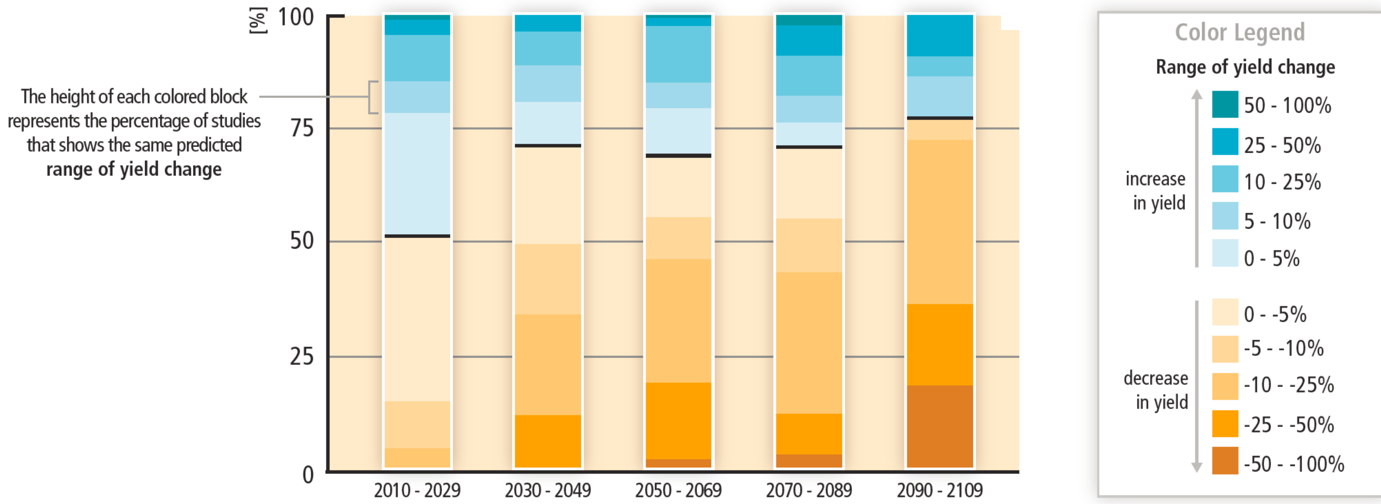

[%]
100
75
50
25
0
The height of each colored block represents the percentage of studies that shows the same predicted range of yield change
2010 - 2029
2030 - 2049
2050 - 2069
2070 - 2089
2090 - 2109
Color Legend
Range of yield change
increase in yield
50 - 100%
25 - 50%
10 - 25%
5 - 10%
0 - 5%
decrease in yield
0 - -5%
-5 - -10%
-10 - -25%
-25 - -50%
-50 - -100%

Figure TS.9.

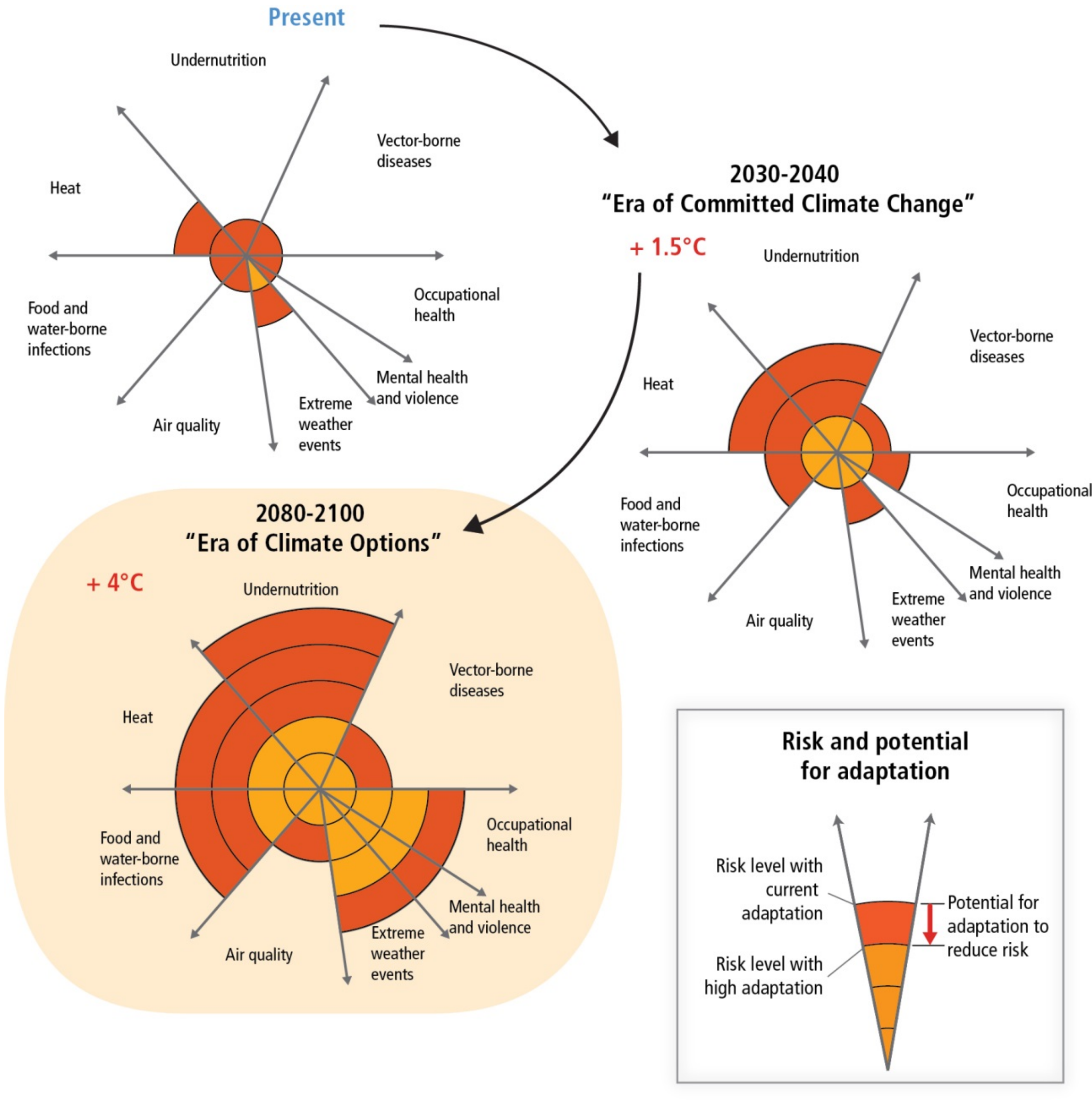

Present
Undernutrition
Vector-borne diseases
Heat
Occupational health
Food and water-borne infections
Mental health and violence
Air quality
Extreme weather events
2030-2040
"Era of Committed Climate Change"
+ 1.5°C
Undernutrition
Vector-borne diseases
Heat
Occupational health
Food and water-borne infections
Mental health and violence
Air quality
Extreme weather events
2080-2100
"Era of Climate Options"
+ 4°C
Undernutrition
Vector-borne diseases
Heat
Occupational health
Food and water-borne infections
Mental health and violence
Air quality
Extreme weather events
Risk and potential for adaptation
Risk level with current adaptation
Risk level with high adaptation
Potential for adaptation to reduce risk

Figure TS.10.

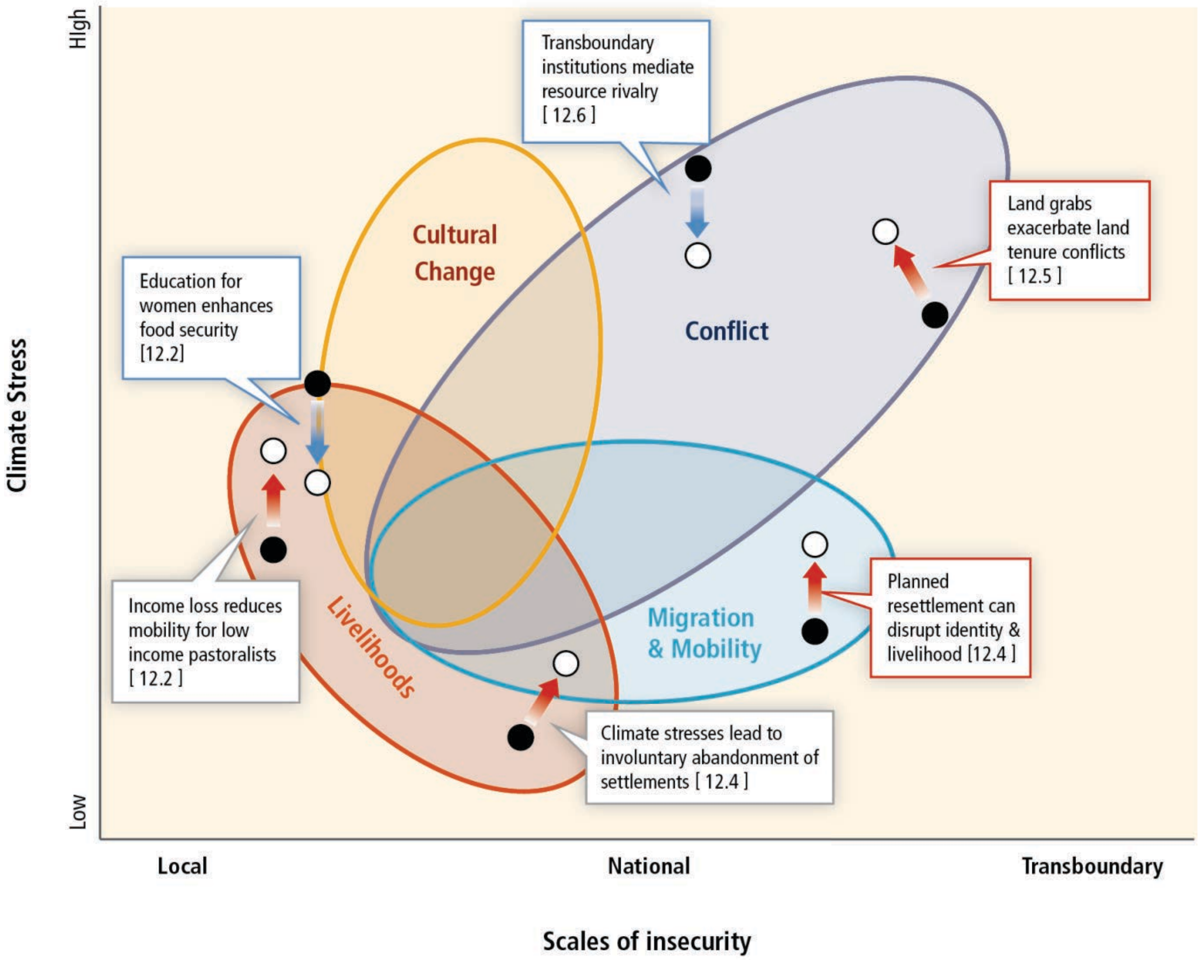
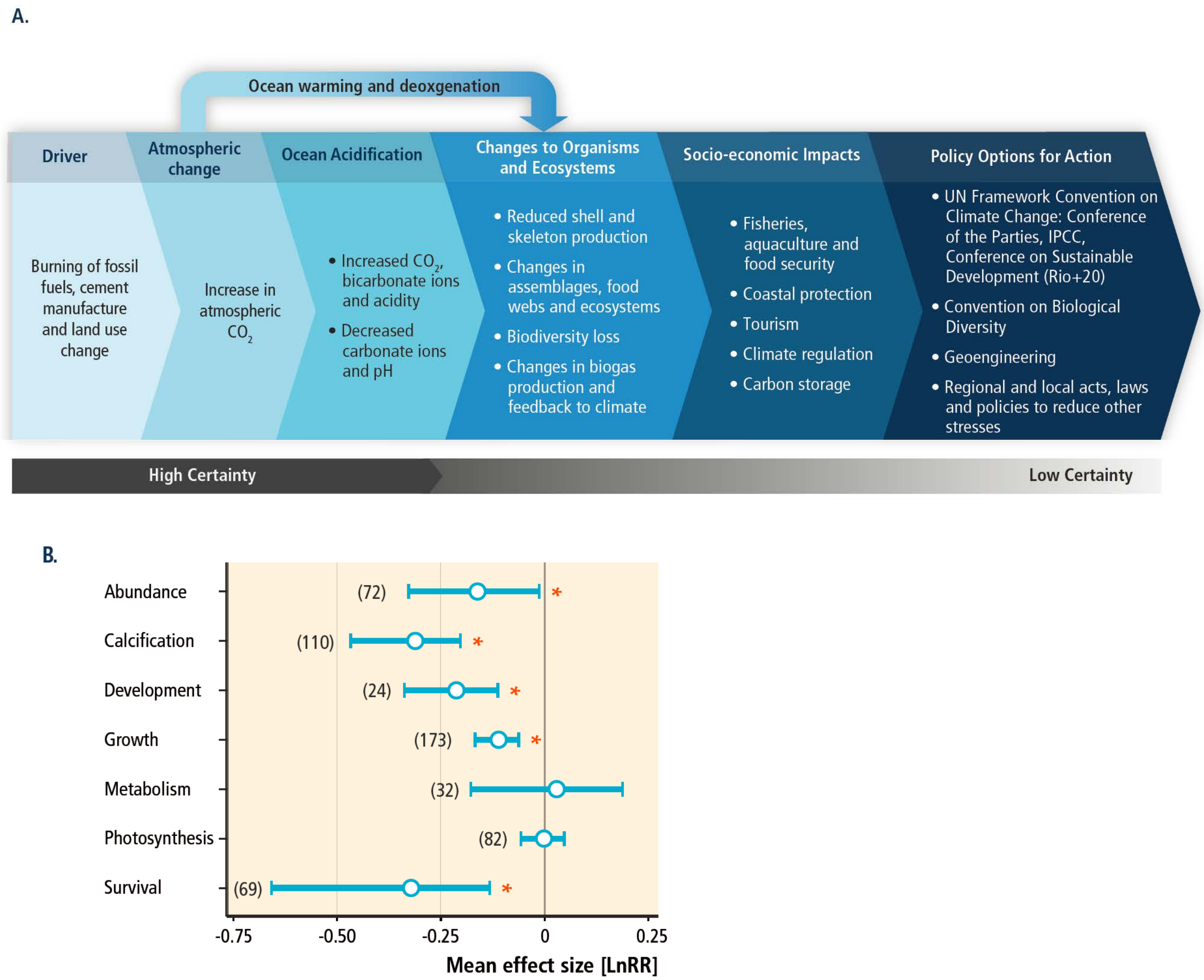

High
Low
Climate Stress
Transboundary institutions mediate resource rivalry [12.6]
Land grabs exacerbate land tenure conflicts [12.5]
Cultural Change
Conflict
Education for women enhances food security [12.2]
Income loss reduces mobility for low income pastoralists [12.2]
Livelihoods
Migration & Mobility
Planned resettlement can disrupt identity & livelihood [12.4]
Climate stresses lead to involuntary abandonment of settlements [12.4]
Local
National
Transboundary
Scales of insecurity

Figure TS.11.



Box TS.7 Figure 1.

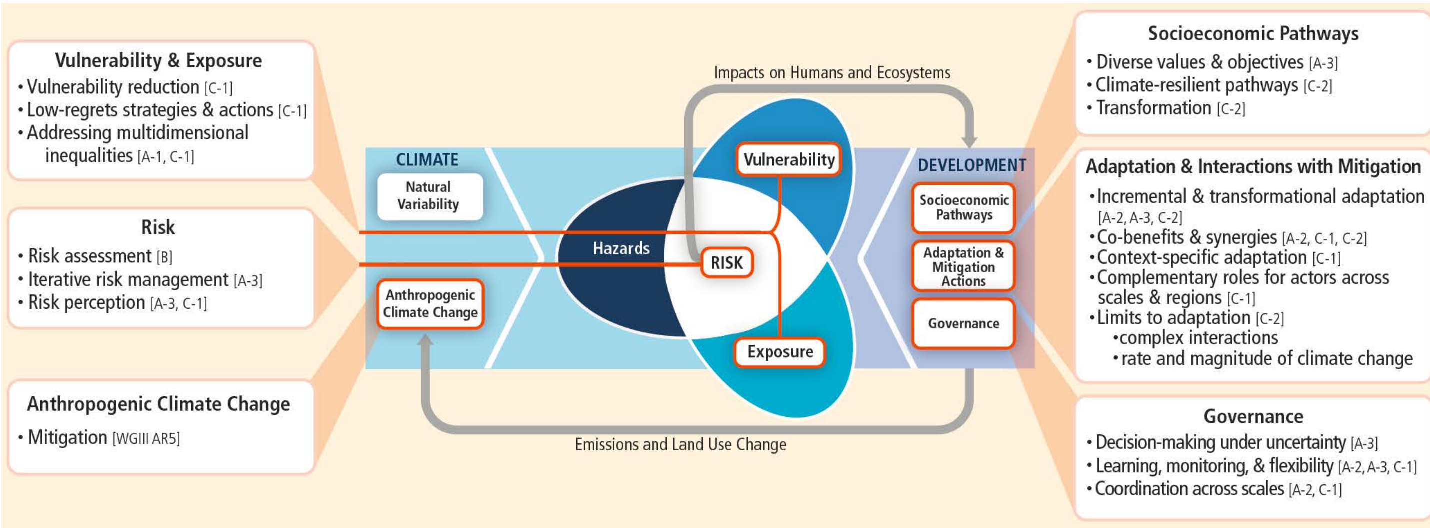

Vulnerability & Exposure
• Vulnerability reduction [C-1]
• Low-regrets strategies & actions [C-1]
• Addressing multidimensional inequalities [A-1, C-1]
Risk
• Risk assessment [B]
• Iterative risk management [A-3]
• Risk perception [A-3, C-1]
Anthropogenic Climate Change
• Mitigation [WGIII AR5]
CLIMATE
Natural Variability
Anthropogenic Climate Change
Impacts on Humans and Ecosystems
Hazards
RISK
Vulnerability
Exposure
Emissions and Land Use Change
DEVELOPMENT
Socioeconomic Pathways
Adaptation & Mitigation Actions
Governance
Socioeconomic Pathways
• Diverse values & objectives [A-3]
• Climate-resilient pathways [C-2]
• Transformation [C-2]
Adaptation & Interactions with Mitigation
• Incremental & transformational adaptation [A-2, A-3, C-2]
• Co-benefits & synergies [A-2, C-1, C-2]
• Context-specific adaptation [C-1]
• Complementary roles for actors across scales & regions [C-1]
• Limits to adaptation [C-2]
• complex interactions
• rate and magnitude of climate change
Governance
• Decision-making under uncertainty [A-3]
• Learning, monitoring, & flexibility [A-2, A-3, C-1]
• Coordination across scales [A-2, C-1]

Figure TS.12.

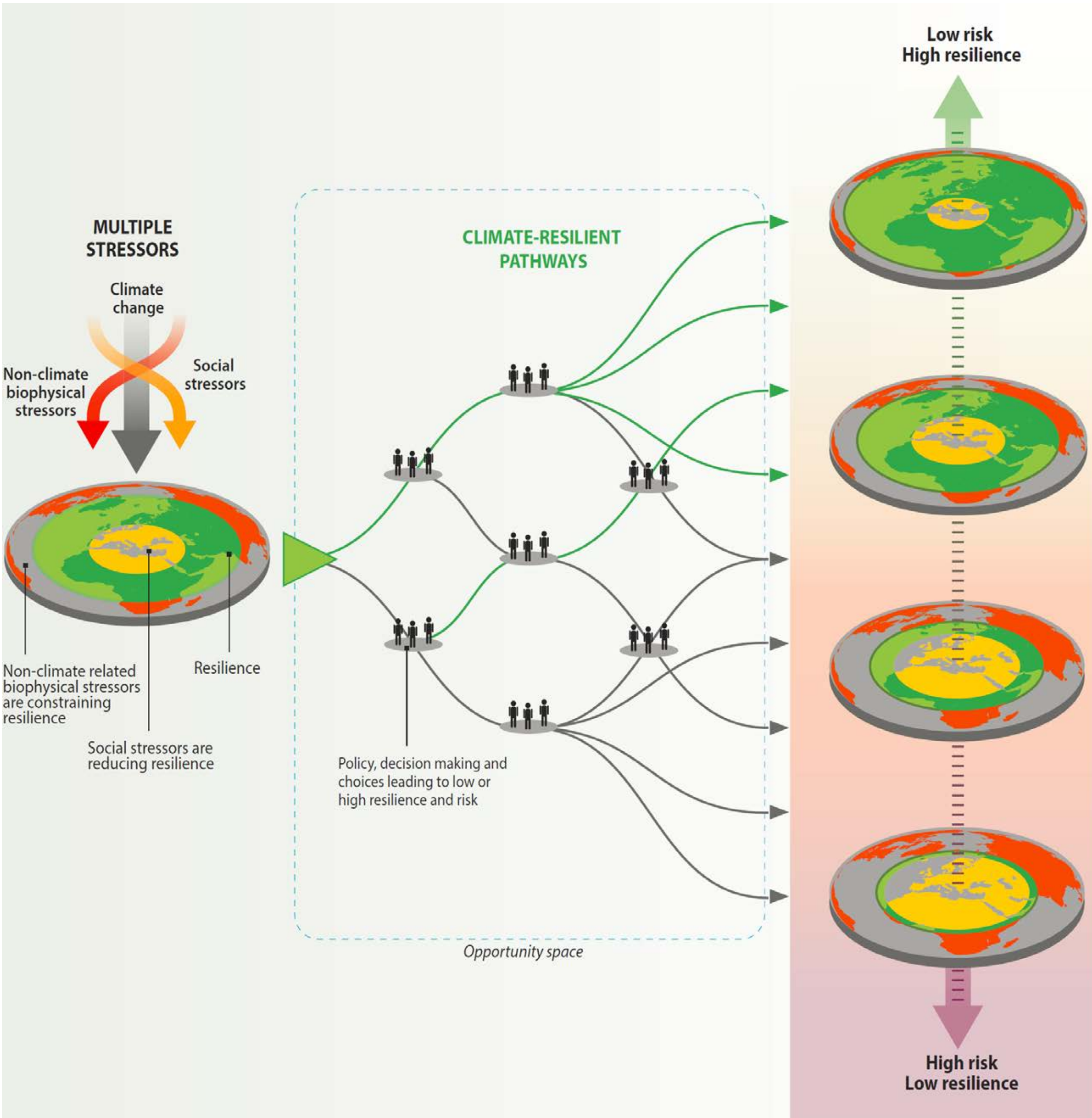
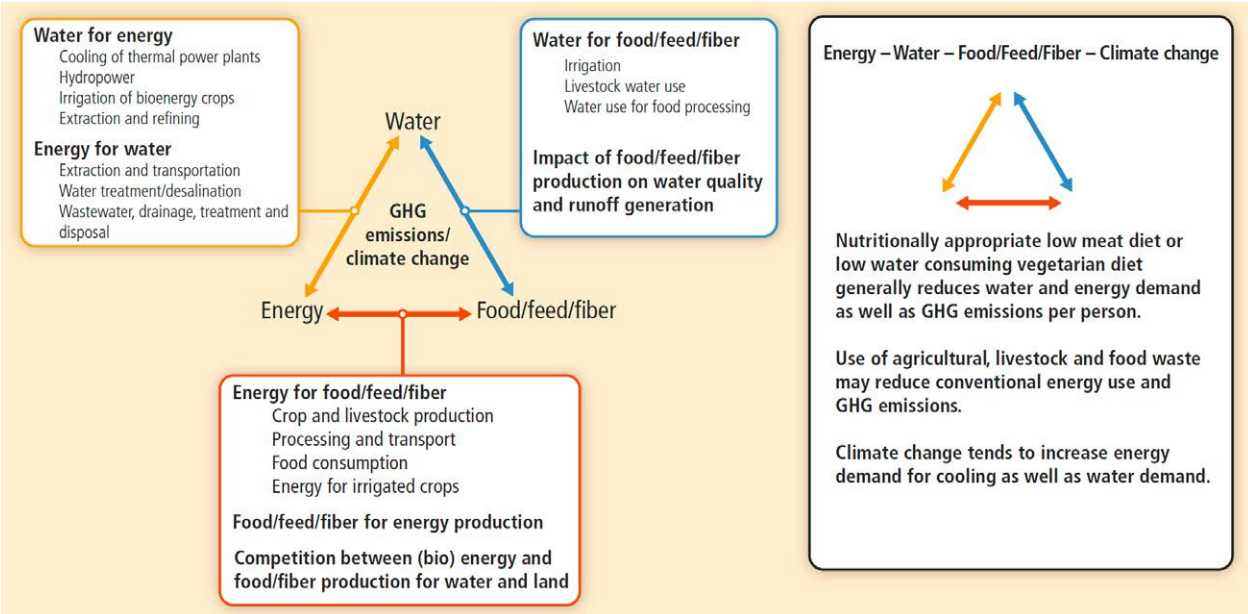

MULTIPLE STRESSORS
Climate change
Non-climate biophysical stressors
Social stressors
Non-climate related biophysical stressors are constraining resilience
Social stressors are reducing resilience
Resilience
CLIMATE-RESILIENT PATHWAYS
Policy, decision making and choices leading to low or high resilience and risk
Opportunity space
Low risk
High resilience
High risk
Low resilience

Figure TS.13.



Box TS.9 Figure 1.

Chapter 1. Point of Departure

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Contents

Executive Summary

The evolution of the IPCC assessments of impacts, adaptation, and vulnerability indicates an increasing emphasis on human beings, their role in managing resources and natural systems, and the societal impacts of climate change. The expanded focus on societal impacts and responses is evident in the composition of the IPCC author teams, the literature assessed, and the content of the IPCC assessment reports. Characteristics in the evolution of the Working Group II assessment reports are an increasing attention to: (i) adaptation limits and transformation in social and natural systems; (ii) synergies between multiple variables and factors that affect sustainable development, (iii) risk management, and (iv) institutional, social, cultural, and value-related issues. [1.1, 1.2]

The literature available for assessing climate change impacts, adaptation, and vulnerability more than doubled between 2005 and 2010, allowing for a more robust assessment that supports policy making *(high confidence).* The diversity of the topics and regions covered by the literature has similarly expanded, as has the geographic distribution of authors contributing to the knowledge base for climate change assessments. Authorship of literature from developing countries has increased, although still representing a small fraction of the total. This unequal distribution of literature presents a challenge to the production of a comprehensive and balanced global assessment. [1.1.1, Figure 1-1]

Rapidly advancing climate science provides policy relevant information that creates opportunities for decision making that can lead to climate-resilient development pathways (*robust evidence, medium agreement*). Climate change is just one of many stressors that influence resilience. The decisions that societies make within this opportunity space, also informed by observation, experience, and other factors, affect outcomes in human and natural systems. [1.1.1, 1.1.4, Figure 1-5]

Adaptation has emerged as a central area of climate change research, in country level planning, and in the implementation of climate change strategies *(high confidence)*. The body of literature, including government and private sector reports, shows an increased focus on adaptation opportunities and the interrelations between adaptation, mitigation, and alternative sustainable pathways. The literature shows an emergence of studies on transformative processes that take advantage of synergies between adaptation planning, development strategies, social protection, and disaster risk reduction and management. [1.1.4]

As a core feature and innovation of IPCC assessment, major findings are presented with defined, calibrated language that communicates the strength of scientific understanding, including uncertainties and areas of disagreement. Each finding is supported by a traceable account of the evaluation of evidence and agreement. 1.1.2.2, Box 1-1]

Impacts assessed in this report are based on climate model projections using both the IPCC Special Report on Emission Scenarios (SRES) and the new Representative Concentration Pathway (RCP) scenarios. The RCPs span the range of SRES scenarios for long-lived greenhouse gases, but they have a narrower range in terms of emissions of ozone and aerosol precursors and related pollutants. The SRES scenarios were used in the TAR and AR4. With AR5, the RCP scenarios present both emissions and greenhouse gas concentration pathways, and corresponding Shared Socio-economic Pathways (SSPs) have been developed. The four RCPs describe different levels of mitigation leading to 21st century radiative forcing levels of about 2.6, 4.5, 6.0 and 8.5 W m^{-2}), whereas the SRES scenarios are policy independent. [1.1.3, 1.3.3, 19.6.3.1, Box 21-1, 21.5.4, 24.3.3, see also WGI Chapters 1, 8, 11, 12]

1.1. The Setting

This chapter describes the information basis for the Fifth Assessment Report (AR5) of IPCC Working Group II (WGII) and the rationale for its structure. As the starting point of AR5 WGII, the chapter begins with an analysis of how the literature for the assessment has developed through time and proceeds with an overview of how the framing and content of the WGII reports have changed since the first IPCC report was published in 1990. The future climate scenarios used in AR5 are a marked change from those used in the Third (TAR, 2001) and Fourth (AR4, 2007) Assessment Reports; and this shift is described here, along with the new AR5 guidance for communicating scientific uncertainty. The chapter provides a summary of the most relevant key findings from the IPCC *Special Report on Renewable Energy Sources and Climate Change Mitigation* (IPCC, 2011a), the IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012), and the AR5 Working Group I (*The Physical Science Basis*) and AR5 Working Group III (*Mitigation of Climate Change*). Collectively these recent reports, new scenarios, and other advancements in climate change science set the stage for an assessment of impacts, adaptation, and vulnerability that could potentially overcome many of the limitations identified in the IPCC WGII AR4, particularly with respect to the human dimensions of climate change.

The critical review and synthesis of the scientific literature published since October 2006 (effective cutoff date for AR4) has required an expanded multidisciplinary approach that, in general, has focused more heavily on societal impacts and responses. This includes an assessment of impacts associated with coupled socio-ecological systems and the rapid emergence of research on adaptation and vulnerability.

AR5 WGII differs from the prior assessments primarily in the expanded outline and diversity of content that stems directly from the growth of the scientific basis for the assessment. AR5 WGII is published in two volumes (Part A. Global and Sectoral Aspects; Part B. Regional Aspects) permitting the presentation of more detailed regional analyses and an expanded coverage of the human dimensions such as adaptation. AR5 WGI was completed approximately six months in advance AR5 WGII, allowing the WGII authors more time to evaluate and include where possible the WGI findings, but AR5 WGIII was developed almost in parallel with the WGII report.

The point of departure in the title alludes to the availability of new information concerning the interactions between climate change and other biophysical and societal stressors. Societal stressors include poverty and inequality, low levels of human development, and psychological, institutional, and cultural factors. Even in the presence of these multiple stressors, policy relevant information from scientific research, direct experience, and observation provides an opportunity space to choose and design climate-resilient development pathways (see 1.1.4; 13.1.1; 14.2; 14.3; Figure 1-5).

1.1.1. Development of the Science Basis for the Assessment

The volume of literature available for assessing Climate Change Impacts, Adaptation and Vulnerability (CCIAV) has grown significantly over the past two decades (Figure 1-1). A bibliometric analysis of reports produced with two bibliographic search tools (Scopus[1] and ISI Web of Science[2]) indicates that fewer than 1,000 articles in journals, books, and conference proceedings were published in English on the topic of “climate change” between 1970 and 1990. By the end of 2012 the total number of such articles was reported as 102,573 (Scopus) and 62,155 (Web of Science). The current doubling rate of “climate change” publications remains short, less than 5 years: Scopus database lists 32,943 articles published between 1970 and 2005, and 76,130 published between 1970 and 2010. A doubling of the total number of publications on the topic of climate change impacts between 2005 and 2010 and on the topic of climate change adaptation between 2008 and 2010 has occurred (Figure 1-1c).

[FOOTNOTE 1: Scopus is a bibliographic database owned by Elsevier that contains abstracts and citations for peer-reviewed literature in the scientific, medical, and social sciences (including arts and humanities). Scopus has over 50 million bibliographic records (about 29 million from 1995 forward and about 21 million from 1823-1996), as of September 2013).]

[FOOTNOTE 2: Web of Science, owned by Thompson Reuters, is a bibliographic database of journals and conference proceedings for the sciences, social sciences, arts, and humanities. Web of Science includes records from over 12,000 journals and 148,000 conference proceedings dating from 1985 to present, as of September 2013.]

Since 1990 the geographic distribution of authors contributing to the climate change literature has expanded from Europe and North America to include a large fraction from Asia and Australasia. Literature from scientists affiliated with institutions in Africa and Central and South America, however, comprised approximately 5% of the total during 2001-2010 (Figure 1-1b). The proportion of literature focusing on individual countries within IPCC regions has also broadened over the past 3 decades, particularly for Asia (Figure 1-1a).[3] This brief chronicle does not differentiate across the various “sub-categories” of the climate literature nor claim to be comprehensive in terms of literature produced in languages other than English.

[INSERT FIGURE 1-1 HERE
Figure 1-1: Number of climate-change publications listed in the Scopus bibliographic database and results of literature searches conducted in four other languages. (a) Number of publications in English (as of July, 2011) summed by country affiliation of all authors of climate change publications and binned into IPCC regions. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (b Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July, 2011) binned into IPCC regions for the decades 1981-1990, 1991-2000, and 2001-2010. Each publication can be counted multiple times if more than one country is listed.) (c) Annual global number of publications in English on climate change and related topics: impacts, adaptation, and costs for the years 1970-2010, as of September 2013. (d) Number of publications in five languages that include the words “climate change” and “climate change” plus “adaptation”, “impact”, and “cost” (translated) in the title, abstract or key words during the three decades ending in 2010. The following individuals conducted these literature searches during January, 2012-March, 2013: Valentin Przyluski (French), Huang Huanping (Chinese), Peter Zavialov and Vasily Kokore (Russian), and Saúl Armendáriz Sánchez (Spanish).]

[FOOTNOTE 3: Russia, Greenland, and Iceland are included with Europe; Mexico is included with North America.]

Recent growth in the total volume of literature about climate change and in particular that devoted to impacts and adaptation has influenced the depth and scope of assessment reports produced by WGII, and it has enabled substantial advances in the assessment of the full range of impacts, adaptation, and vulnerability (Figure 1-1a). The unequal distribution of literature (Figure 1-1a,b, d) presents a challenge to the development of a comprehensive and balanced assessment of the global impacts of climate change. The geographical and topical distribution of literature is influenced by factors such as the availability of funding for scientific research, level of capacity building, regional experience with climate-related disasters, and the availability of long-term observational records.

Literature published on the topic of “climate change” during 1970-1990 focused primarily on changes in the physical climate system and how these changes affected other aspects of the Earth’s physical environment. The proportion of climate-change literature in engineering journals has not changed appreciably over the past four decades, but there was a significant increase in the proportion of literature published in biological and agricultural science journals. The proportion of the literature on the topic of “climate change” published in social science journals increased from 6% (1970s-1980s) to 9% (1990s-2000s). The themes covered by literature on vulnerability to climate change have also expanded to issues of ethics, equity, and sustainable development. From the Scopus database, publications on the topic of climate change “impacts” crossed the threshold of 100 per year in 1991. Publications on climate change “adaptation” and societal “cost” reached this level in 2003.

While authors continue to publish primarily in English, climate-change literature in other languages has also expanded. Literature searches in Chinese, French, Russian, and Spanish revealed roughly a 4-fold or greater increase in literature published on the topic of “climate change” in each language during the past two decades (Figure 1-1d). Scientists from many countries tend to publish their work in English, as indicated by comparing the regional analysis and country affiliation of authors in Figure 1-1b with the results of the literature searches in the five languages. This process of “scientific internationalism”, by which English becomes the primary language of scientific communication, has been described as a growing trend among Russian (Kirchik, Gingras, and Ladviere, 2012), Spanish (Alcaide, Zurián, and Benavent, 2012), and French (Gingras and Mosbah-Natanson, 2010) researchers.

1.1.2. Evolution of the WGII Assessment Reports and Treatment of Uncertainty

1.1.2.1. Framing and Outlines of WGII Assessment Reports

The framing and contents of the IPCC WGII reports have evolved since the First Assessment Report (FAR; IPCC, 1990) as summarized in Figure 1-2. Four characteristics of this evolution are an increasing attention to: (i) adaptation limits and transformation in societal and natural systems; (ii) synergies between multiple variables and factors that affect sustainable development, (iii) risk management, and (iv) institutional, social, cultural, and value-related issues. WGII now focuses on understanding the interactions between the natural climate system, ecosystems, human beings, and societies, this being on top of the long-standing emphasis on the biogeophysical impacts of climate change on sectors and regions.

[INSERT FIGURE 1-2 HERE
Figure 1-2: Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The FAR (IPCC, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change. For the SAR (IPCC, 1996) the WGII contribution included mitigation and adaptation with the impacts assessment. With the TAR (IPCC, 2001) and AR4 (IPCC, 2007) climate change mitigation reverted to WGIII, and WG II remained focused on impacts, adaptation, and vulnerability with an expanded effort on the regional scale.]

The WGII FAR (296 pages) was organized into six major sectors: agriculture and forestry, terrestrial ecosystems, water resources, human settlements, and oceans and coastal zones. The report focused on the anticipated climate changes for a doubling of CO_2. The FAR Summary for Policymakers (SPM) highlighted the coupling of anthropogenic non-climate stresses with climate variability and greenhouse-gas-driven climate change. Given the state of the science in 1990, the FAR has understandably low confidence on some high-vulnerability topics (e.g., global agricultural potential may either increase or decrease), but is more quantitative on large-scale climate impacts (e.g., climatic zones shift poleward by hundreds of km). Health impacts were vague, emphasizing ozone depletion and UV-B damage. The IPCC WGII 1992 Supplementary Report followed with four assigned topics (regional climate change; energy; agriculture and forestry; sea-level rise) and was primarily a strategy report, e.g., urging that studies of change in tropical cyclones are of highest priority (IPCC, 1992).

For the IPCC Second Assessment Report (SAR; IPCC, 1996) WGII reviewed climate change impacts, vulnerability, and adaptation plus mitigation options for greenhouse gases (GHG). There were two introductory primers and eighteen chapters on impacts and adaptation (e.g., forests, rangelands, deserts, human settlements, agriculture, fisheries, financial services, human health) and seven chapters on sectoral mitigation (e.g., energy, industry, forests) but with cost analysis left to WGIII. The SAR made use of the new IPCC 1992 scenarios (IS92). Projections of 2100 sea level rise (15-95 cm) and temperature increase (1.0-3.5°C) were similar to the FAR's doubled-CO_2 scenario. The SAR notes "Impacts are difficult to quantify, and existing studies are limited in scope; Detection [of climate-induced changes] will be difficult," but some specifics are given (e.g., the number of people at risk of flooding from storm surges from sea level rise; the increase in malaria incidence). Vegetation models are used to map out projected changes in major biomes (see SAR WGII SPM Figure 2) – the first prediction figure in a WGII SPM.

The Third Assessment Report of WGII (TAR; IPCC, 2001) retained impacts, adaptation, and vulnerability, leaving the topic of mitigation to WGIII. It included five sectoral chapters (water resources, ecosystems, coastal and marine, human settlements and energy, and financial services), eight regional chapters, plus chapters on (i) adaptation, sustainable development, and equity, and (ii) vulnerability and reasons for concern. The TAR made the first strong conclusion on attributing impacts: "recent regional climate changes, particularly temperature increases, have already affected many physical and biological systems." Recent increases in floods and droughts, while affecting some human systems, could not be tied to GHG-driven climate change. The TAR introduced the "burning embers" diagram (SPM Figure 2, discussed in Chapters 18 and 19 of this report) as a way to represent "reasons for concern." The adaptive capacity, vulnerability, and key concerns for each region were laid out in detail (SPM, Table 2).

The Fourth Assessment Report of WGII (AR4; IPCC, 2007) retained the basic structure of the TAR with chapters on sectors and regions. The first chapter of AR4, drawing from the expanded literature, provided an “Assessment of Observed Changes in Natural and Human Systems”. AR4 incorporated several cross-chapter themes with case studies (such as impacts on deltas) as a unifying construct. Two graphics in the AR4 SPM (SPM Figure 1-2 and Table 1-1) give many examples of projected impacts of climate change, but the state of the science – both of WGI climate projections and WGII impacts – remained too uncertain at the time to give more quantitative estimates of the impacts or necessary adaptation.

This WGII fifth assessment continues and expands the sectoral and regional parts. The AR5 considers a wide and complex range of multiple stresses that influence the sustainability of human and ecological systems. The focus on climate change and related stressors, and the resulting vulnerability and risk, continues throughout this report, including the expanded “reasons for concern” (Chapters 2 and 19, see also Section 1.2.3).

1.1.2.2. Treatment of Uncertainties in IPCC Assessment Reports: a Brief History and Terms Used in AR5

An integral feature of IPCC reports is communication of the strength of and uncertainties in scientific understanding underlying assessment findings. Treatment of uncertainties and corresponding use of calibrated uncertainty language in IPCC reports have evolved across IPCC assessment cycles (Swart et al., 2009; Mastrandrea and Mach, 2011). In WGII, the use of calibrated language began in the SAR (1996), in which most chapters used qualitative levels of confidence in Executive Summary findings. With the TAR (2001), formal guidance across the Working Groups has was developed (Moss and Schneider, 2000) recognizing that “guidelines such as these will never truly be completed,” and an iterative process of learning and improvement of guidance has ensued, informed by experience in each assessment cycle (IPCC, 2005; Mastrandrea et al., 2010). Each subsequent guidance paper has presented related but distinct approaches for evaluating and communicating the degree of certainty in findings of the assessment process.

The AR5 Guidance Note (summarized in Box 1-1) continues to emphasize an overriding theme of clearly linking each key finding and corresponding assignment of calibrated uncertainty language to associated chapter text, as part of the traceable account of the author team’s evaluation of evidence and agreement supporting that finding.

_____ START BOX 1-1 HERE _____

Box 1-1. Communication of Uncertainty in the Working Group II Fifth Assessment

Based on the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties (Mastrandrea et al., 2010), the AR5 WGII relies on two metrics for communicating the degree of certainty in key findings:

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

Each finding has its foundation in an author team's evaluation of associated evidence and agreement. The type and amount of evidence available varies for different topics, and that evidence can vary in quality. The consistency of different lines of evidence can also vary. Beyond consistency of evidence, the degree of agreement indicates the consensus within the scientific community on a topic and the degree to which established, competing, or speculative scientific explanations exist.

The Guidance Note provides summary terms to describe the available evidence: *limited*, *medium*, or *robust*; and the degree of agreement: *low*, *medium*, or *high*. These terms are presented with some key findings. In many cases, author teams additionally evaluate their confidence about the validity of a finding, providing a synthesis of the evaluation of evidence and agreement. Levels of confidence include five qualifiers: *very low*, *low*, *medium*, *high*, and *very high*. Figure 1-3 illustrates the relationship between the summary terms for evidence and agreement and the confidence metric. There is flexibility in this relationship; increasing confidence is associated with increasing evidence and agreement, but different levels of confidence can be assigned for a given evidence and agreement statement. The degree of certainty in findings based on qualitative evidence is expressed using levels of confidence and summary terms.

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

In some cases, available evidence incorporates quantitative analyses, based on which uncertainties can be expressed probabilistically. In such cases, a finding can include calibrated likelihood language or a more precise presentation of probability. The likelihood terms and their corresponding probability ranges are presented below. Use of likelihood is not an alternative to use of confidence: an author team will have a level of confidence about the validity of a probabilistic finding. Unless otherwise indicated, findings assigned a likelihood term are associated with *high* or *very high* confidence. When authors evaluate the likelihood of some well-defined outcome having occurred or occurring in the future, the terms and associated meanings are:

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

* Additional terms used more occasionally are *extremely likely:* 95–100% probability, *more likely than not:* >50–100% probability, and *extremely unlikely:* 0–5% probability.

_____ END BOX 1-1 HERE _____

1.1.3. Scenarios Used as Inputs to Working Group II Assessments

A scenario is a story line or image that describes a potential future, developed to inform decision-making under uncertainty (Parson et al. 2007). Scenarios have been part of IPCC future climate projections since the FAR (1990), where WGIII generated four scenarios (Bau = business-as-usual, B, C, and D) used by WGI to project climate change. The IPCC Supplementary Report (IPCC, 1992), a joint effort of WGI and WGIII, defined six new scenarios (IS92a-f) used in the SAR (1996). For the TAR (2001), the IPCC Special Report on Emissions Scenarios (SRES: Nakicenkovic et al., 2000) created many scenarios from four Integrated Assessment Models (IAMs), out of which a representative range of marker scenarios were selected (A1B, A1T, A1FI, A2, B1, B2). In the SRES, scenarios had had socio-economic storylines but climate-mitigation options were not included. The SRES scenarios carried over into the AR4 (2007) and formed the basis for the large number of ensemble climate simulations (CMIP3), which are still in use for climate-change studies relevant to AR5 WGII.[4]

[FOOTNOTE 4: The Coupled Model Intercomparison Project is an activity of the World Climate Research Programme's Working Group on Coupled Modelling. Climate model output from simulations of the past, present and future climate archived mainly in 2005-2006 constituted phase 3 of the Coupled Model Intercomparison Project (CMIP3). Similar climate simulations by an expanded set of models with a close off date of March 2013 are being used in AR5 and constitute phase 5 of the project (CMIP5). CMIP3 used the SRES scenarios, and CMIP5 used the RCP scenarios.]

With AR5, the development of scenarios fundamentally changed from the IPCC-led SRES process. An ad hoc group of experts, anticipating AR5, built a new structure for scenarios called Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011) using updated IAMs and intended to provide a flexible, interactive, and iterative approach to climate change scenarios. The four RCPs are keyed to a range of trajectories of GHG concentrations and climate forcing. They are labeled by their approximate radiative forcing (RF, W m^{-2}) that is reached during or near the end of the 21st century (RCP2.6, RCP4.5, RCP6.0, RCP8.5). The quantitative link between the socio-economic pathway, human activities and GHG emissions, and subsequently RF is weaker or non-existent with current RCP than with SRES scenarios. For example, the RCPs rely on a single parametric model (Meinshausen et al., 2011; TAR, 2001) to map from emissions to RF; whereas IPCC WGI traditionally assesses this critical linkage using the current state of scientific knowledge (see AR5 WGI Chapters 6, 11, 12, Annex II). In addition, socioeconomic scenarios, emissions, and subsequent radiative forcing pathways were not linked one-to-one in the initial RCPs, however, efforts to derive socio-economic pathways consistent with each RCP are discussed in Chapter 20.

1.1.3.1. Comparison of RCP and SRES Scenarios

While WGI AR5 is based primarily on results from the RCP CMIP5, the AR5 WGII also uses results from the SRES CMIP3, and thus we identify similar or parallel scenarios from each set. The radiative forcing from the SRES and RCP scenarios are compared in Figure 1-4a. For the latter half of the 21st century, SRES A1FI lies above all RCP and other SRES; SRES A2 has a similar trajectory to RCP8.5 with both reaching about 8 W m^{-2} by 2100; and SRES B1 approximately matches RCP4.5 with both leveling off at about 4 W m^{-2}. RCP6.0 starts similarly to both RCP4.5 and SRES B1, but after 2060 it increases to about 5 W m^{-2}. RCP2.6, a strong mitigation scenario with net CO_2 removal by 2100, falls well outside the SRES range B1 to A2, peaking at about 2.6 W m^{-2} in 2040 and dropping thereafter (AR5 WGI, Figure 1-15, Tables AII.6.1-10).

Total RF does not adequately describe the differences in climate change between SRES and RCP scenarios. All RCPs adopted stringent air pollution mitigation policies and thus have much lower tropospheric ozone and aerosol abundances than the SRES scenarios, which ignored the role of air quality regulations (AR5 WGI Tables AII.2.16-22). In terms of ozone and particulate matter precursor emissions, there is almost no overlap between SRES and RCP scenarios (AR5 WGI Tables AII.2.16-22). In terms of surface ozone at the continental scale, after 2060 the RCPs are similar to low-end SRES B1 (AR5 WGI Tables AII.7.1-2).

Global mean surface temperature change for these scenarios is shown in Figure 1-4b, based on AR5 WGI (Chapters 11 & 12, Tables AII.7.5-6) and AR4 WGI (Figure 10.26). For the purposes here, that of understanding differences in impact studies using different scenarios, only model CMIP5 ensemble means are shown for the RCPs. If the standard deviation of the models were plotted, all RCPs would touch or overlap through the century (WGI AII.7.5), but even this range underestimates the uncertainties in temperature change for those scenarios (see WGI Chapter 12). The AR5 RCP data is taken directly from the CMIP5 runs, whereas the AR4 data is based on a simple model, parameterized to match the different CMIP3 models (see figure caption). In terms of temperature change, RCP8.5 is close to SRES A2, but below SRES A1FI. RCP4.5 follows SRES B2 up to 2060, but then drops to track SRES B1. RCP6.0 has lower temperature change to start, following SRES B1, but then increases towards SRES B2 by 2100. In general, scenarios SRES A1B, A1T and B2 lie in the large gap between RCP8.5 and RCP4.5/6.0. The RCP2.6 temperature change stabilizes at about 1°C above the reference period (1986-2005). The other RCPS and all SRES scenarios span the range 1.8 – 4.1 °C for the 2090s. The CMIP5 reference period is about 0.6 °C above earliest observing period 1850-1900 (WGI Chapter 2).

[INSERT FIGURE 1-4 HERE
Figure 1-4: (a) Projected RF (W m^{-2}) and (b) global mean surface temperature change (°C) over the 21st century from the SRES and RCP scenarios. RF for the RCPs are taken from their published CO_2-equivalent (Meinshausen et al., 2011), and RF for SRES are from the TAR Appendix II (Table II.3.11). For RF derived from the CMIP5 models see WGI (Chapter 12.3, Tables AII.6.9-10). The ensemble total effective RF at 2100 for CMIP5 concentration-driven projections are 2.2, 3.8, 4.8 and 7.6 W m^{-2} for RCP2.6, RCP4.5, RCP6.0 and RCP8.5, respectively. The SRES RF are shifted upward by 0.12 W m^{-2} to match the RCPs at year 2000 since (i) the climate change over the 21st century is driven primarily by the changes in RF and (ii) the offset is due primarily to improvements in model physics including the aerosol RF. For more details and comparison with pre-SRES scenarios, see WGI Chapter 1 (Figure 1-15). Temperature changes are decadal averages (e.g., 2020s = 2016-2025) based on the model ensemble mean CMIP5 data for the RCPs (colored lines). The same analysis is applied to CMIP3 SRES A1B (yellow circles). See AR5 WGI Chapters 11, 12, Table AII.7.5. The colored squares show the temperature change for all six SRES scenarios based on a simple climate model tuned to the CMIP3 models (AR4 WG1 Figure 10.26). The difference between the yellow circles and yellow squares reflects differences between the simple model and analysis of the CMIP3 model ensemble in parallel with the CMIP5 data. For an assessment of uncertainties and *likely* ranges of temperature change see WGI Figures 11.24-25, 12.4-5, 12.40.]

1.1.3.2. Shared Socio-Economic Pathways

Shared Socioeconomic Pathways (SSPs) are being generated (Arnell et al., 2011; Kriegler et al., 2012) to form more complete scenarios that link each RCP's climate path to a range of human development pathways. The SSPs include three elements: a) storylines, which are descriptions of the state of the world, b) Integrated Assessment Models (IAMs) quantitative variables (such as population, GDP, technology availability), and c) other variables, not included in the IAMs, such as ecosystem productivity and sensitivity or governance index. With these elements a goal of the SSP effort is to characterize a global socio-economic future for the 21st century as a reference for climate change analysis (O'Neill et al., 2012). Combined SSP-RCP scenarios are needed to support synthesis across all IPCC Working Groups and, particularly for WGII, to facilitate the use of new climate modeling results with impacts, adaptation, and vulnerability (IAV) research. Five basic SSPs have been proposed, representing a wide range of possible development pathways, primarily at global or large regional scales. For each RCP it is expected that one or more SSP could lead to that climate path. Several chapters of this report refer to the SSPs in their discussion of analyses of future impacts and vulnerability. Chapter 20 (20.6.1) describes SSPs in more detail, and Chapter 21 (21.2.2) notes how the time lags in producing SSPs has limited the use of CMIP5-RCP scenarios in AR5.

1.1.4. Evolution of Understanding the Interaction between Climate Change Impacts, Adaptation, and Vulnerability with Human and Sustainable Development

The continuing increase in greenhouse gas emissions has highlighted the commitment to climate change and its varied impacts and has contributed to an increasing emphasis on vulnerability, adaptation, and sustainability. The possible range of socio-economic trajectories in countries with low, medium, high, and very high human development is among the largest sources of uncertainty in scenario building and climate projections. A deeper understanding of development patterns, adaptation limits, and maladaptation, as well as options for more climate resilient pathways, has helped identify a larger range of potential climate change impacts and the risks they pose to society.

The first three WGII reports focused primarily on characterizing the biophysical impacts of climate change, with a progressively more elaborated understanding of economic and social impacts. Literature of the last decade indicates a more integrated understanding of the physical and social impacts of climate change. The extent and structure of AR5 WGII shows such advancements. The AR4 Synthesis Report asserted that "climate change impacts depend on the characteristics of natural and human systems, their development pathways and their specific locations" (IPCC

2007c, p. 64). AR4 WGII Chapter 20 offered a catalogue of multiple stresses jointly impacting people and communities and also highlighted questions of justice and equity in shaping development pathways in the context of climate change.

1.1.4.1. Vulnerability and Multiple Stressors

Climate-related risks interact with other biophysical and social stressors. Vulnerability is defined in the TAR WGII Glossary in terms of susceptibility and as a "function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity". Since then, the understanding of vulnerability has acquired increased complexity as a multi-dimensional concept, with more attention to the relation with structural conditions of poverty and inequality. AR5 WGII defines vulnerability simply as the propensity or predisposition to be adversely affected, and many chapters identify such vulnerabilities through societal risks, particularly in low-income economies. Recent studies suggest that climate impacts could slow down or reverse past development achievements, hinder global efforts on poverty reduction, and lead to human and environmental insecurity, displacement and conflict, maladaptation, and negative synergies (Barnett and O'Neill, 2010; Boyd and Juhola, 2009; Jerneck and Olsson, 2008; Ogallo, 2010; see also 3.5.1; 8.2.4; 12.2.1; 12.4.1; 12.5.1; 13.2.1; and 14.7).

The concept of resilience emerged from ecological sciences and has been increasingly used by social sciences. In climate change literature it describes the ability of a system to respond to disturbances, self-organize, learn, and adapt (Brown, 2013; Turner, 2010; AR5 WGII Glossary). Vulnerability, adaptation, and resilience are determined by multiple stressors, a combination of biophysical and social factors that jointly determine the propensity and predisposition to be adversely affected. For example, adaptive capacity in many urban centers in less developed countries is constrained by poverty, unemployment, quality of housing, or lack of access to potable water, sanitation, health care, and education interacting with land degradation, water stress, or biodiversity loss (8.2.4; 11.6.2; 22.4.4). Adaptation options and limits for high-end warming scenarios are often contextualized in relation to socio-economic vulnerabilities and other stressors (Brown, 2012; Gupta et al., 2010; New et al., 2010; Stafford Smith et al., 2011; World Bank, 2012; see also 16.4.2.4).

1.1.4.2. Adaptation, Mitigation, and Development

Impacts of climate change will vary across regions and populations, through space and time, dependent on myriad factors including non-climate stressors and the extent of mitigation and adaptation. Changes in both climate and development are key drivers of the core components of risk (exposure, vulnerability, and physical hazards). The relations with development are complex and contested. There is disagreement about fundamental issues, such as the compatibility of development goals and climate change mitigation, the prioritization of responses (reducing consumption versus investment in sustainable technologies), and the stage of development at which countries should take action (see Box1-2 for terms used to characterize stages of development) (Brooks, Grist, and Brown, 2009; Grist, 2008; Schipper, 2007). The literature points to how inequalities, trade imbalances, intellectual property rights, gender injustice, or agricultural systems, *inter alia*, cannot be addressed with development focusing solely on increasing economic growth (Alston, 2011; Büscher et al., 2012; McMichael, 2009; OECD, 2013; Pogge, 2008; UNDP, 2007, 2011).

_____ START BOX 1-2 HERE _____

Box 1-2. Country Development Terminology

There are diverse approaches for categorizing countries on the basis of their level of development and for defining terms such as industrialized, developed, or developing. Table 1-1 presents selected categorizations used in this report. In the United Nations system, there is no established convention for the designation of developed and developing countries or areas (UN DESA, 2012). The United Nations Statistics Division specifies developed and developing regions based on "common practice." In addition, specific countries are designated as least developed countries, landlocked developing countries, small island developing states, and transition economies. Many countries appear in more than one of these categories. The World Bank uses income as the main criterion for classifying countries (World Bank, 2013). The UNDP aggregates indicators for life expectancy, educational attainment and income into a single composite human development index (HDI) (UNDP, 2013).

[INSERT TABLE 1-1 HERE
Table 1-1: Selected country development categorizations used in this report.]

_____ END BOX 1-2 HERE _____

The recent literature shows increasing attention to questions of ethics, justice, and responsibilities relating to climate change (Arnold, 2011; Caney, 2012; Gardiner, 2011; Marino and Ribot, 2012; O'Brien et al., 2010; Pelling, 2010; Timmons and Parks, 2007). As basic resources such as energy, land, food, or water become threatened, inequalities and unfairness may deepen leading to maladaptation and new forms of vulnerability. Responses to climate change may have consequences and outcomes that favor certain populations or regions. For example, there are increasing cases of land-grabbing and large acquisitions of land or water rights for industrial agriculture, mitigation projects, or biofuels that have negative consequences on local and marginalized communities (Borras, McMichael, and Scoones, 2011, see also 14.7). Ethical perspectives are also important in relation to adaptation constraints and limits (see 16.7) and mitigation (see 1.3.4 and AR5 WGIII).

Climate change impacts have become a central issue in the work of developmental organizations such as the United Nations specialized agencies, bilateral donor institutions, and non-governmental organizations (NGOs) who link adaptation concerns with ongoing development efforts. The increase in adaptation literature and experience, however, has led to the development of adaptation policies in many parts of the world, as reflected in four chapters here devoted to adaptation (14-17) and all of the regional chapters of this report. At the policy level, individual country National Adaptation Programmes of Action and National Communication reports to the United Nations Framework Convention on Climate Change (UNFCCC) had in the past focused primarily on physical climate change drivers and impacts. An analysis of National Communications documents submitted through 2004 by many of the Annex 1 countries, for example, showed that climate change impacts and adaptation receive very limited attention relative to the discussion of greenhouse gas emissions and mitigation policies (Gagnon-Lebrun and Agrawala, 2006). However, concern and actual progress towards adaptation is evident in Latin America (Gutierrez and Espinosa, 2010) and in recent National Communications of some non-Annex 1 countries, such as India (2012) and Iran (2010), which devoted a substantive part of their recent reports to the topic of adaptation.

Some researchers and institutions have sought to identify a continuum between development, adaptation strategies, and financing, including increasing attention to co-benefits with mitigation (Heltberg, Siegel and Jorgensen, 2009; Mearns and Norton, 2010; Richardson et al., 2011; OECD, 2013; USAID, 2008; World Bank, 2010). "Greener" development and market-based mechanisms are being explored as instruments to achieve synergies between mitigation and adaptation efforts, development financing and planning, and links to energy needs are some of the instruments explored. Large concerns remain, however, about the preconditions needed for market mechanisms to work as intended, the problems of carbon leakage, and the potential negative effects of some mitigation strategies (Liverman, 2010; see also; 13.1.3 and WGIII Chapter 15).

1.1.4.3. Transformation and Climate Resilient Pathways

Transformation – a change in the fundamental attributes of a system including altered goals or values – has emerged as a key concept in describing the dimensions, types, and rates of societal response to climate change. In the context of adaptation, we can distinguish between incremental and transformative adaptation, the latter referring to changes in the fundamental attributes of a system in response to climate change and its effects (WGII Glossary, Park et al., 2012). The SREX recognized transformation in technological, financial, regulatory, legislative, and administrative systems (IPCC, 2012; see 1.3.1; 20.5). Recent literature points to changes in values, norms, belief systems, culture, and conceptions of progress and wellbeing as either facilitating or preventing transformation (Kates et al., 2012; O'Brien, 2013; Pelling, 2011; Stafford Smith et al., 2011). Transformation of this nature requires a particular understanding of risks, adaptive management, learning, innovation, and leadership, and may lead to climate resilient development pathways (see 1.2.3 and Chapter 20). Transformational change is not called for in all circumstances (Pelling, 2010) and in some cases may lead to negative consequences for some locations or social groups, contributing to social inequities (O'Brien, 2013). Climate-resilient pathways include actions, strategies and choices that reduce climate change impacts while assuring that risk management and adaptation can be implemented and sustained.

1.1.4.4. The Opportunity Space for Decision Making

Recognizing the need for policy relevant science, much scientific activity tends to be coordinated through international programmes that focus on, for example, biodiversity, desertification, food security, impacts on social practices and institutions, and monitoring sea level rise. The trend in research is to create synergies across the sciences by including social and human sciences perspectives and transdisciplinarity. The production of information with non-scientific sources such as indigenous knowledge or stakeholder views is also enriching climate change research. This trend has led to the merging of relevant global programmes of the international councils for science and for social science (ICSU and ISSC) under the umbrella "Future Earth" (see also ISSC, 2013). This expanded scientific focus combined with increased practice and experience with adaptation creates a new opportunity space for evaluating policy options and their risks in the search for climate resilient development pathways (Figure 1-5) (2.1; 2.4.3; 20.2 and 20.3.3). Human and social-ecological systems can build resilience through adaptation, mitigation, and sustainable development.

Over the next few decades, global temperatures are projected to increase along broadly similar pathways, whether or not mitigation of greenhouse gases occurs (1.3.3). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate and societal responses, including adaptation, will influence near-term outcomes. In the second half of the 21st century and beyond, global temperature increases diverge across emissions scenarios. During this longer-term era of climate options, near-term and ongoing mitigation efforts as well as development trajectories will determine the risks associated with climate change.

[INSERT FIGURE 1-5 HERE
Figure 1-5: Multiple stressors and climate resilient pathways. The literature assessed in this report shows that climate change is just one of the many stressors that influence resilience. Climate-related risks interact with other biophysical stressors (such as biodiversity loss, soil erosion, and water contamination) and with social stressors (such as inequalities, poverty, gender discrimination, and lack of institutions). Rapid advances in knowledge about climate change and its impacts along with experience and other factors provide policy relevant information for decision making that can lead to climate-resilient development pathways. The decisions that societies make within this opportunity space can increase resilience and lower risks. Such decisions and choices are core elements of an iterative risk management process.]

1.2. Major Conclusions of the WGII Fourth Assessment Report (AR4)

This section presents highlights of AR4 that are particularly relevant to AR5 as a point of departure. These highlights are drawn from the AR4 Synthesis Report, the WGII Summary for Policymakers, and the WGII chapter Executive Summaries.

1.2.1. Observed Impacts

Evidence presented in Chapter 1 of the WGII Fourth Assessment Report (AR4) indicated that physical and biological systems on all continents and in most oceans were being affected by recent climate changes, particularly regional temperature increases (Rosenzweig et al., 2007, page 81). In terrestrial ecosystems, warming trends were consistent with observed change in the timing of spring events and poleward and upward shifts in plant and animal ranges. The authors found that the geographical locations of observed changes during the period 1970-2004 are consistent with spatial patterns of atmospheric warming. The types of hydrologic changes reported included: effects on snow, ice and frozen ground; the number and size of glacial lakes; increased runoff and earlier spring peak discharge in many glacier- and snow-fed rivers; thermal structure and water quality of rivers and lakes; and more intense drought and heavy rains in some regions. The authors concluded from a synthesis of studies "that the spatial agreement between regions of significant warming and the locations of significant observed changes is *very unlikely* to be due solely to natural variability of temperatures or natural variability of the systems" (IPCC, 2007d, page 9).

Observed regional impacts to human systems were less obviously attributed to anthropogenic climate change. The authors of AR4 concluded that "**There is *medium confidence* that other effects of regional climate change on natural and human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers"** (IPCC, 2007c, page 3)**.** They presented evidence on the effects of temperature increases on agricultural and forest management at Northern Hemisphere higher latitudes (e.g. earlier spring planting of crops, alterations in disturbance regimes of forests due to fires and pests); on some aspects of human health (e.g. heat-related mortality in Europe, changes in infectious disease vectors in some areas, and allergenic pollen in Northern Hemisphere high and mid-latitudes); and some human activities in the Arctic (e.g. hunting and travel over snow and ice) and in lower-elevation alpine areas (such as mountain sports).

The authors of AR4 concluded that "Recent climate changes and climate variations are beginning to have effects on many other natural and human systems. However, based on published literature, the impacts have not yet become established trends" (IPCC, 2007d, page 9). Three examples were cited: in mountain regions melting glaciers enhanced risk of glacier lake outburst floods on settlements; in the Sahelian region of Africa warmer and drier conditions had detrimental effects on some crops; and in coastal areas sea-level rise and human development contributed to losses of coastal wetlands and mangroves and to increases in damage from coastal flooding.

1.2.2. Key Vulnerabilities, Risks, and Reasons for Concern

In an effort to provide some insights into the seriousness of the impacts of climate change TAR WGII (Chapter 19) identified five ''Reasons for Concern'' (RFC) focusing on: (1) unique and threatened systems, (2) extreme climate events, (3) distribution of impacts, (4) aggregate impacts, and (5) large scale discontinuities (see Figure SPM-2 in IPCC, 2001c). Considering new evidence of observed changes on every continent, coupled with a more thorough understanding of the concept of vulnerability, the AR4 concluded that the five 'reasons for concern' identified in the TAR remained a viable framework to consider key vulnerabilities (IPCC 2007c, page 19).

The AR4 Synthesis Report Summary for Policymakers concluded with the following key message: **Responding to climate change involves an iterative risk management process that includes both adaptation and mitigation and takes into account climate change damages, co-benefits, sustainability, equity and attitudes to risk** (2007c, page 22). The concept of risk (the confluence of likelihood and consequence) is the focus of this AR5 Report. All chapters, especially 2, 18 and 19, now focus on climate change, related stressors, resulting vulnerabilities, and associated risks. Correlating the risk-based framing of the RFC in AR5 WGII with the conclusions reported the AR4 SPM is straightforward (italics indicate new terms that have been added to the RFC definitions from the IPCC, 2007c, page 19):

- Risks to Unique and Threatened Systems: "There is new and stronger evidence of observed impacts of climate change on unique and vulnerable systems (such as polar and high mountain communities and ecosystems), with increasing levels of adverse impacts as temperatures increase."
- *Risks Associated with* Extreme Weather Events: **"**Responses to some recent extreme events reveal higher levels of vulnerability than the TAR. There is now higher confidence in the projected increases in droughts, heat waves and floods, as well as their adverse impacts."
- *Risks Associated with the* Distribution of Impacts: "There are sharp differences across regions and those in the weakest economic position are often the most vulnerable to climate change. There is increasing evidence of greater vulnerability of specific groups such as the poor and elderly not only in developing but also in developed countries. Moreover, there is increased evidence that low-latitude and less developed areas generally face greater risk, for example, in dry areas and megadeltas."

- *Risks of Associated with* Aggregate Impacts: "Compared to the TAR, initial net market-based benefits from climate change are projected to peak at a lower magnitude of warming, while damages would be higher for larger magnitudes of warming."
- Risks Associated with Large Scale Discontinuities: "There is high confidence that global warming over many centuries would lead to a sea level rise contribution from thermal expansion alone that is projected to be much larger than observed over the 20th century, with loss of coastal area and associated impacts. There is better understanding than in the TAR that the risk of additional contributions to sea level rise from both the Greenland and possibly Antarctic ice sheets may be larger than projected by ice sheet models and could occur on century time scales."

Chapters 18 and 19 of AR5 WGII recognize new evidence about the RFC in the context of risk. Chapter 18 expands our understanding of how observed and attributed impacts, vulnerabilities, and associated risks support the identification of the dependence of the RFC on temperature "up to the present". Chapter 19 extends this analysis to future temperatures. Both chapters demonstrate how accounting for both components of risk in assessing the RFC permits a clearer understanding of "key vulnerabilities".

1.2.3. Interaction of Adaptation and Mitigation in a Policy Portfolio

A conclusion of AR4 is that coping with risks of climate change will involve a portfolio of initiatives that will evolve iteratively over time as new information about the workings of the climate system and new insights into how various responses are actually working and penetrating the global socio-economic structure. The AR4 WGII concluded that (i) neither adaptation nor mitigation alone can avoid all climate change impacts; though together they can significantly reduce the risks of climate change, (ii) adaptation is necessary in the short and longer term to address impacts, even for the lowest stabilization scenarios assessed, but there are barriers, limits and costs, but these are not fully understood, (iii) unmitigated climate change would, in the long term, be *likely* to exceed the capacity of natural, managed and human systems to adapt, and (iv) many impacts can be reduced, delayed or avoided by mitigation, while delayed emission reductions significantly constrain the opportunities to achieve lower stabilization levels and increase the risk of more severe climate change impacts." (IPCC 2007c, page 19).

WGII AR5 devotes considerable attention to the interface of adaptation and mitigation and the mechanisms for iterating decisions as described in a collection of chapters (16, 17, 19, and 20) designed explicitly for this purpose. These chapters build substantially upon key messages from the AR4 chapter entitled "Inter-relationships between adaptation and mitigation" (IPCC 2007b, page 747), including:

- Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes adaptation unavoidable.
- Without mitigation, a magnitude of climate change is likely to be reached that makes adaptation impossible for some natural systems; while for most human systems it would involve very high social and economic costs.
- **"Creating synergies between adaptation and mitigation can increase the cost-effectiveness of actions and make them more attractive to stakeholders, including potential funding agencies (medium confidence)."** Such synergies, however, provide no guarantee that resources are used in the most efficient manner and opportunities for synergies are greater in some sectors (e.g., agriculture and forestry) than others (e.g., energy, health, and coastal systems).
- **"It is not yet possible to answer the question as to whether or not investment in adaptation would buy time for mitigation (high confidence)."** Barriers to understanding the trade-offs of the immediate benefits of localized adaptation and the longer-term global benefits of mitigation, coupled with the limitation of models to simulate the intricacies of the interactions of the two, present a challenge to designing and implementing and "optimal mix" of response strategies.
- **"People's capacities to adapt and mitigate are driven by similar sets of factors (high confidence).** These factors represent a generalised response capacity that can be mobilised for both adaptation and mitigation." The authors noted that even societies with high adaptive capacity can be vulnerable to climate change, variability, and extremes.

1.3. Major Conclusions of More Recent IPCC Reports

Since the publication of the Fourth Assessment Report (AR4) in 2007 the IPCC has produced two Special Reports: the SRREN produced by Working Group III and published in 2011 and the SREX produced jointly by WGI and WGII and published in 2012. In addition, the AR5 has staggered the assessment work for its three working groups. AR5 WGI was published before AR4 WGII in 2013, and AR5 WGIII will be published after, in 2014. In this section we summarize the major conclusions of the SREX, the SRREN, AR5 WGI, and preliminary findings from AR5 WGIII. We focus on the key findings, framings, and conceptual innovations these reports bring to AR5 WGII.

One common theme that cuts across the Working Groups is the connection of three basic elements of climate change: (i) detection of climate change or its impacts; (ii) attribution of that observed climate change to the increases in greenhouse gases (i.e., human cause, WGI) or attribution of local impacts to the observed climate change in that region; and (iii) projection of these impacts and climate change into the 21st century. Table 1-2 gives a summary of phenomena for which such detection, attribution, or projection has been made across the Working Groups. A schematic presentation of this detection-attribution-projection sequence from preceding reports is given in Figure 1-6. For AR5 WGII attributions, see Chapter 18; and for projections, see the other chapters.

[INSERT TABLE 1-2 HERE
Table 1-2: Confidence in the observation, attribution, and projection of changes in climate system phenomena.]

[INSERT FIGURE 1-6 HERE
Figure 1-6: Confidence in the attributed (squares) and projected 21st century (yellow circles) changes in climate system phenomena plotted as a function of confidence in their detection to date. Phenomena and sources (AR4, SREX, AR5 WGI) are given in Table 1-2. Strength of confidence is sorted into the six bins as noted on the axes (very low confidence or not assessed; low or medium confidence; high confidence (no quantification) or likely; very likely; extremely likely; virtually certain). Attribution is to either human influence (blue squares, as used by WGI) or observed local/regional climate change (red squares, as used by WGII). Projections assume global warming exceeding 2°C. For AR5 WGII results see, *inter alia*, Chapters 18 and 19.]

1.3.1. Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)

The SRREN (IPCC, 2011a) assesses literature on the challenges of integrating renewable energy sources into existing energy sources to meet the goals of climate change mitigation and sustainable development. More specifically, it examines six renewable energy sources (bioenergy, direct solar energy, geothermal energy, hydropower, ocean, and wind energy) in terms of available technologies, technological potential, and associated costs. The SRREN found that the deployment of renewable energy technologies has increased rapidly in recent years, often associated with cost reductions that are expected to continue with advancing technology. Despite the small contribution of renewable energy to current energy supplies, SRREN shows the global potential of renewable energy to be substantially higher than the global energy demand. It is therefore not the technological potential of renewable energy that constrains its development, but rather economic factors, system integration, infrastructure constraints, public acceptance, and sustainability concerns (IPCC, 2011a). Several SRREN findings have clear linkages with this assessment of climate change impacts, adaptation and vulnerability, as summarized in Table 1-3.

[INSERT TABLE 1-3 HERE
Table 1-3: Examples of linkages between the SRREN and the AR5 WGII with chapter references in parentheses.]

1.3.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

The SREX (IPCC, 2012) is the first IPCC Special Report produced jointly by Working Groups I and II and is the first IPCC report focused specifically on risk management. The report integrates perspectives from historically distinct research communities studying climate science, climate impacts, extreme events and impacts, climate adaptation, and disaster risk management. It assesses relationships between climate change and the characteristics of extreme weather and climate events. The SREX provides information on existing societal exposure and vulnerability to climate-related extreme events and disasters; observed trends in weather- and climate-related disasters, disaster losses, and in disaster risk management; projected changes in weather and climate extremes during the 21st century; approaches for managing the increasing risks of climate extremes and disasters; and implications for sustainable development. SREX Chapter 9 is devoted to fourteen case studies that illustrate the impacts of extreme climate-related events and options for risk management and adaptation, such as early-warning systems, new forms of insurance coverage, and expansion of social safety nets.

1.3.2.1. Themes and Findings of SREX

The most relevant results of the SREX assessment are presented below. They are synthesized along the major themes – changing weather and climate-related extreme events, trends in disaster losses, and managing the risks of extreme events and disasters. Other examples of findings presented in the SREX concerning the type, magnitude, and frequency of extreme weather and climate events are presented in Table 1-2 of this chapter.

- Based on observations since 1950 there is evidence of changes in some climate-related extremes. It is *very likely* that there had been an overall decrease in the number of cold days and nights, and increase in the number of warm days and nights, at the global scale. [SREX SPM, 3.3.1, Table 3-2] It is *likely* that there has been an increase in extreme coastal high water events related to increases in mean sea level. [SREX SPM, 3.5.3] It is *likely* that anthropogenic influences have led to warming of extreme daily minimum and maximum temperatures at the global scale. [SREX SPM, 3.2.2, 3.3.1, 3.3.2, 3.4.4, 3.5.3, Table 3-1]
- The models project substantial warming in temperature extremes by the end of the 21st century. It is *virtually certain* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas. [SREX SPM, 3.3.2,3.3.4, Table 3-3, Figure 3-5]
- It is *likely* that the frequency of heavy precipitation will increase in the 21st century over many areas of the globe. [SREX SPM, 3.3.2, 3.4.4 Table 3-3, Figure 3-7]
- Economic losses from weather- and climate-related disasters have increased, but with large spatial and interannual variability *(high confidence*, based o*n high agreement, medium evidence*). [SREX SPM, 4.5.1, 4.5.3, 4.5.4] Trends in losses have been heavily influenced by increasing exposure of people and economic assets *(high confidence*). [SREX SPM, 4.5.3]
- Economic, including insured, disaster losses associated with weather, climate related events, and geophysical events are higher in developed countries. Fatality rates and economic losses expressed as a proportion of gross domestic product (GDP) are higher in developing countries (*high confidence*). Deaths from natural disasters occur much more in developing countries. From 1970 to 2008 for example, more than 95% of deaths from natural disasters were in developing countries. [SREX SPM, 4.5.2, 4.5.4]
- Development practice, policy and outcomes contribute to shaping disaster risks (*high confidence*): skewed development that may lead to environmental degradation, unplanned urbanization, failure of governance or reduction of livelihood options result in increased exposure and vulnerability to disasters. [SREX SPM 1.1.2, 1.1.3 and 2.2.2, 2.5]
- Post-disaster recovery and reconstruction provide an opportunity for reducing the risks posed by future weather- and climate-related disasters (robust evidence, high agreement). [SREX SPM, 5.2.3, 8.4.1, 8.5.2]
- Socio-economic, demographic, health related differences, access to livelihoods, good governance and entitlements are some of the factors that lead to inequalities between people and countries. Inequalities influence local coping and adaptive capacity and pose challenges for risk management systems from local to national levels (*high agreement, robust evidence*). [SREX SPM 5.5.1, 6.2, 6.3.2, 6.6]
- The incorporation of climate change adaptation and disaster risk management into the local, national and international developments practices and policies, could bring benefits (*medium evidence, high agreement*). [SREX SPM, 5.4, 5.5, 5.6, 6.3.1, 6.3.2, 6.4.2, 6.6, 7.4]

- Combining local knowledge with scientific and technical expertise helps communities reduce their risk and adapt to climate change (*robust evidence, high agreement*). Risk management works best when tailored to local circumstances. [SREX SPM, 5.4.4]
- Many measures for managing current and future risks have additional benefits, such as improving peoples' livelihoods, conserving biodiversity, and improving human well-being (*medium evidence, high agreement*). [SREX SPM, 6.3.1, Table 6-1]
- Many measures, when implemented effectively, make sense under a range of future climates. These "low regrets" measures include: systems that warn people of impending disasters; changes in land use planning; sustainable land management; ecosystem management; improvements in health surveillance, water supplies, and drainage systems; development and enforcement of building codes; and better education and awareness. [SREX SPM, 5.3,1, 5.3.43, 6.3.1, 6.5.1, 6.5.2, 7.4.3 and Case Studies 9.2.11, 9.2.14]
- An iterative process involving monitoring, research, evaluation, learning and innovation can promote adaptive management and reduce disaster risk in the context of climate extremes (*robust evidence, high agreement*). [SREX SPM, 8.63, 8.7]
- Actions ranging from incremental improvements in governance and technology to more transformational changes are essential for reducing risk from climate extremes (*robust evidence, high agreement*). [SREX SPM, 8.6, 8.6.3, 8.7]

1.3.2.2. Advances in Conceptualizing Climate Change Vulnerability, Adaptation, and Risk Management in the Context of Human Development

The conceptual framing of the SREX reflects the diversity of expert communities involved in that assessment. It links exposure and vulnerability with socio-economic development pathways as determinants of impacts and disaster risk for both human society and natural ecosystems. It is important to note that the SREX acknowledges the fundamental role that values and aspirations play in people's perception of risk, of change and causality, and of imagining present and future situations. This value-based approach is put to work as a tool for managing the risks of extreme events and disasters enabling the recognition that socio-economic systems are in constant flux, and that there are many conflicting and contradictory values in play. The conceptual framing of the problem space offered by the SREX (Figure SPM 1-1) serves as a point of departure for many chapters in the AR5. Equally important is the conceptualization of a feasible solution space offered in the SREX. The solution space is further refined in the AR5 through emphasis on the co-benefits of adaptation and mitigation and the further development of transformational change to enable climate resilient development.

1.3.3. Relevant Findings from IPCC Working Group I Fifth Assessment Report

This section is a WGII synthesis of the AR5 WGI report that focuses on topics relevant to WGII science.[5] The relevant WGI chapters and sections where relevant are denoted in brackets [ ]. Where statements have *high confidence* or *likely* or better quantification, these qualifiers are dropped for readability. Likewise, many phrases are exact quotations but are not presented in quotes. An overall assessment of climate change over the last several decades from WGI is: Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. Human influence on the climate system is clear; it has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes [SPM].

[FOOTNOTE 5: This narrative is taken primarily from the executive summaries of the WGI Final Draft chapters and is updated to reflect the WGI SPM approved on 27 September 2013 in Stockholm. For the most part, WGI findings summarized here have *high confidence* or a *likely* or better quantification are used here, and hence the confidence and likelihood statements have been dropped for readability. All quantitative ranges are *likely* (66% confidence) or *very likely* (90% confidence) or the modeled range (where noted). In a few instances, assessments with *low confidence* are included and so noted. This WGII narrative is intended to be accurate, but for the purpose here the exact WGI language has been edited and concatenated where possible (e.g., 1950 is substituted for "the middle of the 20th century"). Although quotation marks are not used, there remain long phrases that are direct quotes from the

WGI chapters. All numerical values are verbatim. For the level of uncertainty and the precise wording of the WGI assessment refer directly to the WGI approved SPM and the accepted chapters.]

Greenhouse gases and climate forcing. Human activities are the dominant cause of the observed increase in well mixed greenhouse gases (GHGs) since 1750 and of the consequent increase in climate forcing. The GHGs and their forcing continued to increase since AR4 [2, 6, 8]. Ozone and stratospheric water vapor also contribute to this forcing [8]. Aerosols partially offset this forcing and dominate the uncertainty in determining total anthropogenic forcing of climate change [8]. Total anthropogenic climate forcing is positive and has increased more rapidly since 1970 than during prior decades [8]. Present-day (2011) abundances of CO_2, CH_4, and N_2O exceed the range over the past 800,000 years found in ice cores [5, 6]. Annual emission of CO_2 from fossil fuels and cement production was 9.5 GtC in 2011, 54% above the 1990 level [SPM]. More than 20% of added CO_2 will remain in the atmosphere for longer than 1000 years [6]. Anthropogenic land use change has increased the land surface albedo (a negative forcing) and has also affected climate through the hydrologic cycle, but these effects are more uncertain and difficult to quantify [8.3.5]. Spatial gradients in forcing (i.e., aerosols, ozone, land use change) affect regional temperature responses [8]. Cumulative CO_2 emissions from 1750 to 2011 are 365 GtC (fossil fuel and cement) plus 180 GtC (deforestation and other land-use change) [SPM]. This 545 GtC represents about half of the 1000 GtC total that can be emitted and still keep global warming under 2 °C relative to the reference period 1861-1880 [SPM].

Air quality on continental scales. Future surface ozone (air pollution) decreases over most continents for RCP2.6, RCP4.5 and RCP6.0; but it increases for RCP8.5 due to rising CH_4 [11]. Changes in air quality for the RCPs are driven primarily by pollutant emissions and secondarily by climate change [11]. Air pollution is less under RCP scenarios than under SRES scenarios [11].

Surface Temperatures. Global mean surface temperature increased by 0.85 [0.65 to 1.06] °C over the period 1880–2012 (linear trend) [SPM] and by 0.72°C over the period 1951–2012 [2]. Each of the last three decades (from 1983 to 2012) has been successively warmer than any preceding decade since 1850 [SPM]. The decade 2003-2012 has been the warmest over the instrumental record, even though the rate of warming over 1998–2012 is smaller than the average rate since 1951 (0.05°C vs. 0.12°C per decade) [2]. For the Northern Hemisphere, the period 1983–2012 was the warmest of the last 1400 years [5]. The slower surface warming trend over the period 1998–2012 vs. 1951–2012 is due in roughly equal measure to a reduced trend in radiative forcing and a cooling contribution from internal, possibly oceanic variability [SPM]. Models reproduce the overall 1951-2012 warming trend, but not the smaller trend for 1998-2012 [9]. More than half of the 1951-2010 temperature increase is due to the observed anthropogenic increase in GHG [10]. The projected near term (2016-2035) mean surface temperature increase is 0.9–1.3 °C [11], and the long term (2081-2100) ranges from 0.9–2.3 °C (RCP2.6) to 3.2–5.4 °C (RCP8.5) (values are relative to 1850-1900, the earliest period for which global mean surface temperatures have been measured, and include the 0.6°C offset from that period to the model reference period 1986-2005) [SPM, 2, 12].

Global temperatures during the last interglacial period (~120,000 years ago) were never more than 2°C higher than pre-industrial levels [5]. By 2050 the global warming range is 1.5°C to 2.3°C above the 1850-1900 period based on the range across all RCPs and models [11.3.6]. Near the end of the century (2081-2100) warming above 4°C is typical of RCP8.5, while that of RCP2.6 remains below 2°C [12]. Orbital forcing will not trigger widespread glaciation during the next 1,000 years [5].

Climate models reproduce observed continental-scale mean surface temperature patterns; on sub-continental and smaller scales model capability is reduced, but is better than in AR4 [9]. Regional downscaling provides climate information at the smaller scales needed for impact studies and adds value in regions with highly variable topography and for various small-scale phenomena [9]. Anthropogenic warming in the 21st century will proceed more rapidly over land areas than over oceans, and the Arctic region is projected to warm most [11, 12].

Precipitation. Observed trends in global land-average precipitation have *low confidence* prior to 1950 and *medium confidence* thereafter [2]. Simulation of large-scale precipitation patterns has improved somewhat since AR4, but precipitation at regional scales is not well simulated [9]. Precipitation (global annual averages) will increase as temperatures increase, and the contrast between dry and wet regions and that between wet and dry seasons will increase over most of the globe [12]. By 2100 under RCP8.5, high latitudes will experience more precipitation;

many moist mid latitude regions will also experience more; while many mid latitude and subtropical arid and semi-arid regions will experience less [12]. These patterns are also typical of near-term climate change [11]. Trends will not be apparent in all regions, especially in the near term, because of natural variability and possible influences of aerosols and land use change [11].

Extreme temperatures and precipitation. Since 1950, the numbers of cold days/nights have decreased and the numbers of warm days/nights have increased globally [2]; and model simulation of these extreme events has improved since AR4 [9]. Since 1950, anthropogenic forcing has contributed to the observed changes in daily temperature extremes on the global scale [10]. In most regions the frequency of warm days/nights will increase in the next decades, while that of cold days/nights will decrease [11]. Increases in the frequency, duration and magnitude of hot extremes along with heat stress are expected, however occasional cold winter extremes will occur [12]. Extreme high temperatures (20-year return values) are projected to increase at a rate similar to or greater than the rate of increase of summer mean temperatures in most regions [12].

There is *no confidence* level assigned to projected near-term increases in the duration, intensity, and spatial extent of heat waves and warm spells [11], but in the long term heat waves will occur at higher frequency and longer duration in response to increased seasonal mean temperatures [12.4.3]. Since 1950, the frequency or intensity of heavy precipitation events has in North America and Europe [2, SPM]. Trends in small-scale severe weather events (e.g., hail, thunderstorms) have *low confidence* [2]. With global warming, the frequency and intensity of heavy/extreme precipitation events will increase over most mid latitude land and over wet tropical regions [12], and extreme daily precipitation rates will increase faster than the mean time average [7]. Most models underestimate the sensitivity of extreme precipitation to temperature variability/trends, and thus projections may underestimate these extremes [9].

Floods and droughts. In many regions, historical droughts (last 1000 years) and historical floods (last 500 years) have been more severe than those observed since 1900 [5]. Global-scale trends in drought or dryness since 1950 have *low confidence* due to lack of direct observations, methodological uncertainties and geographical inconsistencies; and hence confidence levels in global drought trends since the 1970s as reported in AR4 are overstated [2]. Regional trends are found: the frequency and intensity of drought has increased in the Mediterranean and West Africa, and it has decreased in central North America and north-west Australia since 1950 [2, 2.6.2.2]. There is low confidence in attributing drought changes to human influence [10]. Projected changes in soil moisture and surface runoff have *low confidence* in the near term [11], but by 2100 under RCP8.5, annual runoff will: decrease in parts of southern Europe, Middle East, and southern Africa; and increase in high northern latitudes [12]. Decreases in soil moisture with increased risk of agricultural drought are projected in presently dry regions [12].

Tropical cyclones, storms, and wave heights. Observed changes in tropical cyclone activity on a centennial scale as well as attribution to human influence have *low confidence* [2, 10]; however, the frequency and intensity of the strongest tropical cyclones in the North Atlantic has increased since the 1970s [2]. In a few studies, high-resolution atmospheric models have reproduced the year-to-year variability of Atlantic hurricane counts [9]. Future changes in intensity and frequency of tropical cyclones will vary by region, but basin-specific projections have *low confidence* [11, 14]. The maximum wind speed and precipitation rates of tropical cyclones will increase [14].

Circulation features have moved poleward since the 1970s, including a poleward shift of storm tracks and jet streams [2], and model simulation of these patterns has improved since AR4 [9]. Large-scale trends in storminess over the last century have *low confidence* [2, 2.6.4]. Projections of the position and strength of Northern Hemisphere storm tracks, especially for the North Atlantic basin, have *low confidence* [11, 12, 14]. With global warming, a shift to more intense individual storms and fewer weak storms is projected [12].

Mean significant wave height has increased over much of the Atlantic north of 45°N since 1950, with winter season trends of up to 20 cm/decade (*medium confidence*) [3, 3.4.5]. Wave heights and the duration of the wave season will increase in the Arctic Ocean as a result of reduced sea-ice extent [13]. Wave heights will increase in the Southern Ocean as a result of enhanced wind speeds [13].

Ocean warming, stratification, and circulation. Overall, the ocean has warmed throughout most of its depth over some periods since 1950, and this warming accounts for about 93% of the increase in Earth's energy inventory between 1971 and 2010 [3]. The upper ocean above 700 m has warmed from 1971 to 2010, and the thermal stratification has increased by about 4% above 200 m depth [3]. Anthropogenic forcings have made a substantial contribution this upper ocean warming [10]. Measurement errors in the temperature data sets have been corrected since the AR4 [10]. The global ocean continues to warm in all RCP scenarios [11, 12]. To date there is no observational evidence of a long-term trend in Atlantic Meridional Overturning Circulation [3]; and over the 21st century it is projected to weaken but not undergo an abrupt transition or collapse [12].

Ocean acidification and low-oxygen. Oceanic uptake of anthropogenic CO_2 results in gradual acidification of the ocean [3]. Since 1750 the pH of seawater has decreased by 0.1 (a 26% increase in hydrogen ion concentration) [3]. Increased storage of carbon by the oceans over the 21st century will increase acidification, decreasing pH further by 0.065 for RCP2.6 and 0.31 for RCP8.5 [6]. Aragonite under-saturation becomes widespread in parts of the Arctic and Southern Oceans and in some coastal upwelling systems at atmospheric CO_2 levels of 500–600 ppm [6]. Oxygen concentrations have decreased since the 1960s in the open ocean thermocline of many regions (*medium confidence*) [3]. By 2100, the oxygen content of the ocean will decrease by a few percent [6]. There is no consensus on projection of the very low oxygen (hypoxic or suboxic) waters in the open ocean [6].

Sea ice. Continuing the trends reported in AR4, the annual Arctic sea ice extent decreased at rate of 3.5 to 4.1 %/decade between 1979 and 2012 [4]. Over the past three decades, Arctic summer sea ice retreat was unprecedented and Arctic sea surface temperatures were anomalously high, compared with the last 1,450 years [SPM]. The Arctic average winter sea ice thickness decreased between 1980 and 2008 [4]. Current climate models reproduce the seasonal cycle and downward trend of Arctic sea-ice extent [9]. Anthropogenic forcings have contributed to Arctic sea ice loss since 1979 [10]. With global warming, further shrinking and thinning of Arctic sea ice cover is projected, and the Arctic Ocean will be nearly ice-free in September before 2050 for the high-warming scenarios like RCP8.5 [11, 12]. There is little evidence in climate models of an Arctic Ocean tipping point, i.e. the transition from a perennially ice-covered to a seasonally ice-free beyond which further sea ice loss is unstoppable and irreversible [12]. Annual Antarctic sea ice extent increased by 1.2 to 1.8 %/decade between 1979 and 2012 [4]. The scientific understanding of this observed increase has *low confidence* [10]. With global warming, Antarctic sea ice extent and volume is expected to decrease (*low confidence*) [12].

Ice sheets, glaciers, snow cover and permafrost. During periods over the past few million years that were globally warmer than present, the Greenland and West Antarctic Ice Sheets were smaller [5]. The Antarctic and Greenland Ice Sheets have on average lost ice during the last two decades, and the rate of loss has increased over the most recent decade to a sea-level rise equivalent of 0.6 mm/y for Greenland and 0.4 mm/yr for Antarctica [4]. Anthropogenic influences have contributed to Greenland ice loss since 1990 and to the retreat of glaciers since the 1960s, but there is *low confidence* in attributing the causes of Antarctic ice loss [10]. With global warming, model studies agree that the Greenland Ice Sheet will significantly decrease in area and volume, while the Antarctic Ice Sheet increases in most projections (*confidence* not assessed) [12, 13.4.4]. Global warming above a certain threshold (e.g., 2°C to 4°C above the 1850-1900 period) would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed) [13]. There is *low confidence* and little consensus on the likelihood of abrupt or nonlinear changes in components of the climate system over the 21st century [12].

Multiple lines of evidence support very substantial Arctic warming since the mid-20th century [SPM]. Almost all glaciers world-wide have continued to shrink since AR4 [4]. Over the last decade, most ice was lost from glaciers in Alaska, Canadian Arctic, Greenland Ice Sheet periphery, Southern Andes, and Asian Mountains [4]. Current glacier extents are out of balance with current climate, and glaciers will continue to shrink even without further warming [4]. Snow cover extent has decreased in the Northern Hemisphere, particularly in spring [4]; and reductions since 1970 have an anthropogenic component [10]. Permafrost temperatures have increased in most regions since the early 1980s: observed warming was up to 3°C in parts of Northern Alaska and 2°C in parts of the Russian European North [4, SPM]. With global warming, Northern Hemisphere snow cover extent and permafrost extent will decrease further [11, 12]. By 2100 the decrease in near-surface permafrost area ranges from 37% (RCP2.6) to 81% (RCP8.5) (*medium confidence*) [12].

Sea level rise. During the last interglacial period, when global mean temperatures were no more than 2°C above pre-industrial values (*medium confidence*), maximum global mean sea level was, for several thousand years, 5 m to 10 m higher than present [SPM, 5, 5.3.4, 5.6.1, 5.6.2, 13, 13.2.1] with substantial contributions from Greenland and Antarctic Ice Sheets [5, 13]. The rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia [SPM]. Global mean sea level has risen at an average rate of 1.7 mm/yr from 1901 to 2010 and at a faster rate, 3.2 mm/yr, from 1993 to 2010 [3]. There is a substantial anthropogenic contribution to the global mean sea level rise since the 1970s [10]. The rate of global mean sea level rise during the 21st century will exceed that observed during 1971–2010 for all RCP scenarios [13]. For the period 2081–2100 compared to 1986–2005, process-based models project a global mean sea level rise ranging from 0.26 to 0.55 m (RCP2.6) up to 0.45 to 0.82 m (RCP8.5) [13]. By 2100 for RCP8.5, this rise is 0.52 to 0.98 m with a rate of rise reaching 8 to 16 mm/yr [SPM, 13]. Only collapse of marine-based sectors of the Antarctic Ice Sheet could cause global mean sea level to rise substantially above these projections, probably not exceeding several tenths of a meter (*medium confidence*) by 2100 [13]. Semi-empirical projections of 2100 sea level rise have a wide spread across models, some overlapping with the process-based models and some twice as large; however there is *low confidence* in these projections [13, 13.5.2-3]. If global warming exceeds a certain threshold resulting in near-complete loss of the Greenland Ice Sheet over a millennium or more (*confidence* not assessed), global mean sea level would rise about 7 m [13]. Future sea level change will vary regionally, but about 70% of the global coastlines are projected to experience a sea level change within 20% of the global mean [13].

The magnitude of extreme high sea level events has increased since 1970 [3]. Future sea level extremes will become more frequent beyond 2050, primarily as a result of increasing mean sea level [13]. By 2100 the frequency of current sea level extremes will increase by large factors in some regions [13, 13.7.2]. Region-specific projections of storminess and associated storm surges have *low confidence* [13].

<u>Climate patterns</u>. The El Niño-Southern Oscillation (ENSO) system has remained highly variable throughout the past 7,000 years with no discernible evidence of orbital modulation [5]. The observed variability of the ENSO in the tropical Pacific is now reproduced in most climate models [9]. Models project an eastward shift in the ENSO teleconnection patterns of temperature and precipitation variations over the North Pacific and North America [14]. ENSO remains the dominant mode of interannual climate variability in the future, and the ENSO precipitation anomalies will intensify due to increased moisture [14]. Aggregated over all monsoon systems and over the 21st century, the monsoon will increase in area and intensity while its circulation weakens [14]. Monsoon onset dates become earlier or do not change and monsoon retreat dates delay, lengthening the monsoon season [14]. Reduced warming and decreased precipitation is projected in the eastern tropical Indian Ocean, with increased warming and precipitation in the western, influencing East Africa and Southeast Asia precipitation [14].

1.3.4. Relevant Findings from IPCC Working Group III Fifth Assessment Report

The WGIII report assesses scientific research related to the mitigation of climate change. Because mitigation lowers the effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts. Both mitigation (WGIII) and adaptation (WGII) involve risk management in the context of many prevailing uncertainties. Uncertainties arise not only in the natural but also in human and social systems, including responses of these to policy interventions. It is possible that extreme climate impacts could play a central role in determining the level of mitigation, adaptation, and other policy responses to climate change [WGIII-2].

Over the last two WGIII assessment reports, one of the most important shifts in the scientific literature reflects underlying changes in the structure of the world economy: the underlying determinants of emissions – such as technologies, investment patterns, resource use, lifestyles, and development pathways in general – have not substantially shifted toward a low-GHG pattern despite the adoption of the UNFCCC and the Kyoto Protocol. In 2010, GHG emissions surpassed 50 Gt CO_2-eq (13.6 GtC), higher than in any previous year since 1750. Most of the emission growth between 2000 and 2010 came from fossil-fuel use in the energy and industry sectors, and took place in emerging economies. This emission growth was not met by significant GHG emission cuts in the industrialized country group, which continued to dominate historical long-term contributions to global CO_2 emissions. In 2010, median per capita GHG emissions in high income countries were roughly ten times higher than in low-income countries [WGIII-1, WGIII-5].

One of the central messages of AR5 WGIII is that technological and behavioural options exist that would allow the world's economies to follow pathways to much lower future emissions of GHGs. Since AR4 a substantial scenario literature has emerged on the technological, economic, and institutional conditions needed to achieve different long-term pathways leading to a stabilization of atmospheric GHG concentrations at different levels. A continuation of current trends of technological change in the absence of explicit climate change mitigation policies is not sufficient to bring about stabilization of greenhouse gases. Scenarios, which are more likely than not, to limit temperature increase to 2° C are becoming increasingly challenging, and most of these include a temporary overshoot of this concentration goal requiring net negative CO_2 emissions after 2050 and thus large-scale application of carbon dioxide removal technologies (CDR) [WGIII-6]. CDR methods are not mature and have biogeochemical and technological limitations to their potential on a global scale and carry side effects and long-term consequences on a global scale [WGI-SPM, WGIII g]. The increasing dependence of pathways on CDR options reduces the ability of policymakers to hedge risks freely across the mitigation technology portfolio [WGIII 6]. The literature highlights the importance of a systemic, cross-sectoral approach to mitigation. Approaches that emphasize only a subset of sectors or a subset of actions may miss synergies between sectors, raise the costs of mitigation, cause unexpected consequences, and prove insufficient to meet long-term mitigation goals [WGIII 6-11]. The costs of mitigation grow over-proportionally with the stringency of the stabilization target. Delays in mitigation and the unavailability of individual mitigation technologies increase the cost of mitigation and negatively affect the probability of meeting ambitious long-term atmospheric stabilization goals [WGIII 6].

Mitigation policies involve multiple actors and institutions at the international, regional, national and sub-national scales—from global treaties to firms and individual households. Since AR4 a body of literature has been emerging to explain how this multiplicity of actors and levels, focused on a multiplicity of interacting goals, affects the design and evolution of mitigation policy [WGIII-13, WGIII- 14, WGIII- 15]. Approaches to international cooperation in climate policies have increased and become more diverse ranging from strong multi-lateralism to harmonized national and regional policies [WGIII-13]. Linkages among regional, national, and sub-national programs may complement international cooperation. Carbon markets have been the focus of regional policy due, in part, to the greater opportunities for trade as carbon markets expand [WGIII-13, WGIII-14]. A combination of policies that address providing a price signal, removing barriers, and promoting long-term investments could be most effective. If there is no coordination within an integrated perspective then results in one area may be undone by results in another area, for instance through leakage and rebound effects [WGIII-15].

While mitigation efforts generate costs and trade-offs, they also offer possible synergies because many of the policies that can mitigate GHGs also help address other policy goals, such as managing air pollution, water scarcity, or energy security. Since AR4 a substantial literature has emerged on this topic, underscoring the link of mitigation to a wide range of societal goals, often designated sustainable development [WGIII-3, WGIII-4, WGIII-15].

Frequently Asked Questions

FAQ 1.1: On what information is the new assessment based, and how has that information changed since the last report, the IPCC Fourth Assessment Report in 2007? *[to be placed in Section 1.1.1, near Figure 1-1]*
Thousands of scientists from around the world contribute voluntarily to the work of the IPCC, which was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific assessment of the current scientific literature about climate change and its potential human and environmental impacts. Those scientists critically assess the latest scientific, technical, and socio-economic information about climate change from many sources. Priority is given to peer-reviewed scientific, technical, and social-economic literature, but other sources such as reports from government and industry can be crucial for IPCC assessments.

The body of scientific information about climate change from a wide range of fields has grown substantially since 2007, so the new assessment reflects the large amount that has been learned in the past six years. To give a sense of how that body of knowledge has grown, between 2005 and 2010 the total number of publications just on climate change impacts, the focus of Working Group II, more than doubled. There has also been a tremendous growth in the proportion of that literature devoted to particular countries or regions.

FAQ 1.2: How is the state of scientific understanding and uncertainty communicated in this assessment?
[to be placed in Section 1.1.2.2]

While the body of scientific knowledge about climate change and its impacts has grown tremendously, future conditions cannot be predicted with absolute certainty. Future climate change impacts will depend on past and future socioeconomic development, which influences emissions of heat-trapping gases, the exposure and vulnerability of society and ecosystems, and societal capacity to respond.

Ultimately, anticipating, preparing for, and responding to climate change is a process of risk management informed by scientific understanding and the values of stakeholders and society. The Working Group II assessment provides information to decisionmakers about the full range of possible consequences and associated probabilities, as well as the implications of potential responses. To clearly communicate well-established knowledge, uncertainties, and areas of disagreement, the scientists developing this assessment report use specific terms, methods, and guidance to characterize their degree of certainty in assessment conclusions.

FAQ 1.3: How has our understanding of the interface between human, natural,and climate systems expanded since the 2007 IPCC Assessment? *[to be placed in Section 1.1.4]*

Advances in scientific methods that integrate physical climate science with knowledge about impacts on human and natural systems have allowed the new assessment to offer a more comprehensive and finer-scaled view of the impacts of climate change, vulnerabilities to those impacts, and adaptation options, at a regional scale. That's important because many of the impacts of climate change on people, societies, infrastructure, industry, and ecosystems are the result of interactions between humans, nature, and specifically climate and weather, at the regional scale.

In addition, this new assessment from Working Group II greatly expands the use of the large body of evidence from the social sciences about human behavior and the human dimensions of climate change. It also reflects improved integration of what is known about physical climate science, which is the focus of Working Group I of the IPCC, and what is known about options for mitigating greenhouse gas emissions, the focus of Working Group III. Together this coordination and expanded knowledge inform a more advanced and finer-scaled, regionally detailed assessment of interactions between human and natural systems, allowing more detailed consideration of sectors of interest to Working Group II such as water resources, ecosystems, food, forests, coastal systems, industry, and human health.

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Table 1-1: Selected country development categorizations used in this report.

Categorization Approach	**Categories**	**Criteria**	**Reference**
United Nations	Developing regions Developed regions	--Common practice	UN DESA, 2012
	Least Developed Countries	--Gross National Income (GNI) per capita --Human assets --Economic vulnerability to external shocks	UN DESA, 2008
	Landlocked Developing Countries	-- Lack of territorial access to the sea --Remoteness and isolation from world markets --High transit costs	United Nations, 2003
	Small Island Developing States	--Low lying coastal countries sharing similar socio-economic and environmental vulnerabilities	United Nations, 1993
	Economies in Transition/Transition Economies	--Countries changing from central planning to free markets	UN DESA, 2013
World Bank	Low Income Lower Middle Income Upper Middle Income High Income	--GNI per capita	World Bank, 2013
UNDP	Low Human Development Medium Human Development High Human Development Very High Human Development	--GNI per capita --Life expectancy at birth --Mean years of schooling --Expected years of schooling	UNDP, 2013

Table 1-2: Confidence in the observation, attribution, and projection of changes in climate system phenomena.

Phenomenon	Change	Observed to 2010 X-axis Fig 1-6	Attributed (**humans** or **obs. climate change**) Y-axis ■ ■	Projected 2050-2100 Y-axis ●	Source
Greenhouse gases: CO_2, CH_4, N_2O	∧	****	****	**** (RCPs: CO_2,N_2O)	AR5 I-2, I-10, I-11, I-12
Global Mean Surface Air Temperature (GMST)	∧	****	***	****	AR5 I-2, I-10, I-11, I-12
GMST over all continents except Antarctica	∧	****	*	****	AR5 I-2, I-10, I-11, I-12
Global mean sea level	∧	****	**	****	AR5 I-3, I-10, I-13
Arctic sea ice cover	∨	****	**	**	AR5 I-4, I-10, I-11, I-12
Hot days and nights over land (warmth, frequency)	∧	**	**	****	AR5 SPM-1
Cold days and nights over land (warmth, frequency)	∨	**	**	****	AR5 SPM-1
Extreme high sea level (incidence, magnitude)	∧	* (since 1970)	X	**	AR5 SPM-1
Heat waves and warm spells over land (frequency, duration)	∧∨	**MC**	*	**	AR5 SPM-1

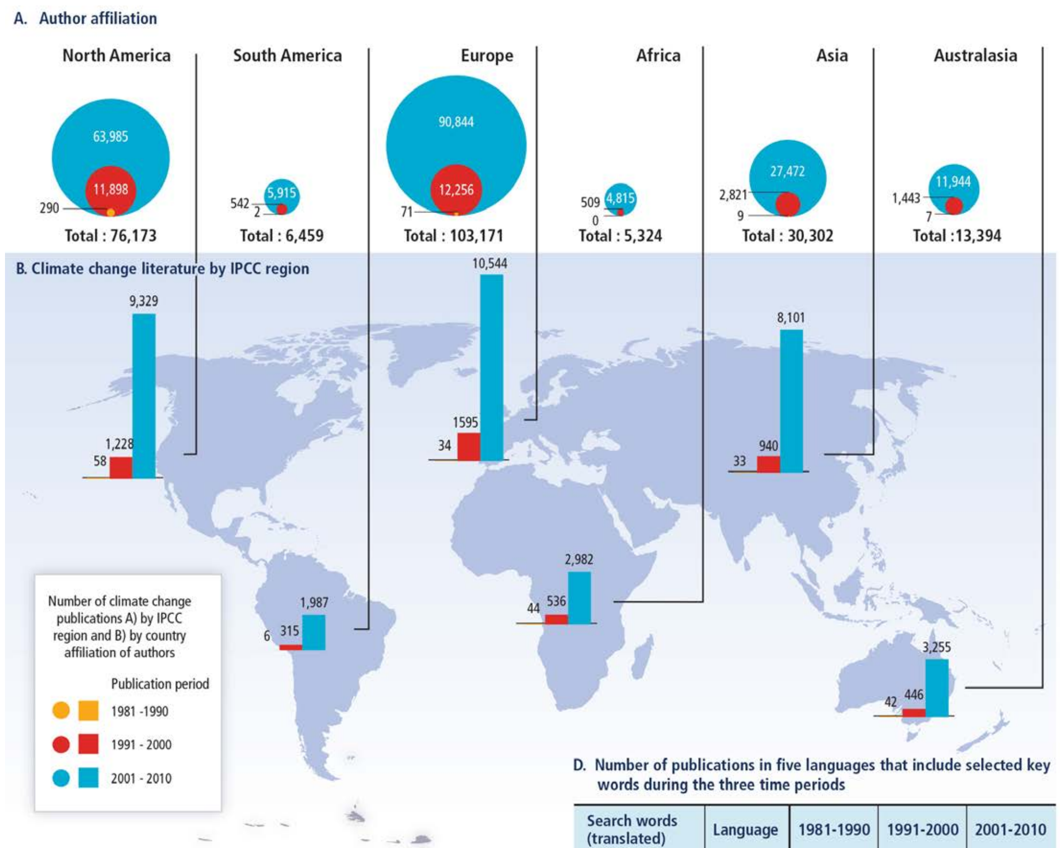
Heavy precipitation events	∧∨	*	**MC**	**	AR5 I-2, I-10, I-12
Drought (intensity, duration)	∧∨	**MC** (some regions)	**LC**	*	AR5 SPM-1, SREX-4
Tropical cyclones (intensity, frequency, some basins)	~	**LC**	**LC**	**MC** (intensity increase, some basins)	AR5 SPM-1
Global mean precipitation	∧	**LC**	**LC**	****	AR5 I-2, I-10, I-11, I-12
Contrast between wet and dry regions	∧	X	X	**HC**	AR5 I-12
Snow cover (NH, extent)	∨	**HC**	**HC**	**HC**	AR5 I-4, I-10, I-12
Permafrost regions (degrade)	∨	**MC**	X	**MC**	AR5 I-4, I-12
Storm tracks (shift poleward)	∧	*	X	*	AR5 I-2, I-12
Wave heights (different oceans)	∧	**MC** (N. Atlantic)	X	** * (Arctic) (Southern)	AR5 I-3, I-13
Upper ocean (warming)	∧	****	***	***	AR5 I-3, I-10, I-11, I-12
Ocean acidification	∧	****	***	****	AR5 I-3, I-10, I-6
Oceanic oxygen	∨	**MC**	**MC**	**	AR5 I-3, I-10, I-6
Floods (magnitude, frequency)	~	**LC**	**LC**	**LC**	SREX-3
Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	∧	**HC**	**HC**	**HC**	SREX-3, AR4 SyR
Monsoons	~	**LC**	**LC**	**LC**	SREX-3
Plant and animal species (move poleward or up in altitude)	∧	**HC**	**HC**	**HC**	AR4 II-SPM, AR4-SyR
Mountain phenomena (slope instabilities, mass movement, glacial lake outbursts)	∧	**HC**	**HC**	**HC**	SREX-3, AR4 SyR
Timing of spring events (earlier leafing, greening, planting, bird migration, …)	∧	**HC**	**HC**	**HC**	AR4 SyR
Marine / freshwater biological systems (shifts in algal, plankton and fish range)	~	**HC**	**HC**	**HC**	AR4 SyR
Human health (heat-related mortality, infectious disease vectors)	∧	**MC**	**MC**	X	AR4 SyR
Water resources	∨	X	X	(many regions)	AR4 SyR-SPM
Mountain glaciers	∨	**HC**	X	**HC**	AR4 II-SPM
Coral degradation, bleaching	∧	**HC**	X	**HC**	AR4 II-SPM, SyR-SPM
Economic losses from weather- and climate-related disasters	∧	**HC**	X	**HC**	SREX-4
Annual costs of climate change	∧	X	X	**	Ar4 SyR-SPM

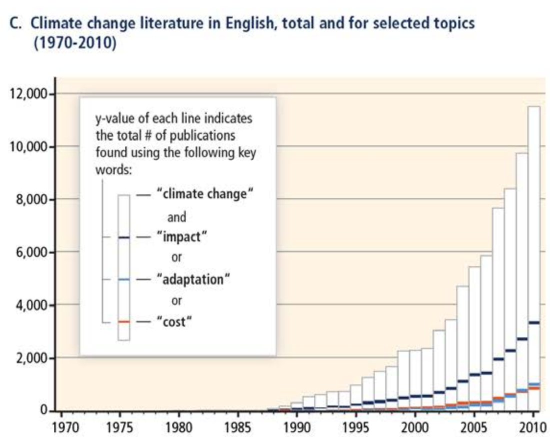
Table 1-2 Notes: Attribution in the top-half of the table is to human forcing of the climate, primarily through the increase in greenhouse gases (WGI). Attribution in the bottom-half, impacts, adaptation and vulnerability is to the observed local or regional climate change (WGII).

Trend		Confidence Assessment		Likelihood Assessment	
∧	Increasing overall	**HC**	High or Very High confidence	****	*Virtually Certain* 99% - 100%
∨	Decreasing overall	**MC**	Medium confidence	***	*Extremely Likely* 95% - 100%
∧∨	More regions increasing than decreasing	**LC**	Low confidence	**	*Very Likely* 90% - 100%
∧∨	More regions decreasing than increasing	×	Very low or no confidence	*	*Likely* 66% - 100%
~	Regionally varies or no clear trend	X	No assessment made		

Table 1-3: Examples of linkages between the SRREN and the AR5 WGII with chapter references in parentheses.

SRREN findings	**WGII-AR5 findings**
Water resources	
Water availability limits the development of water cooled thermal power and hydropower. Environmental issues will continue to affect hydropower opportunities. (5.1, 5.6, 9.3)	Climate change is predicted affect surface and groundwater supplies. Development of water-dependent energy resources can also affect freshwater ecosystems. (4.4, 19.3)
Ocean systems	
Most ocean energy technologies are at the conceptual phase. Potential technologies include submarine turbines for tidal currents, ocean thermal energy conversion, and devices that harness energy of waves and salinity gradients. (6.2, 6.3, 6.5)	Offshore renewable energy introduces additional drivers of change for near- and offshore coastal and marine ecosystems and species. Ocean geoengineering approaches may have large environmental footprints. (5.5, 6.4)
Land cover changes	
The sustainability of bioenergy (i.e. lifecycle GHG emissions) is influenced by land and biomass resource management practices. (2.2, 2,8, 9.3)	Land cover change associated with biofuel production has food security implications; related land use change can alter ecosystems, species, and carbon storage. (19.4, 19.4, 27.2)
Resilient pathways	
Higher energy prices associated with transitions from fossil fuels to biofuels and other renewable energy sources may have adverse effects on socio-economic development. (9.4, 10.5)	The challenge is to identify and implement mixes of technological options that reduce net carbon emissions and support sustained economic and social growth. (20.3)
Regional effects	
Latin America is second to Africa for technical potential in producing bioenergy from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands. (2.2)	Bioenergy production requires large areas with risk of environmental degradation and may involve strong economic teleconnections (e.g., Latin America). (27.2, 27.3)
The quantity of water resources availability in Central and South America is the largest in the world. The region has the largest proportion of electricity generated through hydropower facilities. (5.2)	Hydropower, the main source of renewable energy available in Central and South America, is prone to serious effects of climate change. Altered river flows affect development in this region and use of land for biofuel production (27.3, 27.6, 27.8)





D. Number of publications in five languages that include selected key words during the three time periods

Search words (translated)	Language	1981-1990	1991-2000	2001-2010
"climate change"	English	990	12,686	61,485
	Chinese	1,454	6,353	22,008
	French	1	108	815
	Russian	67	210	1,443
	Spanish	3	82	1,381
"climate change" and "impacts"	English	232	3,001	16,218
	Chinese	133	515	1,780
	French	0	1	95
	Russian	0	72	403
	Spanish	0	7	103
"climate change" and "adaptation"	English	14	373	3,661
	Chinese	6	58	321
	French	0	7	110
	Russian	0	7	44
	Spanish	0	5	103
"climate change" and "cost"	English	24	699	4,099
	Chinese	1	22	162
	French	0	7	36
	Russian	0	1	24
	Spanish	0	2	11

Figure 1-1: Number of climate-change publications listed in the Scopus bibliographic database and results of literature searches conducted in four other languages. (a) Number of publications in English (as of July, 2011) summed by country affiliation of all authors of climate change publications and binned into IPCC regions. Each publication can be counted multiple times (i.e., the number of different countries in the author affiliation list). (b Number of climate change publications in English with individual countries mentioned in title, abstract, or key words (as of July, 2011) binned into IPCC regions for the decades 1981-1990, 1991-2000, and 2001-2010. Each publication can be counted multiple times if more than one country is listed.) (c) Annual global number of publications in English on climate change and related topics: impacts, adaptation, and costs for the years 1970-2010, as of September 2013. (d) Number of publications in five languages that include the words "climate change" and "climate change" plus "adaptation", "impact", and "cost" (translated) in the title, abstract or key words during the three decades ending in 2010. The following individuals conducted these literature searches during January, 2012-March, 2013: Valentin Przyluski (French), Huang Huanping (Chinese), Peter Zavialov and Vasily Kokore (Russian), and Saúl Armendáriz Sánchez (Spanish).

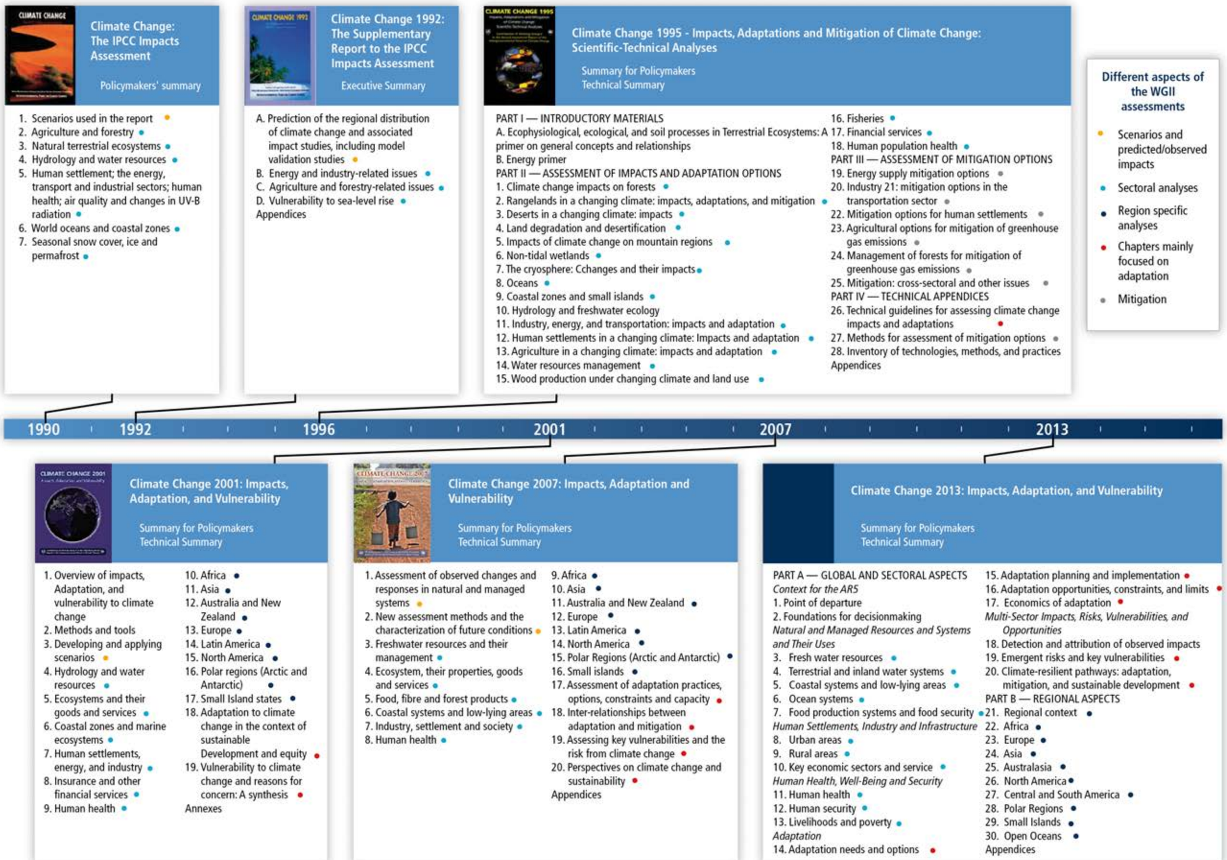


Figure 1-2: Tables of Contents for the Working Group II contributions to the IPCC Assessments since 1990. The FAR (IPCC, 1990) of IPCC Working Group II (WGII) focused on the impacts of climate change. For the SAR (IPCC, 1996) the WGII contribution included mitigation and adaptation with the impacts assessment. With the TAR (IPCC, 2001) and AR4 (IPCC, 2007) climate change mitigation reverted to WGIII, and WG II remained focused on impacts, adaptation, and vulnerability with an expanded effort on the regional scale.

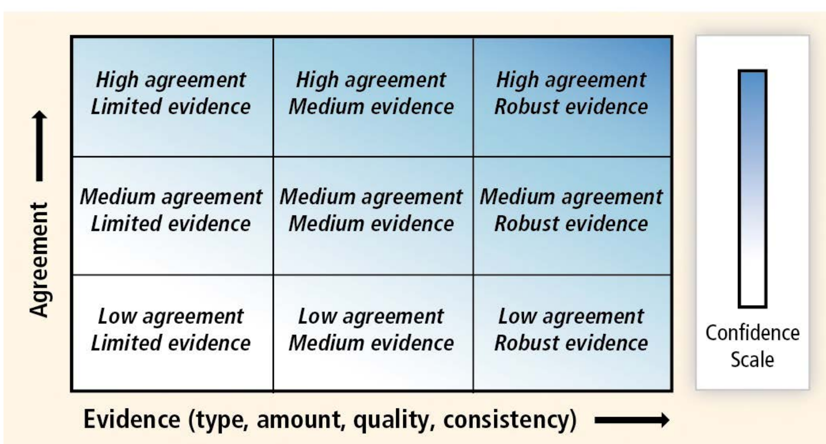


Figure 1-3: Evidence and agreement statements and their relationship to confidence. The coloring increasing towards the top-right corner indicates increasing confidence. Generally, evidence is most robust when there are multiple, consistent independent lines of high-quality evidence.

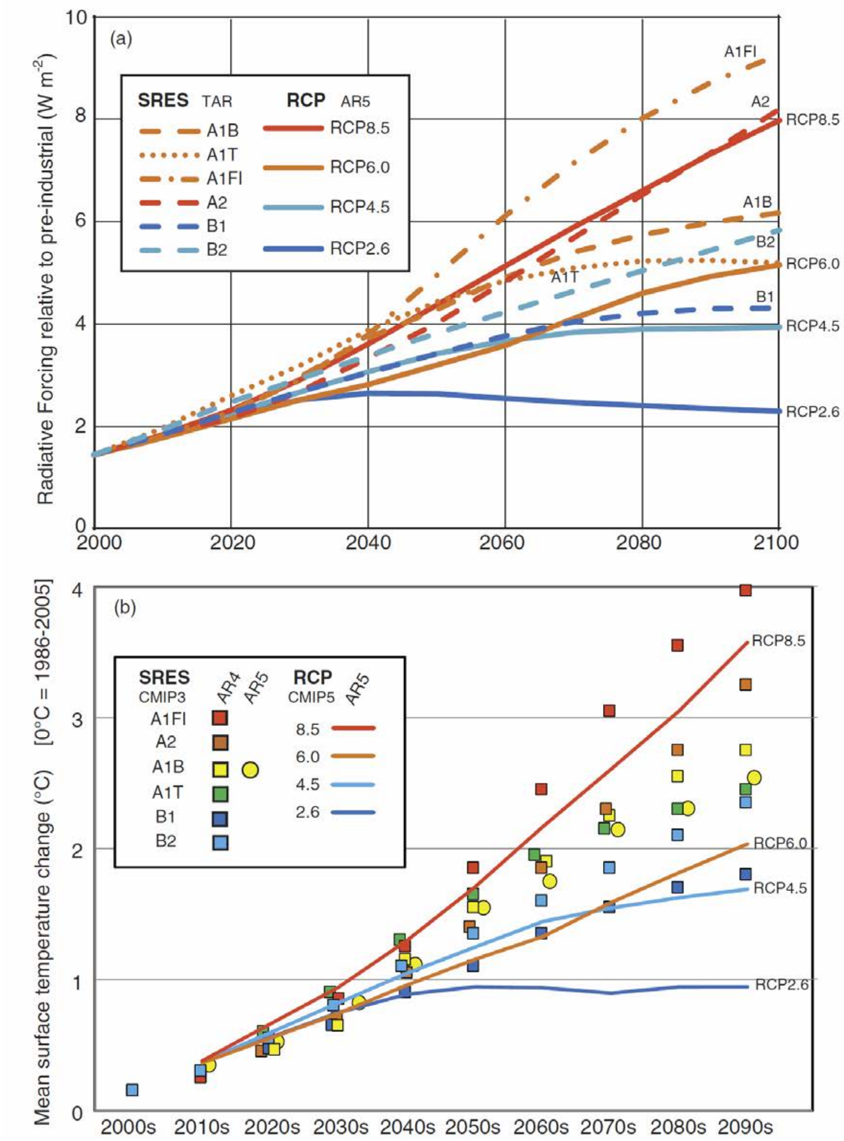


Figure 1-4: (a) Projected RF (W m^{-2}) and (b) global mean surface temperature change (°C) over the 21st century from the SRES and RCP scenarios. RF for the RCPs are taken from their published CO_2-equivalent (Meinshausen et al., 2011), and RF for SRES are from the TAR Appendix II (Table II.3.11). For RF derived from the CMIP5 models see WGI (Chapter 12.3, Tables AII.6.9-10). The ensemble total effective RF at 2100 for CMIP5 concentration-driven projections are 2.2, 3.8, 4.8 and 7.6 W m^{-2} for RCP2.6, RCP4.5, RCP6.0 and RCP8.5, respectively. The SRES RF are shifted upward by 0.12 W m^{-2} to match the RCPs at year 2000 since (i) the climate change over the 21st century is driven primarily by the changes in RF and (ii) the offset is due primarily to improvements in model physics including the aerosol RF. For more details and comparison with pre-SRES scenarios, see WGI Chapter 1 (Figure 1-15). Temperature changes are decadal averages (e.g., 2020s = 2016-2025) based on the model ensemble mean CMIP5 data for the RCPs (colored lines). The same analysis is applied to CMIP3 SRES A1B (yellow circles). See AR5 WGI Chapters 11, 12, Table AII.7.5. The colored squares show the temperature change for all six SRES scenarios based on a simple climate model tuned to the CMIP3 models (AR4 WG1 Figure 10.26). The difference between the yellow circles and yellow squares reflects differences between the simple model and analysis of the CMIP3 model ensemble in parallel with the CMIP5 data. For an assessment of uncertainties and *likely* ranges of temperature change see WGI Figures 11.24-25, 12.4-5, 12.40.
[Illustration to be redrawn to conform to IPCC publication specifications.]

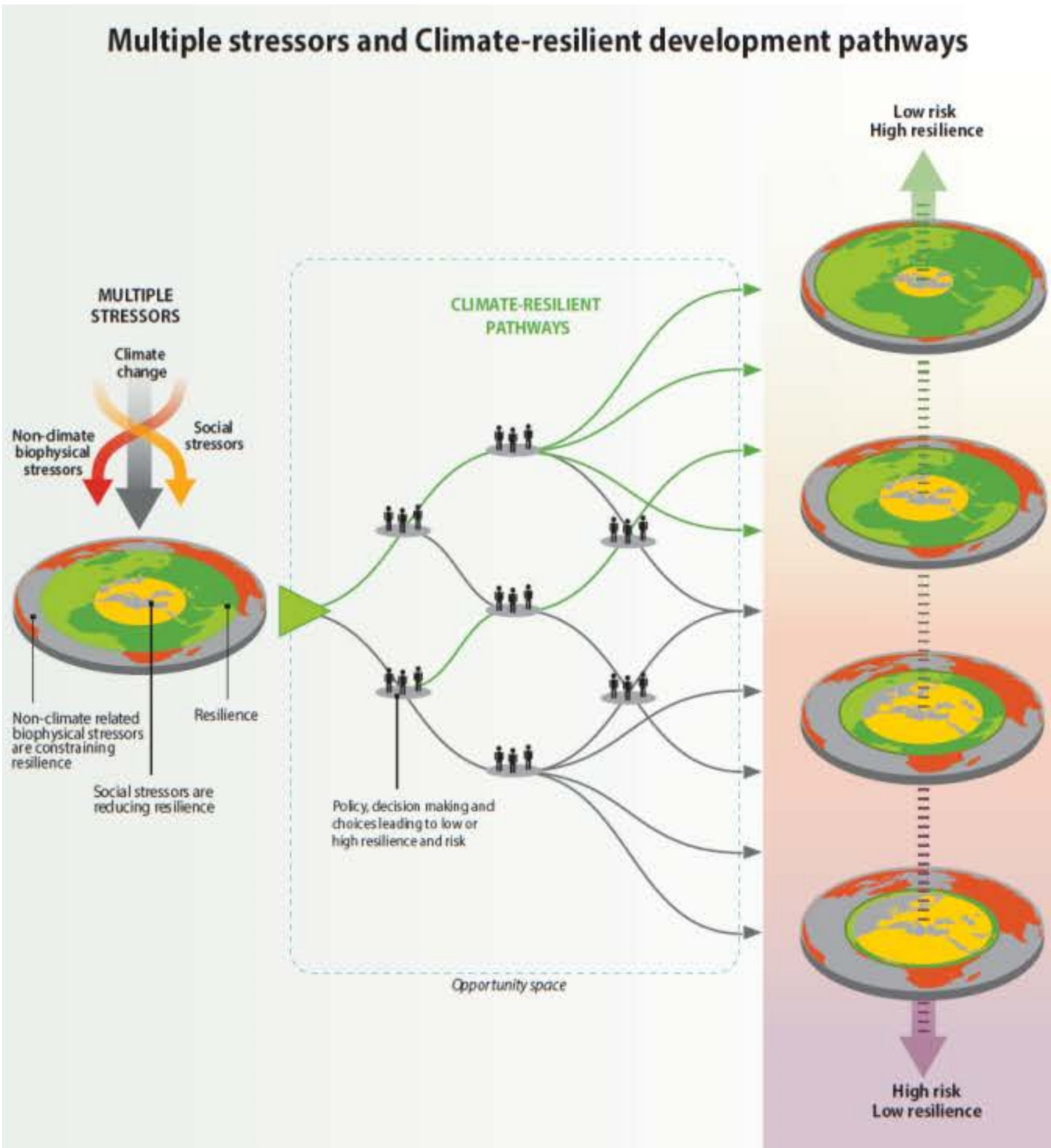


Figure 1-5: Multiple stressors and climate resilient pathways. The literature assessed in this report shows that climate change is just one of the many stressors that influence resilience. Climate-related risks interact with other biophysical stressors (such as biodiversity loss, soil erosion, and water contamination) and with social stressors (such as inequalities, poverty, gender discrimination, and lack of institutions). Rapid advances in knowledge about climate change and its impacts along with experience and other factors provide policy relevant information for decision making that can lead to climate-resilient development pathways. The decisions that societies make within this opportunity space can increase resilience and lower risks. Such decisions and choices are core elements of an iterative risk management process.
[Illustration to be redrawn to conform to IPCC publication specifications.]

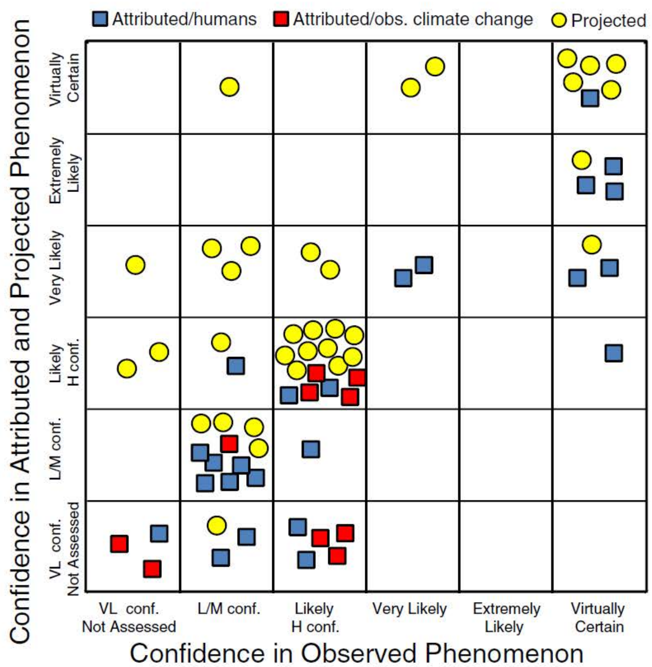


Figure 1-6: Confidence in the attributed (squares) and projected 21st century (yellow circles) changes in climate system phenomena plotted as a function of confidence in their detection to date. Phenomena and sources (AR4, SREX, AR5 WGI) are given in Table 1-2. Strength of confidence is sorted into the six bins as noted on the axes (very low confidence or not assessed; low or medium confidence; high confidence (no quantification) or likely; very likely; extremely likely; virtually certain). Attribution is to either human influence (blue squares, as used by WGI) or observed local/regional climate change (red squares, as used by WGII). Projections assume global warming exceeding 2°C. For AR5 WGII results see, *inter alia*, Chapters 18 and 19.
[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 2. Foundations for Decision Making

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Contents

Executive Summary

Decision support for impacts, adaptation and vulnerability is expanding from science-driven linear methods to a wide range of methods drawing from many disciplines *(high agreement, robust evidence)*. [2.1] This chapter introduces new material from disciplines including behavioural science, ethics and cultural and organizational theory, thus providing a broader perspective on climate change decision-making. Previous assessment methods and policy advice have been framed by the assumption that better science will lead to better decisions. [2.1.1] Extensive evidence from the decision sciences shows that while good scientific and technical information is necessary, it is not sufficient, and decisions require context-appropriate decision-support processes and tools *(high agreement, robust evidence)*. [2.1.2, 2.1.3, 2.2, 2.3] There now exists a sufficiently rich set of available methods, tools, and processes to support effective CCIAV decisions in a wide range of contexts *(medium agreement, medium evidence)*, although they may not always be appropriately combined or readily accessible to decision makers. [2.1.2, 2.1.3, 2.3]

Risk management provides a useful framework for most climate change decision making. [2.1.2] Iterative risk management is most suitable in situations characterised by large uncertainties, long time frames, the potential for learning over time, and the influence of both climate as well as other socio-economic and bio-physical changes *(high agreement, robust evidence)*. [2.1.2, 2.4.3] Complex decision-making contexts will ideally apply a broad definition of risk, address and manage relevant perceived risks, and assess the risks of a broad range of plausible future outcomes and alternative risk management actions *(medium agreement, robust evidence)*. [2.3] The resulting challenge is for people and organisations to apply CIAV decision-making processes in ways that address their specific aims. [2.2.1]

Decision support is situated at the intersection of data provision, expert knowledge and human decision-making at a range of scales from the individual to the organization and institution. Decision support is defined as a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use. [2.1.3, 2.2.1, 2.2, 2.3] Such support is most effective when it is context-sensitive, taking account of the diversity of different types of decisions, decision processes, and constituencies *(high agreement, robust evidence)*. [2.3.1, 2.3.3, 2.3.4] Boundary organizations, including climate services, play an important role in climate change knowledge transfer and communication, including translation, engagement and knowledge exchange *(high agreement, medium evidence)*. [2.2.2.1, 2.4.1, 2.4.2, 2.4.3]

Scenarios are a key tool for addressing uncertainty *(high agreement, robust evidence)*. They can be divided into those that explore how futures may unfold under various drivers (problem exploration) and those that test how various interventions may play out (solution exploration). [2.2.1.3][2.3.2] Historically, most scenarios used for CIAV assessments have been of the former type, though the latter are becoming more prevalent *(high agreement, medium evidence)*. The new RCP scenario process can address both problem and solution framing in ways that previous IPCC scenarios have not been able to *(medium agreement, limited evidence)*. [2.3.2]

CIAV decision making involves ethical judgments expressed at a range of institutional scales; the resulting ethical judgements are a key part of risk governance *(medium agreement, robust evidence)*. [2.2.1.1, 2.2.1.2, 2.2.1.4] Recognition of local and indigenous knowledge, and diverse stakeholder interests, values and expectations is fundamental to building trust within decision-making processes *(high agreement, robust evidence)* [2.2.1.2, 2.2.1.3, 2.4, 2.4.1].

Climate services aim to make knowledge about climate accessible to a wide range of decision makers. [2.4.1] In doing so they have to consider information supply, competing sources of knowledge and user demand. Knowledge transfer is a negotiated process that takes a variety of cultural values, orientations and alternative forms of knowledge into account *(high agreement, medium evidence)*. [2.4.1, 2.4.2]

Climate change response can be linked with sustainable development through actions that enhance resilience, the capacity to change in order to maintain the same identity while also maintaining the capacity to adapt, learn and transform. Mainstreamed adaptation, disaster risk management, and new types of governance and institutional arrangements are being studied for their potential to support the goal of enhanced resilience *(high agreement, medium evidence)*. [2.5.2]

Transformational adaptation may be required if incremental adaptation proves insufficient *(high agreement, medium evidence)*. This process may require changes in existing social structures, institutions, and values, which can be facilitated by iterative risk management and triple-loop learning that considers a situation and its drivers, along with the underlying frames and values that provide the situation context. **[2.1.2, 2.5.3]**

2.1. Introduction and Key Concepts

This chapter addresses the foundations of decision making with respect to climate impact, adaptation and vulnerability (CIAV). The Fourth Assessment Report (AR4) summarized methods for assessing CIAV (Carter et al., 2007), which we build on by surveying the broader literature relevant for decision making.

Decision making under climate change has largely been modelled on the scientific understanding of the cause-and-effect process whereby increasing greenhouse gas emissions cause climate change, resulting in changing impacts and risks, potentially increasing vulnerability to those risks. The resulting decision-making guidance on impacts and adaptation follows a rational-linear process that identifies potential risks then evaluates management responses (e.g., Carter et al., 1994; Feenstra et al., 1998; Parry and Carter, 1998; Fisher et al., 2007). This process has been challenged on the grounds that it does not adequately address the diverse contexts within which climate decisions are being made, often neglects existing decision-making processes, and overlooks many cultural and behavioural aspects of decision-making (Smit and Wandel, 2006; Sarewitz and Pielke Jr, 2007; Dovers, 2009; Beck, 2010). While more recent guidance on CIAV decision-making typically accounts for sectoral, regional and socio-economic characteristics (21.3), the broader decision-making literature is still not fully reflected in current methods. This is despite an increasing emphasis on the roles of societal impacts and responses to climate change in decision-making methodologies *(high confidence)* (1.1, 1.2, 21.2.1).

The main considerations that inform the decision-making contexts addressed here are knowledge generation and exchange, who makes and implements decisions, the issues being addressed and how these can be addressed. These decisions occur within a broader social and cultural environment. Knowledge generation and exchange includes knowledge generation, development, brokering, exchange and application to practice. Decision makers include policy-makers, managers, planners and practitioners, and range from individuals to organizations and institutions (Table 21-1). Relevant issues include all areas affected directly and indirectly by climate impacts or by responses to those impacts, covering diverse aspects of society and the environment. These issues include consideration of values, purpose, goals, available resources, the time over which actions are expected to remain effective and the extent to which the objectives being pursued are regarded as appropriate. The purpose of the decision in question; e.g., assessment, strategic planning or implementation, will also define the framework and tools needed to enable the process. This chapter does not provide any standard template or instructions for decision-making, nor does it endorse particular decisions over others.

The remainder of this chapter is organized as follows. Section 2.1.2 addresses risk management, which provides an overall framework suitable for CIAV decision-making; Section 2.1.3 introduces decision support, Section 2.2 discusses contexts for decision-making, Section 2.3 methods, tools and process, Section 2.4 support for and application of decision-making and Section 2.5 describes some of the broader contexts influencing CIAV decision making.

2.1.1. Decision-Making Approaches in this Report

The overarching theme of the chapter and the AR5 report is managing current and future climate risks (1.2.4, 16.2, 19.1), principally through adaptation (Chapters 14–17), but also through resilience and sustainable development informed by an understanding of both impacts and vulnerability (19.2). The International Standard ISO:31000 defines risk as *the effect of uncertainty on objectives* (ISO, 2009) and the Working Group II glossary defines risk as: *The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain* (Rosa, 2003). However, the glossary also refers to a more operational definition for assessing climate-related hazards: *risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.* Risk can also refer to an uncertain opportunity or benefit (see 2.2.1.3). This chapter takes a broader perspective than the latter by including risks associated with taking action (e.g., will this adaptation strategy be successful?) and the broader socially-constructed risks that surround 'climate change' (e.g., fatalism, hope, opportunity and despair).

Because all decisions on CIAV are affected by uncertainty and focus on valued objectives, all can be considered as decisions involving risk (e.g., Giddens, 2009)*(high confidence)*. AR4 endorsed iterative risk management as a suitable decision-support framework for CIAV assessment because it offers formalized methods for addressing uncertainty, involving stakeholder participation, identifying potential policy responses, and evaluation of those responses (Carter et al., 2007; IPCC, 2007a; Yohe et al., 2007). The literature shows significant advances on all these topics since AR4 (1.1.4), greatly expanding methodologies for assessing impacts, adaptation and vulnerability in a risk context (Agrawala and Fankhauser, 2008; Hinkel, 2011; Jones and Preston, 2011; Preston et al., 2011).

Many different risk methodologies, such as financial, natural disaster, infrastructure, environmental health and human health risk methodologies are relevant for CIAV decision-making *(very high confidence)*. Each methodology utilizes a variety of different tools and methods. For example, the standard CIAV methodology follows a top-down cause and effect pathway as outlined above. Others follow a bottom-up pathway, starting with a set of decision-making goals that may be unrelated to climate and consider how climate may affect those goals (see also 15.2.1, 15.3.1). Some methodologies such as vulnerability, resilience and livelihood assessments are often considered as being different from traditional risk assessment, but may be seen as dealing with particular stages within a longer term iterative risk management process. For example, developing resilience can be seen as managing a range of potential risks that are largely unpredictable; and sustainable development aims to develop a social-ecological system robust to climate risks.

A major aim of decision-making is to make good or better decisions. Good and better decisions with respect to climate adaptation are frequently mentioned in the literature but no universal criterion exists for a good decision, including a good climate-related decision (Moser and Ekstrom, 2010). This is reflected in the numerous framings linked to adaptation decision making, each having its advantages and disadvantages (Preston et al., 2013; 15.2.1). Extensive evidence from the decision sciences shows that good scientific and technical information alone is rarely sufficient to result in better decisions (Bell and Lederman, 2003; Jasanoff, 2010; Pidgeon and Fischhoff, 2011) *(high confidence)*. Aspects of decision-making that distinguish climate change from most other contexts are the long time scales involved, the pervasive impacts and resulting risks and the 'deep' uncertainties attached to many of those risks (Kandlikar et al., 2005; Ogden and Innes, 2009; Lempert and McKay, 2011). These uncertainties include not only future climate but also socio-economic change and potential changes in norms and values within and across generations.

2.1.2. Iterative Risk Management

Iterative risk management involves an ongoing process of assessment, action, reassessment, and response (Kambhu et al., 2007; IRGC, 2010) that will continue – in the case of many climate-related decisions – for decades if not longer (Committee on America's Climate Choices National Research Council, 2011). This development is consistent with an increasing focus on risk governance (Power, 2007; Renn, 2008), the integration of climate risks with other areas of risk management (Hellmuth et al., 2011; Measham et al., 2011) and a wide range of approaches for structured decision-making involving process uncertainty (Ohlson et al., 2005; Wilson and McDaniels, 2007; Ogden and Innes, 2009; Martin et al., 2011).

[INSERT FIGURE 2-1 HERE
Figure 2-1: Iterative risk management framework depicting the assessment process, and indicating multiple feedbacks within the system and extending to the overall context. Adapted from Willows and Connell (2003).]

Two levels of interaction can be recognised within the iterative risk management process: one internal and one external (Figure 2-1). External factors are present through the entire process and shape the process outcomes. The internal aspects describes the adaptation process itself. The first major internal iteration (in yellow) reflects the interplay with the analysis phase by addressing the interactions between evolving risks and their feedbacks (not shown) and during the development and choice of options. This process may also require a revision of criteria and objectives. This phase ends with decisions on the favoured options being made. A further internal iteration covers the implementation of actions and their monitoring and review (in orange). Throughout all stages the process is reflexive, in order to enable changes in knowledge, risks or circumstances to be identified and responded to. At the end of the implementation stage, all stages are evaluated and the process starts again with the scoping phase. Iterations can be successive, on a set timetable, triggered by specific criteria or informally by new information informing risk or a change in the policy environment. An important aspect of this process is to recognise emergent risks and respond to them (19.2.3–5, 19.3).

Complexity is an important attribute for framing and implementing decision-making processes *(very high confidence)*. Simple, well-bounded contexts involving cause and effect can be addressed by straightforward linear methods. Complicated contexts require greater attention to process but can generally be unravelled providing an ultimate solution (Figure 2-2). However, when complex environments interact with conflicting values they become associated with wicked problems. Wicked problems are not well bounded, are framed differently by various groups and individuals, harbour large scientific to existential uncertainties and have unclear solutions and pathways to those solutions (Rittel and Webber, 1973; Australian Public Service Commission, 2007). Such ‘deep uncertainty’ cannot easily be quantified (Dupuy and Grinbaum, 2005; Kandlikar et al., 2005). Another important attribute of complex systems is *reflexivity*, where cause and effect feed back into each other (see glossary). For example, actions taken to manage a risk will affect the outcomes, requiring iterative processes of decision-making *(very high confidence)*. Under climate change, calculated risks will also change with time as new knowledge becomes available (Ranger et al., 2010).

[INSERT FIGURE 2-2 HERE
Figure 2-2: Hierarchy of simple, complicated, and complex risks, showing how perceived risks multiply and become less connected with calculated risk with increasing complexity. Also shown are major characteristics of assessment methods for each level of complexity.]

In complex situations, socio-cultural and cognitive-behavioural contexts become central to decision-making. This requires combining the scientific understanding of risk with how risks are framed and perceived by individuals, organisations and institutions (Hansson, 2010). For that reason, formal risk assessment is moving from a largely technocratic exercise carried out by experts to a more participatory process of decision support (Fiorino, 1990; Pereira and Quintana, 2002; Renn, 2008), although this process is proceeding slowly (Christoplos et al., 2001; Pereira and Quintana, 2002; Bradbury, 2006; Mercer et al., 2008).

Different traditional and modern epistemologies, or 'ways of knowing' exist for risk (Hansson, 2004; Althaus, 2005; Hansson, 2010), vulnerability (Weichselgartner, 2001; O'Brien et al., 2007) and adaptation assessments (Adger et al., 2009) affecting the way they are framed by various disciplines and are also understood by the public (Garvin, 2001; Adger, 2006; Burch and Robinson, 2007). These differences have been identified as a source of widespread misunderstanding and disagreement. They are also used to warn against a uniform epistemic approach (Hulme, 2009; Beck, 2010), a critique that has been levelled against previous IPCC assessments (e.g., Hulme and Mahony, 2010).

The following three types of risk have been identified as important epistemological constructs (Thompson, 1986; Althaus, 2005; Jones, 2012):

1) Idealized risk: the conceptual framing of the problem at hand. For example, dangerous anthropogenic interference with the climate system is how climate change risk is idealized within the UNFCCC.
2) Calculated risk: the product of a model based on a mixture of historical (observed) and theoretical information. Frequentist or recurrent risks often utilize historical information whereas single-event risks may be unprecedented, requiring a more theoretical approach.
3) Perceived risk: the subjective judgement people make about an idealized risk (see also 19.6.1.4).

These different types show risk to be partly an objective threat of harm and partly a product of social and cultural experience (Kasperson et al., 1988; Kasperson, 1992; Rosa, 2008). The aim of calculating risk is to be as objective as possible, but the subjective nature of idealized and perceived risk reflects the division between positivist (imposed norms) and constructivist (derived norms) approaches to risk from the natural and social sciences respectively (Demeritt, 2001; Hansson, 2010). Idealized risk is important for framing and conceptualising risk and will often have formal and informal status in the assessment process, contributing to both calculated and perceived risk. These types of risk combine at the societal scale as socially constructed risk, described and assessed in a wide range of research literature such as psychology, anthropology, geography, ethics, sociology and political science (2.2.1.2, 19.6.1.4).

Acceptance of the science behind controversial risks is strongly influence by social and cultural values and beliefs (Leiserowitz, 2006; Kahan et al., 2007; Brewer and Pease, 2008). Risk perceptions can be amplified socially where events pertaining to hazards interact with psychological, social, institutional, and cultural processes in ways that heighten or attenuate individual and social perceptions of risk and shape risk behaviour (Kasperson et al., 1988; Renn et al., 1992; Pidgeon et al., 2003; Rosa, 2003; Renn, 2011). The media have an important role in propagating both calculated and perceived risk (Llasat et al., 2009), sometimes to detrimental effect (Boykoff and Boykoff, 2007; Oreskes and Conway, 2010; Woods et al., 2012).

Understanding how these perceptions resonate at an individual and collective level can help overcome constraints to action (Renn, 2011). Science is most suited to calculating risk in areas where it has predictive skill and will provide better estimates than may be obtained through more informal methods (Beck, 2000), but an assessment of what is at risk generally needs to be accepted by stakeholders (Richard Eiser et al., 2012). Therefore, the science always sits within a broader social setting (Jasanoff, 1996; Demeritt, 2001; Wynne, 2002; Demeritt, 2006), often requiring a systems approach where science and policy are investigated in tandem, rather than separately (Pahl-Wostl, 2007; Ison, 2010) *(very high confidence)*. These different types of risk give rise to complex interactions between formal and informal knowledge that cannot be bridged by better science or better predictions but require socially and culturally mediated processes of engagement *(high confidence)*.

2.1.3. Decision Support

The concept of *decision support* provides a useful framework for understanding how risk-based concepts and information can help enhance decision-making (McNie, 2007; National Research Council (US) Panel on Design Issues for the NOAA Sectoral Applications Research Program et al., 2007; Moser, 2009; Romsdahl and Pyke, 2009; Kandlikar et al., 2011; Pidgeon and Fischhoff, 2011) The concept also helps situate methods, tools, and processes intended to improve decision-making within appropriate institutional and cultural contexts.

Decision support is defined as "a set of processes intended to create the conditions for the production of decision-relevant information and its appropriate use" (National Academy of Sciences, 2009). Information is decision-relevant if it yields deeper understanding of, or is incorporated into making a choice that improves outcomes for decision makers and stakeholder or precipitates action to manage known risks. Effective decision support provides users with information they find useful because they consider it credible, legitimate, actionable, and salient (e.g., Jones et al., 1999; Cash et al., 2003; Mitchell, 2006; Reid et al., 2007). Such criteria can be used to evaluate decision support and such evaluations lead to common principles of effective decision support, which have been summarized in (National Research Council, 2009) as:

1) Begins with user's needs, not scientific research priorities. Users may not always know their needs in advance, so user needs are often developed collaboratively and iteratively among users and researchers.
2) Emphasizes processes over products. While the information products are important, they are likely to be ineffective if they are not developed to support well-considered processes.
3) Incorporates systems that link users and producers of information. These systems generally respect the differing cultures of decision makers and scientists, but provide processes and institutions that effectively link individuals from these differing communities
4) Builds connections across disciplines and organizations, in order to provide for the multidisciplinary character of the needed information and the differing communities and organizations in which this information resides
5) Seeks institutional stability, either through stable institutions and/or networks, which facilitates building the trust and familiarity needed for effective links and connections among information users and producers in many different organizations and communities.
6) Incorporates learning, so that all parties recognize the need for and contribute to the implementation of decision support activities structured for flexibility, adaptability, and learning from experience.

These principles can lead to different decision support processes depending on the stage and context of the decision in question. For instance, decision support for a large water management agency operating an integrated system serving millions of people will have different needs than a small town seeking to manage its ground water supplies. A community in the early stages of developing a response to climate change may be more focused on raising awareness of the issue among its constituents, while a community with a well-developed understanding of its risks may be more focused on assessing trade-offs and allocating resources.

2.2. Contexts for Decision-Making

This section surveys aspects of decision-making that relate to context setting. Social context addresses cultural values, psychology, language and ethics (2.2.1) and institutional context covers institutions and governance (2.2.2).

2.2.1. Social Context

Decision support for CIAV must recognize that diverse values, language uses, ethics and human psychological dimensions play a crucial role in the way that people use and process information and take decisions (Kahan and Braman, 2006; Leiserowitz, 2006). As illustrated in Figure 2-1, the context defines and frames the space in which decision-making processes operate.

2.2.1.1. Cultural Values and Determinants

Cultural differences allocate values and guide socially mediated change. Five value dimensions that show significant cross-national variations are: power distance, individualism/collectivism, uncertainty avoidance, long/short term orientation and masculinity/femininity (Hofstede, 1980; Hofstede and Hofstede, 2001; Hofstede et al., 2010). Power distance and individualism/collectivism both show a link to climate via latitude; the former relates to willingness to conform to top-down directives, whereas the latter relates to the potential efficacy of market/community-based strategies. Uncertainty avoidance and long-term orientation show considerable variation between countries (Hofstede et al., 2010) potentially producing significant differences in risk perception and agency.

Environmental values have also been linked to cultural orientation. Schultz et al. (2004) identified the association between self and nature in people as being implicit – informing actions without specific awareness. A strong association was linked to a more connected self and a weaker association with a more egoistic self. Explicit environmental values can substantially influence climate change-related decision-making processes (Nilsson et al., 2004; Milfont and Gouveia, 2006; Soyez et al., 2009) and public behaviour toward policies (Stern and Dietz, 1994; Xiao and Dunlap, 2007). Schaffrin (2011) concludes that geographical aspects, vulnerability and potential policy benefits associated with a given issue can influence individual perceptions and willingness to act (De Groot and Steg, 2007, 2008; Shwom et al., 2008; Milfont et al., 2010). Cultural values can interrelate with specific physical situations of climate change (Corraliza and Berenguer, 2000), or seasonal and meteorological factors influencing people's implicit connections with nature (Duffy and Verges, 2010). Religious and sacred values are also important (Goloubinoff et al., 1998; Katz et al., 2002; Lammel et al., 2008), informing the perception of climate change and risk, as well as the actions to adapt (Crate and Nuttal, 2009; 16.3.1.3). The role of protected values (values that people will not trade off, or negotiate) can also be culturally and spiritually significant (Baron and Spranca, 1997; Baron et al., 2009; Hagerman et al., 2010). Adger et al. (2013) emphasise the importance of cultural values in assessing risks and adaptation options, suggesting they are at least as important as economic values in many cases, if not more so. These aspects are important for framing and conceptualizing CIAV decision-making. Cultural and social barriers are described in Chapter 16.3.2.7.

Two distinct ways of thinking – holistic and analytical thinking – reflect the relationship between humans and nature and are cross-culturally and even intra-culturally diverse (Gagnon Thompson and Barton, 1994; Huber and Pedersen, 1997; Atran et al., 2005; Ignatow, 2006; Descola, 2010; Ingold, 2011). Holistic thinking is primarily gained through experience and is dialectical, accepting contradictions and integrating multiple perspectives. Characteristic of collectivist societies, the holistic conceptual model considers that social obligations are reciprocal and individuals take an active part in the community for the benefit of all (Peng and Nisbett, 1999; Nisbett et al., 2001; Lammel and Kozakai, 2005; Nisbett and Miyamoto, 2005). Analytical thinking isolates the object from its broader context, understanding its characteristics through categorization, and predicting events based on intrinsic rules. In the analytic conceptual model, individual interests take precedence over the collective; the self is independent and communication comes from separate fields. These differences influence the understanding of complex systemic phenomena such as climate change (Lammel et al., 2011; Lammel et al., 2012; Lammel et al., 2013) and decision making practices (Badke-Schaub and Strohschneider, 1998; Strohschneider and Güss, 1999; Güss et al., 2010).

The above models vary greatly across the cultural landscape, but neither model alone is sufficient for decision making in complex situations *(high confidence)*. At a very basic level, egalitarian societies may respond more to community based adaptation in contrast to more individualistic societies that respond to market-based forces *(medium confidence)*. In small-scale societies, knowledge about climate risks are often integrated into a holistic view of community and environment (e.g., Katz et al., 2002; Strauss and Orlove, 2003; Lammel et al., 2008). Many studies highlight the importance of integrating local, traditional knowledge with scientific knowledge when assessing CIAV (Magistro and Roncoli, 2001; Krupnik and Jolly, 2002; Vedwan, 2006; Nyong et al., 2007; Dube and Sekhwela, 2008; Crate and Nuttal, 2009; Mercer et al., 2009; Roncoli et al., 2009; Green and Raygorodetsky, 2010; Orlove et al., 2010; Crate, 2011; Nakashima et al., 2012; Chapter 12.3, 12.3.1, 12.3.2, 12.3.3, 12.3.4, 14.4.5, 14.4.7, 15.3.2.7, 25.8.2, 28.2.6.1, 28.4.1). For example, a case study in Labrador (Canada) demonstrated the need to account for local material and symbolic values because they shape the relationship to the land, underlie the way of life, influence the intangible effects of climate change, and can lead to diverging views on adaptations (Wolf et al., 2012). In Kiribati, the integration of local cultural values attached to resources/assets is fundamental to adaptation planning and water management, otherwise technology will not be properly utilised (Kuruppu, 2009).

2.2.1.2. Psychology

Psychology plays a significant role in climate change decision-making (Gifford, 2008; Swim et al., 2010; Anderson, 2011). Important psychological factors for decision-making include: perception, representation, knowledge acquisition, memory, behaviour, emotions and understanding of risk (Böhm and Pfister, 2000; Leiserowitz, 2006; Lorenzoni et al., 2006; Oskamp and Schultz, 2006; Sterman and Sweeney, 2007; Gifford, 2008; Kazdin, 2009; Sundblad et al., 2009; Reser et al., 2011; Swim et al., 2011).

Psychological research contributes to understanding on both risk perception and the process of adaptation. Several theories, such as multi-attribute utility theory (Keeney, 1992), prospect theory (Kahneman and Tversky, 1979; Hardman, 2009), and cumulative prospect theory relate to decision making under uncertainty (Tversky and Kahneman, 1992), especially to risk perception and agency. Adaptation in complex situations pits an unsure gain against an unsure loss, so creates an asymmetry in preference that magnifies with time as gains/losses are expected to accrue in future. Decisions focusing on values and uncertainty are therefore subject to framing effects. Recent cognitive approaches include the one-reason decision process that uses limited data in a limited time period (Gigerenzer and Goldstein, 1996) or decision by sampling theory that samples real-world data to account for the cognitive biases observed in behavioural economics (Stewart et al., 2006; Stewart and Simpson, 2008). Risk perception is further discussed in Chapter 19.6.1.4.

Responses to new information can modify previous decisions, even producing contradictory results (Grothmann and Patt, 2005; Marx et al., 2007). Although knowledge about climate change is necessary (Milfont, 2012), understanding such knowledge can be difficult (Rajeev Gowda et al., 1997; Boyes et al., 1999; Andersson and Wallin, 2000). Cognitive obstacles in processing climate change information include psychological distances with four theorized dimensions: temporal, geographical, social distance and uncertainty (Spence et al., 2012, see also 25.4.3). Emotional factors also play an important role in climate change perception, attitudes, decision making and actions (Meijnders et al., 2002; Leiserowitz, 2006; Klöckner and Blöbaum, 2010; Fischer and Glenk 2011; Roeser, 2012) and even shape organizational decision making (Wright and Nyberg, 2012). Other studies on attitudes and behaviours relevant to climate change decision-making, include place attachment (Scannell and Gifford, 2013; chapter 25.4.3), political affiliation (Davidson and Haan, 2011), and perceived costs and benefits (Tobler et al., 2012). Time is a critical component of action-based decision making (Steel and König, 2006). As the benefits of many climate change actions span multiple temporal scales, this can create a barrier to effective motivation for decisions through a perceived lack of value associated with long term outcomes.

Protection Motivation Theory (Rogers, 1975; Maddux and Rogers, 1983), which proposes that a higher personal perceived risk will lead to a higher motivation to adapt, can be applied to climate change-related problems (e.g., Grothmann and Reusswig, 2006; Cismaru et al., 2011). The Person-relative-to-event approach predicts human coping strategies as a function of the magnitude of environmental threat (Mulilis and Duval, 1995; Duval and Mulilis, 1999; Grothmann et al., 2013). People’s responses to environmental hazards and disasters are represented in the multistage Protective Action Decision Model (Lindell and Perry, 2012). This model helps decision makers to respond to long-term threat and apply it in long-term risk management. Grothmann and Patt (2005) developed and tested a socio-cognitive model of proactive private adaptation to climate change showing that perceptions of adaptive capacities were important as well as perceptions of risk. If a perceived high risk is combined with a perceived low adaptive capacity (see 2.4.2.2; Glossary), the response is fatalism, denial and wishful thinking.

Best-practice methods for incorporating and communicating information about risk and uncertainties into decisions about climate change (Climate Change Science Program, 2009; Pidgeon and Fischhoff, 2011) suggests that effective communication of uncertainty requires products and processes that: i) closes psychological distance, explaining why this information is important to the recipient; ii) distinguishes between and explains different types of uncertainty; iii) establishes self-agency, explaining what the recipient can do with the information and ways to make decisions under uncertainty (e.g., precautionary principle, iterative risk-management); iv) recognizes that each person's view of risks and opportunities depends on their values; v) recognizes that emotion is a critical part of judgment; vi) provides mental models that help recipients to understand the connection between cause and effect. Information providers also need to test their messages, since they may not be communicating what they think they are.

2.2.1.3. Language and Meaning

Aspects of decision-making concerned with language and meaning include framing, communication, learning, knowledge exchange, dialogue and discussion. Most IPCC-related literature on language and communication deals with definitions, predictability and incomplete knowledge, with less emphasis given to other aspects of decision-support such as learning, ambiguity, contestedness and complexity. Three important areas assessed here are definitions, risk language and communication, and narratives.

Decision-making processes need to accommodate both specialist and non-specialist meanings of the concepts they apply. Various disciplines often have different definitions for the same terms or use different terms for the same action or object, which is a major barrier for communication and decision-making (Adger, 2003; Chapter 21). For example, adaptation is defined differently with respect to biological evolution, climate change and social adaptation. Budescu et al. (2012) found that people prefer imprecise wording but precise numbers when appropriate. Personal lexicons vary widely, leading to differing interpretations of uncertainty terms (Morgan et al., 1990); in the IPCC's case leading to uncertainty ranges often being interpreted differently than intended (Patt and Schrag, 2003; Patt and Dessai, 2005; Budescu et al., 2012). Addressing both technical and everyday meanings of key terms can help bridge the analytic and emotive aspects of cognition. For example, words like danger, disaster, uncertainty and catastrophe have technical and emotive aspects (Britton, 1986; Carvalho and Burgess, 2005). Terms where this issue is especially pertinent include adaptation, vulnerability, risk, dangerous, catastrophe, resilience and disaster. Other words have definitional issues because they contain different epistemological frames; sustainability and risk being key examples (Harding, 2006; Hamilton et al., 2007). Many authors advocate that narrow definitions focused solely on climate need to be expanded to suit the context in which they are being used (Huq and Reid, 2004; O'Brien et al., 2007; Schipper, 2007). This is a key role for risk communication, ensuring that different types of knowledge are integrated within decision context and outlining the different values – implicit and explicit – involved in the decision process (e.g., Morgan, 2002; Lundgren and McMakin, 2013).

The language of risk has a crucial role in framing and belief. Section 2.1.2 described over-arching and climate-specific definitions but risk enters into almost every aspect of social discourse, so is relevant to how risk is framed and communicated (e.g., Hansson, 2004). Meanings of risk range from its ordinary use in everyday language to power and political discourse, health, emergency, disaster and seeking benefits, ranging from specific local meanings to broad-ranging concepts such as the risk society (Beck and Ritter, 1992; Beck, 2000; Giddens, 2000). Complex framings in the word risk (Fillmore and Atkins, 1992; Hamilton et al., 2007) feature in general English as both a noun and a verb, reflecting harm and chance with negative and positive senses (Fillmore and Atkins, 1992). Problem analysis applies risk as a noun (at-risk), whereas risk management applies risk as a verb (to-risk) (Jones, 2011). For simple risks, this transition is straightforward because of agreement around values and agency (Figure 2-2). In complex situations, risk as a problem and as an opportunity can compete with each other, and if socially amplified can lead to action paralysis (Renn, 2011). For example, unfamiliar adaptation options that seem to be risky themselves will force a comparison between the risk of maladaptation and future climate risks, echoing the risk trap where problems and solutions come into conflict (Beck, 2000). Fear-based dialogues in certain circumstances can cause disengagement (O'Neill and Nicholson-Cole, 2009), by emphasising risk aversion. Young (2013) proposes framing adaptation as a solution to overcome the limitations of framing through the problem, and links it to innovation, which provides established pathways for the implementation of actions, proposing a problem-solution framework linking decision-making to action. Framing decisions and modelling actions on positive risk-seeking behaviour can help people to address uncertainty as opportunity (e.g., Keeney, 1992).

Narratives are accounts of events with temporal or causal coherence that may be goal directed (László and Ehmann, 2012) and play a key role in communication, learning and understanding. They operate at the personal to societal scales, are key determinants of framing and have a strong role in creating social legitimacy. Narratives can also be non-verbal: visualization, kinetic learning by doing and other sensory applications can be used to communicate science and art, and to enable learning through play (Perlovsky, 2009; Radford, 2009). Narratives of climate change have evolved over time and invariably represent uncertainty and risk (Hamblyn, 2009) being characterised as tools for analysis, communication and engagement (Cohen, 2011; Jones et al., 2013; Westerhoff and Robinson, 2013) by:

1) Providing a social and environmental context to modelled futures (Arnell et al., 2004; Kriegler et al., 2012; O'Neill et al., 2013), by describing aspects of change that drive or shape those futures as part of scenario construction (Cork et al., 2012).
2) Communicating knowledge and ideas to increase understanding and increase agency framing it in ways so that actions can be implemented (Juhola et al., 2011) or provide a broader socio-ecological context to specific knowledge (Burley et al., 2012). These narratives bridge the route between scientific knowledge and local understandings of adaptation, often by working with multiple actors in order to creatively explore and develop collaborative potential solutions (Turner and Clifton, 2009; Paton and Fairbairn-Dunlop, 2010; Tschakert and Dietrich, 2010).
3) Exploring responses at an individual/institutional level to an aspect of adaptation, and communicate that experience with others. (Bravo, 2009; Cohen, 2011). For example, a community that believes itself to be resilient and self-reliant is more likely to respond proactively, contrasted to a community that believes itself to be vulnerable (Farbotko and Lazrus, 2012). Bravo (2009) maintains that narratives of catastrophic risk and vulnerability demotivate indigenous peoples whereas narratives combining scientific knowledge and active citizenship promote resilience (2.5.2).

2.2.1.4. Ethics

Climate ethics can be used to formalize objectives, values (2.2.1.1), rights and needs into decisions, decision-making processes and actions (see also 16.7). Principal ethical concerns include: intergenerational equity; distributional issues; the role of uncertainty in allocating fairness or equity; economic and policy decisions; international justice and law; voluntary and involuntary levels of risk; cross-cultural relations; and human relationships with nature, technology and the socio-cultural world. Climate change ethics have been developing over the last 20 years (Jamieson, 1992, 1996; Gardiner, 2004; Gardiner et al., 2010), resulting in a substantial literature (Garvey, 2008; Harris, 2010; O'Brien et al., 2010; Arnold, 2011; Brown, 2012; Thompson and Bendik-Keymer, 2012). Equity, inequity and responsibility are fundamental concepts in the United Nations Framework Convention on Climate Change (United Nations, 1992) and therefore are important considerations in policy development for CIAV. Climate ethics examine effective responsible and 'moral' decision-making and action, not only by governments but also by individuals (Garvey, 2008).

An important discourse on equity is that industrialized countries have, through their historical emissions, created a natural debt (Green and Smith, 2002). Developing nations experience this debt through higher impacts and greater vulnerability combined with limited adaptive capacity. Regional inequity is also of concern (Green and Smith, 2002), particularly indigenous or marginalized populations exposed to current climate extremes, who may become more vulnerable under a changing climate (Tsosie, 2007; 12.3.3). With respect to adaptation assessment, cost-benefit or cost effectiveness methods combined with transfer of funds will not satisfy equity considerations (Broome, 2008; 17.3.1.4) and modifications such as equity weighting (Kuik et al., 2008) and cost-benefit under uncertainty (17.3.2.1), have not been widely used. Adaptation measures need to be evaluated by considering their equity implications (17.3.1.4) especially under uncertainty (Hansson, 2004).

Intergenerational issues are frequently treated as an economic problem, with efforts to address them through an ethical framework proving to be controversial (Nordhaus, 2007; Stern and Treasury of Great Britain, 2007; Stern, 2008). However, future harm may make the lives of future generations difficult or impossible, dilemmas that involve ethical choices (Broome, 2008), therefore discount rates matter (17.4.4.4). Some authors question whether the rights and interests of future people should even be subject to a positive discount rate Caney (2009). Future generations cannot defend themselves within current economic frameworks (Gardiner, 2011) nor can these frameworks properly account for the dangers, interdependency and uncertainty under climate change (Nelson, 2011), even though peoples' values may change over time (16.7). The limits to adaptation raise questions of irreversible loss and the loss of unique cultural values that cannot necessarily be easily transferred (16.7), contributing to key vulnerabilities and informing ethical issues facing mitigation (see 19.7.1).

Environmental ethics considers the decisions humans may make concerning a range of biotic impacts (Schalow, 2000; Minteer and Collins, 2010; Nanda, 2012; Thompson and Bendik-Keymer, 2012). Intervention in natural systems through 'assisted colonization' or 'managed relocation' raises important ethical and policy questions (Minteer and Collins, 2010)(4.4.2.4) that include the risk of unintended consequences (4.4.4). Various claims are made for a more pragmatic ethics of ecological decision-making (Minteer and Collins, 2010), consideration of moral duties toward species (Sandler, 2009) and ethically explicit and defendable decision-making (Minteer and Collins, 2005b, a).

Cosmopolitan ethics and global justice can lead to successful adaptation and sustainability (Caney, 2006; Harris, 2010) and support collective decision-making on public matters through voting procedures (Held, 2004). Ethics also concerns the conduct and application of research, especially research involving stakeholders. Action-based and participatory research requires that a range of ethical guidelines be followed, taking consideration of the rights of stakeholders, respect for cultural and practical knowledge, confidentiality, dissemination of results and development of intellectual property (Macaulay et al., 1999; Kindon et al., 2007; Daniell et al., 2009; Pearce et al., 2009). Ethical agreements and processes are an essential part of participatory research, whether taking part as behavioural change processes promoting adaptation or projects of collaborative discovery *(High confidence)*. Although the climate change ethics literature is rapidly developing, the related practice of decision-making and implementation needs further development. Ethical and equity issues are discussed in WG III, Chapter 3 *Social, Economic, and Ethical Concepts and Methods*.

2.2.2. Institutional Context

2.2.2.1. Institutions

Institutions are rules and norms held in common by social actors that guide, constrain, and shape human interaction (North, 1990; Glossary). Institutions can be formal, such as laws and policies, or informal, such as norms and conventions. Organizations – such as parliaments, regulatory agencies, private firms, and community bodies – develop and act in response to institutional frameworks and the incentives they frame (Young et al., 2008). Institutions can guide, constrain, and shape human interaction through direct control, through incentives, and through processes of socialization (Glossary). Virtually all CIAV decisions will be made by or influenced by institutions because they shape the choices made by both individuals and organizations (Bedsworth and Hanak, 2012). Institutional linkages are important for adaptation in complex and multi-layered social and biophysical systems such as coastal areas (5.5.3.2) and urban systems (8.4.3.4), and are vital in managing health (11.6), human security (12.5.1, 12.6.2) and poverty (13.1). Institutional development and interconnectedness are vital in mediating vulnerability in social-ecological systems to changing climate risks, especially extremes (Chapters 5, 7–9, 11–13).

The role of institutions as actors in adaptation are discussed in Chapter 14.4, in planning and implementing adaptation in Chapter 15.5 and in providing barriers and opportunities in Chapter 16.3. Their roles can be very diverse. Local institutions usually play important roles in accessing resources and in structuring individual and collective responses (Agarwal, 2010; 14.4.2) but Madzwamuse (2010) found that in Africa, state level actors had significantly more influence on formal adaptation policies than did civil society and local communities. This suggests a need for greater integration and cooperation among institutions of all levels (15.5.1.2). Chapter 14 identifies four institutional design issues: flexibility; potential for integration into existing policy plans and programs; communication, coordination and cooperation; and the ability to engage with multiple stakeholders (14.2.3).

Institutions are instrumental in facilitating adaptive capacity, by utilising characteristics such as variety, learning capacity, room for autonomous change, leadership, availability of resources and fair governance (Gupta et al., 2008). They play a key role in mediating the transformation of coping capacity into adaptive capacity and in linking short and long-term responses to climate change and variability (Berman et al., 2012). Most developing countries have weaker institutions that are less capable of managing extreme events, increasing vulnerability to disasters (Lateef, 2009; Biesbroek et al., 2013). Countries with strong functional institutions are generally assumed to have a greater capacity to adapt to current and future disasters. However, Hurricane Katrina of 2005 in the USA and the European heat wave of 2003 demonstrate that strong institutions and other determinants of adaptive capacity do not necessarily reduce vulnerability if the mechanisms are not translated to actions (IPCC, 2007b; Box 2-1, 2.4.2.2).

To facilitate adaptation under uncertainty, institutions need to be flexible enough to accommodate adaptive management processes such as evaluation, learning and refinement (Agarwal, 2010; Gupta et al., 2010; 14.2.3). Organizational learning can lead to significant change in organizations' purpose and function (Bartley, 2007), for example where non-governmental organizations have moved from advocacy to program delivery with local stakeholders (Ziervogel and Zermoglio, 2009; Kolk and Pinkse, 2010; Worthington and Pipa, 2010).

Boundary organisations are increasingly being recognised as important to CIAV decision support (Guston, 2001; Cash et al., 2003; McNie, 2007; Vogel et al., 2007). A boundary organization is a bridging institution, social arrangement, or network that acts as an intermediary between science and policy (Glossary). Its functions include facilitating communication between researchers and stakeholders, translating science and technical information, and mediating between different views of how to interpret that information. It will also recognize the importance of location-specific contexts (Ruttan et al., 1994), provide a forum in which information can be co-created by interested parties (Cash et al., 2003), and develop boundary objects, such as scenarios, narratives and model-based decision support systems (White et al., 2010). Adaptive and inclusive management practices are considered to be essential, particularly in addressing wicked problems such as climate change (Batie, 2008). Boundary organisations also link adaptation to other processes managing global change and sustainable development.

Boundary organizations already contributing to regional CIAV assessments include in the US, the Great Lakes Integrated Sciences and Assessments Center – GLISA (GLISA web site: http://www.glisa.umich.edu/), part of the Regional Integrated Sciences and Assessment s (RISA) Program of the US Government (Pulwarty et al., 2009), the UK Climate Impacts Program – UKCIP (UK Climate Impacts Program, 2011), the Alliance for Global Water Adaptation – AGWA (AGWA web site: http://alliance4water.org) and institutions working on water issues in the U.S., Mexico and Brazil (Kirchhoff et al., 2012; Varady et al., 2012).

2.2.2.2. Governance

Effective climate change governance is important for both adaptation and mitigation and is increasingly being seen as a key element of risk management *(high confidence)* (Renn, 2008; Renn et al., 2011). Some analysts propose that governance of adaptation requires knowledge of anticipated regional and local impacts of climate change in a more traditional planning approach (e.g., Meadowcroft, 2009), whereas others propose governance consistent with sustainable development and resilient systems (Adger, 2006; Nelson et al., 2007; Meuleman and in 't Veld, 2010). Quay (2010) proposes 'anticipatory governance'- a flexible decision framework based on robustness and learning (2.3.3, 2.3.4). Institutional decisions about climate adaptation are taking place within a multi-level governance system (Rosenau, 2005; Kern et al., 2008). Multi-level governance could be a barrier for successful adaptation if there is insufficient coordination as it is comprised of different regulatory, legal and institutional systems (16.3.1.4), but is required to manage the 'adaptation paradox' (Local solutions to a global problem), unclear ownership of risks and the adaptation bottleneck linked to difficulties with implementation (14.5.3). Lack of horizontal and vertical integration between organizations and policies leads to insufficient risk governance in complex social-ecological systems such as coasts (5.5.3.2) and urban areas (8.4), including in the management of compound risks (19.3.2.4).

Legal and regulatory frameworks are important institutional components of overall governance, but will be challenged by the pervasive nature of climate risks *(high confidence)*(Craig, 2010; Ruhl, 2010a, b). Changes proposed to better manage these risk under uncertainty include integration between different areas of law, jurisdictions and scale, changes to property rights, greater flexibility with respect to adaptive management and a focus on ecological processes rather than preservation (Craig, 2010; Ruhl, 2010a; Abel et al., 2011; Macintosh et al., 2013). With respect to human security, this report does not see them as an issue of rights alone, given that a minimum set of universal rights exists but they are not always exercised (Box 12-1) but instead investigates a wide range of forces. Internationally, sea level rise could alter the maritime boundaries of many nations that may lead to new claims by affected nations or loss of sovereignty (Barnett and Adger, 2003). New shipping routes, such as the North West Passage, will be opened up by losses in Arctic sea ice (6.4.1.6, 28.2.6). Many national and international legal institutions and instruments need to be updated to face climate related challenges and decision implementation *(medium confidence)* (Verschuuren, 2013).

2.3. Methods, Tools, and Processes for Climate-Related Decisions

This section deals with methods, tools and processes that deal with uncertainties (2.3.1), describe scenarios (2.3.2), cover trade-offs and multi-metric valuation (2.3.3) and learning review and reframing (2.3.4).

2.3.1. Treatment of Uncertainties

Most advice on uncertainty, including the latest guidance from the IPCC (Mastrandrea et al., 2010; 1.1.2.2), deals with uncertainty in scientific findings and to a lesser extent confidence. While this is important, uncertainty can invade all aspects of decision making, especially in complex situations. Whether embodied in formal analyses or in the training and habits of decision makers, applied management is often needed because unaided human reasoning can produce mismatches between actions and goals (Kahneman, 2011). A useful high-level distinction is between ontological uncertainty – what we know – and epistemological uncertainty – how different areas of knowledge and 'knowing' combine in decision making (van Asselt and Rotmans, 2002; Walker et al., 2003). Two other areas of relevance are ambiguity (Brugnach et al., 2008) and contestedness (Klinke and Renn, 2002; Dewulf et al., 2005), commonly encountered in wicked problems/systemic risks (Renn and Klinke, 2004; Renn et al., 2011).

Much of this uncertainty can be managed through framing and decision-processes. For example, a predict-then-act framing is different to an assess-risk-of-policy framing (IPCC SREX 6.3.1 and Fig 6.2; Lempert et al., 2004). In the former, also known as 'top-down'; model or impacts-first; science-first; or standard approach, climate or impact uncertainty is described independently of other parts of the decision problem. For instance, probabilistic climate projections (see Chapter 21, Fig. 21-4 or IPCC WG1 Chapters 11 and 12; Murphy et al., 2009) are generated for wide application, thus are not tied to any specific choice. This follows the cause and effect model described in Section 2.1. The basic structure of IPCC Assessment Reports follows this pattern, with WGI laying out what is known and uncertain about current and future changes to the climate system. Working Groups II and III then describe impacts resulting from and potential policy responses to those changes (Jones and Preston, 2011).

In contrast, the 'assess-risk-of-policy' framing (Lempert et al., 2004; UNDP, 2005; Carter et al., 2007; Dessai and Hulme, 2007) starts with the decision-making context. This framing is also known as 'context-first' (Ranger et al., 2010), 'decision scaling' (Brown et al., 2011), 'bottom-up'; vulnerability, tipping point (Kwadijk et al., 2010), critical threshold (Jones, 2001), or policy-first approaches (IPCC SREX 6.3.1). In engaging with decision-makers, the 'assess-risk-of-policy' approach often requires that information providers work closely with decision makers to understand their plans and goals, before customizing the uncertainty description to focus on those key factors. This can be very effective, but often needs to be individually customized for each decision context (Lempert and Kalra, 2011; Lempert, 2012) requiring collaboration between researchers and users (see Box 2-1). A 'predict-then-act' framing is appropriate when uncertainties are shallow, but when uncertainties are deep, an 'assess-risk-of-policy' framing is more suitable (Dessai et al., 2009).

The largest focus on uncertainty in CIAV has been on estimating climate impacts such as streamflow or agricultural yield changes and their consequent risks. Since AR4, the treatment of these uncertainties has advanced considerably. For example, multiple models of crop responses to climate change have been compared to estimate intermodel uncertainty (Asseng et al., 2013). Although many impact studies still characterise uncertainty by using a few climate scenarios, there is a growing literature that uses many climate realisations and also assesses uncertainty in the impact model itself (Wilby and Harris, 2006; New et al., 2007). Some studies propagate uncertainties to evaluate adaptation options locally (Dessai and Hulme, 2007) by assessing the robustness of a water company's plan to climate change uncertainties or regionally (Lobell et al., 2008) by identifying which regions are most in need of adaptation to food security under a changing climate. Alternatively, the critical threshold approach, where the likelihood of a given criterion can be assessed as a function of climate change, is much less sensitive to input uncertainties than assessments estimating the 'most likely' outcome (Jones, 2010). This is one of the mainstays of robustness assessment discussed in Section 2.3.3.

2.3.2. Scenarios

A scenario is a story or image that describes a potential future, developed to inform decision making under uncertainty (1.1.3). A scenario is not a prediction of what the future will be but rather a description of how the future might unfold (Jäger et al., 2008). Scenario use in the CIAV research area has expanded significantly beyond climate into broader socio-economic areas as it has become more mainstream *(high confidence)* (1.1.3, 2.4.2.1). Climate change has also become a core feature of many scenarios used in regional and global assessments of environmental and socio-economic change (Carpenter et al., 2005; Raskin et al., 2005). Scenarios can be used at a number of stages within an assessment process or can underpin an entire assessment. They serve a variety of purposes, including informing decisions under uncertainty, scoping and exploring poorly understood issues, and integrating knowledge from diverse domains (Parson et al., 2007; Parson, 2008).

Scenarios also contribute to learning and discussion, facilitate knowledge exchange and can be expressed using a range of media. Local scale visualization of impacts and adaptation measures, depicted on realistic landscapes, is an emerging technology that is being tested to support dialogue on adaptation planning at the local scale (Schroth et al., 2011; Sheppard, 2012). Although visual representations of scenario-based impact assessments may be available for a location, scenario-based adaptation assessments are usually not. Artistic depictions of potential adaptation measures and outcomes are being negotiated and assessed with local stakeholders in communities within Metro Vancouver, Canada (Shaw et al., 2009; Burch et al., 2010; Sheppard et al., 2011).

Climate, socio-economic or other types of scenarios are widely used to assess the impacts of climate change. Fewer studies report on the use of scenarios as participatory tools to enable decision-making on adaptation (e.g., Harrison et al., 2013). However, the scenario literature emphasises the importance of process over product. The new generation of climate and socio-economic scenarios being developed from the representative concentration pathways (RCP; 1.1.3.1) and Shared Socioeconomic Pathways (SSP; 1.1.3.2), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012) have yet to be applied within CIAV studies in any substantive way (Ebi et al., 2013; van Ruijven et al., 2013).

By separating risks into simple and systemic or wicked-problem risks, scenario needs for decision-making can be better identified *(medium confidence)*. For simple risks, if probabilities cannot be easily calculated then scenarios can be used to explore the problem, test for acceptable or unacceptable levels of risk and illustrate alternative solutions for evaluation and testing. Wicked problems will need to be thoroughly scoped to select the most suitable decision-making process, with scenarios playing an important role. They may require separate applications of problem (exploratory or descriptive) and solution-based (normative or positive) scenarios or the development of reflexive scenarios, the latter being updated with new knowledge over time that may re-examine values and goals (van Notten, 2006; Wilkinson and Eidinow, 2008; Jones, 2012); these categories can also be structured as top-down, bottom-up and interactive (Berkhout et al., 2013). Even if conditional probabilities can be used to illustrate climate futures, scenarios are needed to explore the solutions space involving strategic actions, options planning and governance using both process and goal-oriented methods *(high confidence)*.

2.3.3. Evaluating Trade-Offs and Multi-Metric Valuation

Decision makers bring diverse aims, interests, knowledge and values to CIAV decision-making. With effective decision support, parties to a decision can manage competing views by more clearly articulating their goals, understanding how various options affect trade-offs between goals, and making informed choices that participants regard as legitimate, salient, and credible *(high confidence)* (Cash et al., 2003). The decision theory, risk governance, and ethical reasoning literatures use two broad sets of criteria for decision making: outcome-based criteria focus on whether a decision is likely to meet specified goals; process-based criteria compare alternative actions according to the process by which a decision is arrived. In particular, decision process aims to help stakeholders choose between the risks, costs, and obligations being proposed (Morgan et al., 1990), including specified levels of risk tolerance. Such choices around risk tolerance, including acceptable levels of risk, are ethical choices (DesJardins, 2012; Nanda, 2012). Selection strategies informing context and process are described in

Section 14.3.5. Decision criteria inform the discussions of adaptation options, planning, and economics in Chapters 14–17 and WG III Chapter 2.

Multi-attribute decision theory (Keeney and Raiffa, 1993), or multi-criteria decision analysis (MCDA), provides the most general framework for assessing outcomes-based criteria. MCDA concepts and tools organize and display the implications of alternative decisions on differing objectives (e.g., cost and environmental quality), order and test preferences among trade-offs between potentially incommensurate objectives, and show how alternative processes for choosing options can lead to different decisions. Cost-benefit analysis under uncertainty, one key tool for evaluating trade-offs, is described in Chapter 17.3.2.1. Simple MCDA tools include scorecards that graphically display how alternative policy choices affect different goals. For example the 'burning embers' diagram displays how risks to various attributes (e.g., health of unique systems, extreme weather events) depend on targets for a given global mean temperature increase (Figure 19-5). More sophisticated MCDA tools can optimise a portfolio of choices in a variety of ways; for example, one recent method applies scenarios representing significant uncertainty to optimise between four or more choices in order to identify robust combinations and system vulnerabilities (e.g., Kasprzyk et al., 2013). Successfully use of MCDA in CIAV decisions, include the U.S. Bureau of Reclamation helping stakeholders with diverse interests and values to consider 26 alternative performance measures for the Colorado River system, agree on potential climate-related risks and consider options for reducing those risks. Trade-offs also occur where adaptation measures produce negative impacts in other areas of value; e.g., where adaptation in agricultural and urban areas negatively affect ecosystems (4.3.3.3). Korteling et al. (2013) assess the robustness of adaptation options for six criteria including risk of water shortage, environmental impact, local self-sufficiency, cost, carbon footprint and social acceptability. Chapter 17 describes many criteria commonly used in MCDA analyses.

Robustness is often nominated as the most appropriate criterion for managing large decision uncertainty. It is a satisficing (sufficient rather than optimal) criteria (Rosenhead, 1989) that seeks decisions likely to perform well over a wide range of plausible climate futures, socio-economic trends, and other factors (Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Robust decisions often perform better than other methods if the future turns out differently than expected. Testing for robustness can often illuminate trade-offs that help decision makers achieve consensus even when they have different future expectations. Robust choices often trade some optimality for being able to manage unanticipated outcomes. Many forms of the precautionary principle are consistent with robustness criteria (Lempert and Collins, 2007). Flexible and reversible options are often needed to manage situations with significant potential for unanticipated outcomes and differences in values and interests among decision makers (Gallopín, 2006; Hallegatte, 2009; 2.3.4, 5.5.3.1). Flexibility is signalled by reaching of specific management thresholds, critical control points or design states (Box 5-1). The literature disagrees on the relationship between robustness and resilience (Folke, 2006). Chapter 20 describes resilience as a property of systems that might be affected by decision makers' choices, while robustness is a property of the choices made by those decision makers (SREX, Chapter 1).

Process-based criteria focus on the credibility and legitimacy of a decision process. Institutional (2.2.2) and cultural and ethical (2.2.1) contexts will strongly influence the appropriateness and importance of such criteria in a given situation *(high confidence)*. Process criteria provide institutional rules, and governance for decision-making in a wide range of circumstances (Dietz and Stern, 2008; Sen, 2009). For instance, many environmental laws require advanced notice and periods of public comment before any regulations are issued. Water rights can be made tradable, giving users extra flexibility during times of water shortage or oversupply. Participants may regard any decision that fails to respect such rights as illegitimate. In complex situations of a collaborative nature, both outcome and process-related criteria will be needed in a decision-making process *(high confidence)*.

Stakeholder involvement is a central process for climate-related decision making and since the AR4 has grown in importance, particularly for adaptation decision-making (e.g., Lebel et al., 2010), covering methods (Debels et al., 2009; Gardner et al., 2009; Salter et al., 2010; André et al., 2012) and reflecting concrete experiences with stakeholder involvement in CIAV assessments and adaptation processes (de la Vega-Leinert et al., 2008; Ebi and Semenza, 2008; Posthumus et al., 2008; Raadgever et al., 2008; Tompkins et al., 2008a; Tompkins et al., 2008b; Preston et al., 2009). Lebel et al. (2010) differentiate six advantages of social learning and stakeholder involvement for adaptation to climate change: i) reducing informational uncertainty; ii) reducing normative uncertainty; iii) helps to build consensus on criteria for monitoring and evaluation; iv) can empower stakeholders to influence adaptation and take appropriate actions themselves by sharing knowledge and responsibility in participatory processes; v) can reduce conflicts and identify synergies between adaptation activities of various stakeholders, thus improving overall chances of success; and vi) can improve the likely fairness, social justice and legitimacy of adaptation decisions and actions by addressing the concerns of all relevant stakeholders. Complex settings will require a detailed mapping of stakeholder roles and responsibilities (André et al., 2012).

2.3.4. Learning, Review, and Reframing

Effective decision support processes generally includes learning (Figure 2-1), where learning and review become important to track decision progress (National Research Council, 2009; see Box 2-1). This can be achieved by developing an ongoing monitoring and review process during the scoping stage of a project or program. If circumstances change so much that desired outcomes may not be achieved, then reframing of the decision criteria, process and goals may be required. This iterative approach begins with the many participants to a decision working together to define its objectives and other parameters, working with experts to generate and interpret decision-relevant information, and then revisiting the objectives and choices based on that information (Figure 2-1). Again, process is important. Pelling et al. (2008) found that accounting for different personal values in both an official and informal capacity could enhance social learning and therefore adaptive capacity. Measuring progress on adaptation and adaptive capacity, though tracking impacts, vulnerability and related adaptation metrics, and process indicators is discussed in Chapter 14.6. Such metrics are needed to transfer wider learning on adaptation to new situations.

Learning and review can range from periodic reporting through to adaptive management. Adaptive management refers to a choice of policy required to generate reliable new information (Holling, 1978, 1996) and involves a process of adjusting approaches in response to observations of their effect and changes in the system brought on by resulting feedback effects and other variables (Glossary). Adaptive strategies are designed to be robust over a wide range of futures by evolving over time in response to new information (Rosenhead, 1989; Walker et al., 2001; Lempert and Schlesinger, 2002; Swanson et al., 2006). Necessary components include: separating immediate actions from those that can be deferred (and that may require additional information); an explicit process to generate new information; institutional mechanisms for incorporating and acting on new information; and some understanding of the policy limits that, if exceeded, should lead to its re-evaluation (Swanson et al., 2012; Box 5-1). As indicated by Fig 2-1, effective decision making not only requires flows of appropriate information but people willing and able to act on it. While most policies change over time, very few follow the steps of an intentional adaptive strategy *(high confidence)*. For instance, McCray et al. (2010) survey 32 examples of U.S. environmental, health, and safety regulations – all legally required to be adaptive – and find only five instances where any policy change occurred as intended.

Reframing of an action can occur when an existing set of decisions and actions are failing to adequately manage risks (See Box 2-1).

_____ START BOX 2-1 HERE _____

Box 2-1. Managing Wicked Problems with Decision Support

A well-designed decision support process, combined with favourable political conditions, can effectively address ‘wicked’ (Section 2.1) decision challenges. The State of Louisiana faces a serious problem of coastal land loss, exposing the region’s fisheries and heightening the risk of storm surge damage to the City of New Orleans, one of the United States’ largest ports with facilities that account for about 20% of U.S. oil and gas production (Coastal Protection and Restoration Authority, 2007). Previous efforts at comprehensive coastal protection had been stymied by, among other factors, numerous competing jurisdictions and stakeholders with a wide range of conflicting interests.

In the aftermath of Hurricane Katrina, the state embarked on a new coastal planning effort, this time with extensive decision support. The Louisiana state Coastal Protection and Restoration Authority organized an extension decision support effort with a network of about a dozen research institutions interacting with a 33-member stakeholder group consisting of representatives from business and industry, federal, state, and local governments, nongovernmental organizations and coastal institutions. In dozens of workshops over the course of two years, these stakeholders influenced the development of and interacted with a decision support system consisting of two parts: 1) a regional model that integrated numerous strands of scientific data into projections of future flood risk (Fischbach et al., 2012) and 2) a multi-attribute planning tool that allowed stakeholders to explore the implications of alternative portfolios of hundreds of proposed risk reduction projects over alternative sea level rise scenarios (Groves et al., 2012). This decision support system allowed decision makers and stakeholders to first formulate alternative risk reduction plans and then to visualize outcomes and trade-offs up to fifty years into the future.

The resulting Master Plan for a Sustainable Coast passed the state legislature on a unanimous vote in May 2012. Deviating strongly from past practice, the plan allocates far more resources to restoring natural barriers than to structural measures such as levees. The plan balances between the interests of multiple stakeholders and contains some projects that offer near-term benefits and some whose benefits will be largely felt decades from now. Many participants and observers of this process credited the extensive analytic decision support for significant contributions to this plan.

_____ END BOX 2-1 HERE _____

Based on experience to date, there now exists a sufficiently rich set of available methods, tools, and processes to support effective CCIAV decisions in a wide range of contexts *(medium confidence)*, although they may not be combined appropriately, accessible or readily used by decision makers (Webb and Beh, 2013). Tools for decision-making, planning and development, transfer and diffusion are discussed in Chapter 15.4.

2.4. Support for Climate-Related Decisions

Growing understanding of the aspects of decision-making (2.2) and methods and tools (2.3) have led to improved support for CIAV decisions as shown by the provision of climate information and services (2.4.1), methods for impacts and vulnerability assessments (2.4.2) action, and decision support in practice (2.4.3). Figure 2-3 divides the decision-making process into four stages: scoping, analysis, implementation and review, outlining institutional, leadership, knowledge and information characteristics for each stage. Most effort in CIAV research has been put into the first two stages, whereas decision implementation and follow-up have been minimal. This does not imply that the analysis stage is discounted. Problem analysis and solution evaluation are significant undertakings in any decision process, but that is where most current climate change assessments stop. Note that each of these stages can be divided into other quite distinct process elements.

[INSERT FIGURE 2-3 HERE
Figure 2-3. Four-stage process of decision making. Note that while adaptive management is located in the decision review quadrant here, when applied it will influence the entire process.]

2.4.1. Climate Information and Services

Climate Services are institutions that bridge the generation and application of climate knowledge. Their history and concepts are described in 2.4.1.1; how they apply decision support in 2.4.1.2, and the policy implications of climate services as a global practice in 2.4.1.3. They supply climate information on local, regional, national and global scales for the monitoring of risks, mitigation and adaptation planning “as an important component of sustainable development” (Sivakumar et al., 2011). The Global Framework for Climate Services (Hewitt et al., 2012) aims to “enable better management of the risks of climate variability and change and adaptation to climate change, through the development and incorporation of science-based climate information and prediction into planning, policy and practice on the global, regional and national scale” (http://www.wmo.int/pages/gfcs/index_en.php). Climate services focus on the connection between climate science and the public demand for information, however their development and deployment needs support from many other disciplines (Miles et al., 2006). This extended reach requires measures such as case-specific communication, engagement and knowledge exchange skills *(high confidence)*.

While many countries have already established national and regional climate services or are on the way to doing so, they show significant differences. The development of Regional Climate Services in the US and parts of Europe, with their increasing focus on communication and decision support, is well documented (DeGaetano et al., 2010; von Storch et al., 2011). Developing countries are becoming increasingly aware of the need for climate services (Semazzi, 2011), which is in part reflected in the migration of regional climate models into those countries. In 2001 only around 21 (mostly OECD) countries were running regional climate models (RCMs), but today over 100 countries are trained in using the PRECIS RCM (Jones et al., 2004; Edwards, 2010). Regional Climate Services are expanding geographically, shifting from simple understandings of climate cause and effect to ever more complex and wicked problem situations and are becoming more interdisciplinary.

2.4.1.1. Climate Services: History and Concepts

Early climate services in North America were seen as an expansion of weather services, mainly dealing with forecasts, seasonal outlooks, risk assessment in a mostly stationary but variable climate (Changnon et al., 1990; Miles et al., 2006; DeGaetano et al., 2010). This mainly technical outlook had limited effectiveness; for example, decision makers had difficulties understanding and using climate data for planning purposes (Changnon et al., 1990; Miles et al., 2006; Visbeck, 2008) and the data were slow to access and of poor quality (Changnon et al., 1990). As these services developed, formal definitions of their mission and scope shifted to being user-centric, focusing on active research, data stewardship and effective partnership (National Research Council, 2001). Climate services were understood as a clearinghouse and technical access point to stakeholders, providing education and user access to experts; the latter informing the climate forecast community of information needs, largely to inform adaptation (Miles et al., 2006).

Downscaling is a key product demanded by users for decision making (21.3.3.2). For example, in Africa, regional climate models play an increasing role in Regional Climate Outlook Forums arranged by WMO. The Global Framework for Climate Services was created in order to coordinate and strengthen activities and develop new infrastructure where needed, focusing on developing countries (World Meteorological Organization, 2011; Hewitt et al., 2012). From initially being supply-focused and static, public climate services increasingly need communication skills, engagement and knowledge exchange in a highly challenging environment of technical and institutional networks, monitoring systems, and collaborations with other institutions, stakeholders and decision-makers (DeGaetano et al., 2010).

2.4.1.2. Climate Services: Practices and Decision Support

Decision support is generally acknowledged as an integral part of climate services *(high confidence)* (Miles et al., 2006; DeGaetano et al., 2010). Depending on the stage and context in question (see 2.1.3.), ‘best’ data as framed by experts should be reconciled with user needs in order to produce scientific information that is relevant and suitable for decision making. Social and cultural determinants have to be taken into account (see 2.2.) and require the communication of scientific data to be context specific. Decision support for climate services consists of “processes of interaction, different forms of communication, potentially useful data sets or models, reports and training workshops, data ports and websites, engaging any level of governance, at any stage in the policy- or decision-making process” (Moser, 2009). The climate service is a “process of two-way communication” and “involves providing context that turns data into information” (Shafer, 2004). Capacity building is required on all sides of the communication process. For Regional Climate Services, a successful learning process, engages both users and providers of knowledge in knowledge exchange. For example, the uptake and utility of climate forecasts in rural Africa is described in Box 9-4.

As knowledge brokers, climate services have to establish an effective dialogue between science and the public (von Storch et al., 2011). This dialogue undertakes two main tasks: One is to understand the range of perceptions, views, questions, needs, concerns and knowledge in the public and among stakeholders about climate, climate change and climate risks. The other task is to convey the content of scientific knowledge to the public, media and stakeholders.

This includes communicating the limitations of such knowledge, the known uncertainties and the unknowable, as well as the appropriate role of science in complex decision processes (von Storch et al., 2011).

2.4.1.3. The Geo-Political Dimension of Climate Services

Climate knowledge is continually being documented and assessed by the social sciences within a policy-relevant context (Yearley, 2009; Grundmann and Stehr, 2010). One focus is on the spread of climate knowledge into developing countries. Climate models distributed to users with no in-house capacity for model development build capacity in regional climate science, producing high resolution data for local decision-making. This mobility of knowledge has far-reaching implications for how climate knowledge is produced; strengthening the influence of epistemic communities such as the IPCC and other global governance mechanisms (Mahony and Hulme, 2012). Thus, while regional climate models play an increasingly important role in decision making processes, critics argue that climate monopolises planning and development strategies, rendering other forms of knowledge subordinate to this ‘climate reductionism’ (Dessai et al., 2009; Hulme, 2011).

Indigenous forms of knowledge – including the specialized knowledge of any stakeholder – are becoming increasingly relevant for climate services *(high confidence)* (Strauss and Orlove, 2003; Crate and Nuttal, 2009; Crate, 2011; Ulloa, 2011; Krauss and von Storch, 2012). Local forms of knowledge and scientific climate models are not necessarily mutually exclusive; individual case studies show how both forms of knowledge contribute jointly to place-based adaptation (Strauss and Orlove, 2003; Orlove and Kabugo, 2005; Orlove, 2009; Strauss, 2009; Orlove et al., 2010). Indigenous knowledge in the form of oral histories and other traditional knowledge are being compared or combined with remote sensing technologies and model-based scenarios to co-produce new knowledge, and to create a new discourse on adaptation planning (Nakashima et al., 2012; Table 15.1). The challenge will be to collaborate in a way that enables their integration into a shared narrative on future adaptation choices.

These examples show that adaptation needs both to be implemented locally and to be informed by larger scale (inter-) national policies and directions. One strategy will not suit every location. Endfield (2011) argues for a ‘reculturing and particularizing of climate discourses’ in order to successfully localize global and scientific meta-narratives. Climate service development combines very different types of knowledge and the social, cultural and communication sciences play a decisive role in this process (Pidgeon and Fischhoff, 2011; von Storch et al., 2011). To position itself and to react according to the diverse demands, science-based climate services have to become “rooted in society” (Krauss, 2011). The climate science community does not necessarily take the lead, but becomes part of an inter- and trans-disciplinary process, where politics, culture, religion, values and so forth become part of climate communication *(medium confidence)*.

2.4.2. Assessing IAV on a Range of Scales

CIAV assessments address the ‘adapt to what’ question, which can enable a dialogue among practitioners, stakeholders, and the public on planning and implementation of adaptation measures within prevailing mechanisms for governance. To date, however, assessments have focused more on I than A (see Chapter 1, Figure 1-1d). A number of global initiatives are taking place to enable knowledge generation, transfer and use, including the Programme of Research on Climate Change Vulnerability, Impacts and Adaptation – PROVIA (http://www.provia-climatechange.org/), the Nairobi Work Programme on impacts, vulnerability and adaptation to climate change (http://unfccc.int/adaptation/nairobi_work_programme/items/3633.php), and work by the World Bank and regional development banks (http://climatechange.worldbank.org/).

2.4.2.1. Assessing Impacts

For scenario-based impact assessments to contribute to vulnerability and risk assessment, a series of translations need to be performed. Scenarios of projected greenhouse gas concentrations are converted to changes in climate, impacts are assessed, perhaps with autonomous adaptation, leading to the evaluation of various adaptation options.

This series of translations requires the transformation of data across various scales of time and space, between natural and social sciences, utilizing a wide variety of analytical tools representing areas such as agriculture, forestry, water, economics, sociology, and social-ecological systems. Climate scenarios are translated into scenarios or projections for biophysical and socio-economic impact variables such as river flow, food supply, coastal erosion, health outcomes and species distribution (e.g., European Climate Adaptation Platform, http://climate-adapt.eea.europa.eu). Climate services help establish and support the translation process (Section 2.4.1).

The resulting climate impacts and risks are then subject to decision making on risk management and governance. Assessments of observed events combine biophysical and socioeconomic assessments of the past and present (Table 2-1, top row). Most scenario-based assessments superimpose biophysical 'futures' onto present-day socio-economic conditions (Table 2-1, middle row). This is useful for assessing the how current socio-economic conditions may need to change in response to biophysical impacts but raises inconsistencies when future socio-economic states are out of step with biophysical states. This will hamper assessments of future adaptation responses in coupled social-ecological systems (see Chapter 16). An important challenge, therefore, is to construct impact assessments in which biophysical futures are coupled with socioeconomic futures (Table 2-1, bottom row). A new set of socioeconomic futures, known as Shared Socioeconomic Pathways (SSP), which are storylines corresponding to the new RCPs (Moss et al., 2010; Kriegler et al., 2012) are being developed to assist this process (1.1.3.2).

[INSERT TABLE 2-1 HERE
Table 2-1: Nature of published IAV assessments.]

A new generation of assessments links biophysical, economic and social analysis tools in order to describe the interactions between projected biophysical changes and managed systems. For example, Ciscar et al. (2011) estimated the costs of potential climate change impacts, without public adaptation policies, in four European market sectors (agriculture, river floods, coastal areas, and tourism) and one nonmarket sector (human health). A similar study in the UK was conducted for tourism, health and transportation maintenance, buildings and transportation infrastructure, and residential water supplies (Hunt, 2008). In the US, Backus et al. (2013) assessed national and state level GDP and employment impacts, incorporating direct impacts on water resources, secondary impacts on agriculture and other water interests, and indirect impacts through interstate migration of affected populations. Decision support tools are being integrated into scenario-based impact and adaptation assessments. For example, the Water Evaluation and Planning System model has been used to assess a community water system in British Columbia, Canada (Harma et al., 2012). Incorporation of stakeholder dialogue processes within scenario construction (Parson, 2008), and Participatory Integrated Assessment (Salter et al., 2010), enables inclusion of local knowledge as part of scenario-based assessments.

2.4.2.2. Assessing Vulnerability, Risk, and Adaptive Capacity

The adaptation to climate change, disaster risk management, and resilience literatures all address the concept of vulnerability, defined as a susceptibility to loss or damage (Adger, 2006; Füssel, 2007), or, the propensity or predisposition to be adversely affected (glossary). Within IPCC AR4, Schneider et al. (2007) identified vulnerabilities that might be considered 'key', and therefore potentially 'dangerous' (see glossary). Criteria denoting a key vulnerability include its magnitude and timing, persistence and reversibility, and the likelihood and confidence that the contributing event(s) would occur (Sections 19.2.5, 19.6). Other criteria include the importance of a location or activity to society, society's exposure to potential loss and its capacity to adapt. Adaptive capacity has been defined as the ability to adjust, to take advantage of opportunities, or to cope with consequences (Adger et al., 2007; glossary). However, adaptive capacity is context specific, related to both availability of resources, capacity to learn, and governance measures (Gupta et al., 2010; 14.5); Section 14.5). Actions that illustrate how adaptive capacity and climate resilience can be mutually reinforcing include disaster risk management (2.5.2, 15.3.2, 16.7.2) and 'triple-win' interventions where adaptation, mitigation, and sustainable development goals are integrated so as to find climate-resilient pathways (20.3.3, 20.4.2).

The concept of an 'adaptation deficit' (Burton and May, 2004) is applicable to cases such as Hurricane Katrina (Committee on New Orleans Regional Hurricane Protection Projects, 2009; Freudenberg et al., 2009; Box 2-1) or the 2003 European heat wave (Haines et al., 2006) where substantial vulnerability follows a climate event. An adaptation deficit represents a gap between an existing state of adaptation and an idealized state of adaptation where adverse impacts are avoided (Chapter 17, Glossary). The adaptation deficit has also been related to 'residual impacts', which occur due to insufficient adaptation to current or future climate (IPCC, 2007b). Within developing countries, Narain et al. (2011) consider the adaptation deficit as being part of a larger 'development deficit'. Cardona et al. (2012) cite other 'deficit' indicators, including a Disaster Deficit Index (extreme event impact combined with financial ability to cope), structural deficit (low income, high inequality, lack of access to resources, etc.), and a risk communication deficit. Maladaptation occurs where a short-term response inadvertently leads to an increase in future vulnerability (Glantz, 1988; Barnett and O'Neill, 2010; McEvoy and Wilder, 2012). Barriers unrelated to scientific knowledge can hamper effective decision making (Adger and Barnett, 2009; Berrang Ford et al., 2011). This may help to explain why some extreme events create surprising levels of damage within developed countries. The adaptation deficit has also been related to 'residual impacts', which occur due to insufficient adaptation to current or future climate (IPCC, 2007b).

The assessment of potential future damages and loss requires approaches that link bio-physical and socio-economic futures. An example is the assessment of climate change effects on human health, including research-to-decision pathways, monitoring of social vulnerability indicators and health outcomes (English et al., 2009; Portier et al., 2010), and tools for enabling adaptive management (Hess et al., 2012). Examples of regional scale scenario-based vulnerability assessments are case studies for North Rhine-Westphalia in Germany (Holsten and Kropp, 2012) and agriculture in Mexico (Monterroso et al., 2012). An example of a larger scale study is a vulnerability assessment of ecosystem services for Europe, in which future adaptive capacity was based on indicators from the SRES storylines (Metzger and Schröter, 2006). Difficulty in separating the relative influences of changing climate and development patterns hampers assessments of observed trends in property damage caused by atmospheric extreme events. Recent increases in economic losses may be due to changes in probabilities of extreme events, changes in human development patterns (more people in harm's way) without changes in climatic extremes, or a combination of both (Pielke, 1998; Mills, 2005; Munich Re Group, 2011). IPCC (2012) concluded that increasing exposure has been the major cause, but a role for climate change has not been excluded.

Development choices taken in the current or near term can potentially influence future vulnerability to projected climate change, hence the interest in the study of emergent risks (Sections 19.3, 19.4). Interactions between development pathways, and climate change impacts and responses, could create situations with little or no precedent. Assessments based on gradual shifts in mean conditions could underestimate future risk and consequent damage, suggesting the need for process-based methodologies that focus on enhancing resilience (Jones et al., 2013; Sections 2.5.2, 20.2.3). An example of assessing this type of risk, and the costs and benefits of potential adaptation responses, is a resilience assessment framework for infrastructure networks (Vugrin et al., 2011; Turnquist and Vugrin, 2013).

2.4.3. Climate-Related Decisions in Practice

Implementation of adaptation actions, resilience strategies and capacity building can take place as stand-alone actions or be integrated into other management plans and strategies. Recent literature on potential climate change effects on natural resources, public health and community planning and management is reviewed in Chapters 3–12. As the complexity of management challenges increases due to climate change, development and other pressures, a range of reflexive decision-making processes are emerging under the general topics of adaptive management, iterative risk management and community-based adaptation (e.g., 5.5.4.1). However, there are few assessments of adaptation delivery and effectiveness (15.6). Cross-sectoral integrated approaches such as Integrated Water Resources Management (IWRM), sustainable forestry management (SFM) and Integrated Coastal Zone Management (ICZM) are viewed as being more effective than stand-alone efforts (16.5.1).

Adaptive approaches to water management can potentially address uncertainty due to climate change (3.6.1) but there is a limited number of examples in practice (3.6.4). Examples of recent strategies include an IWRM roadmap prepared for the state of Orissa, India (Jønch-Clausen, 2010) and seven cases in the US (Bateman and Rancier, 2012) some of which are applying adaptive water management using a scenario-based experimental approach intending to align with IWRM and promote resilience. Adaptations in urban systems following integrated urban water management principles are becoming widespread (8.3.3.4) and in rural systems are more advanced in developed countries and less so in developing countries, especially those within transboundary basins (9.4.3.2, 24.4.1.5, 24.4.2.5, 25.5.3, 26.3.3, 27.3.1.2, 27.3.2.2).

Adaptation in agriculture ranges from small adjustments made to current activities through to transformative adaptations across whole systems. (7.5.1, 9.4.3.1, 22.4.5.7, 23.4.1, 24.4.4.5, 25.7.2, 26.5.4, 27.3.4.2). Diversified systems are more resilient with some diversification coming from off farm sources (9.4.3.1). There are few unequivocal adaptations to climate, but the development of adaptive capacity is more widespread (7.5.1.2). Adaptation in forestry has expanded since the AR4 (9.4.3.3) and is aiming to develop towards SFM by focusing on biological diversity, productive and protective functions of forests, maintenance of their social and economic benefits, and governance (McDonald and Lane, 2004; Wijewardana, 2008; Montréal Process, 2009). Although SFM is still largely an abstract concept (Seppälä et al., 2009), managing climate change risks is seen as necessary for achieving its objectives (Montréal Process, 2009). Governments and companies are also considering assisted migration of forest species as an adaptation strategy (Pedlar et al., 2012) and payment for ecosystem services is becoming more common (9.4.3.3). Sustainable Fisheries Management has long-term ecological and productivity goals (FAO, 2013) but climate change has generally not been included in strategic guidance for fisheries management (Brander, 2010). Ecosystem-based approaches to management e.g., (Zhou et al., 2010) and transformative approaches will be required (7.5.1.1.2, 9.4.3.4). Sustainable livelihoods approaches are also being applied for populations dependent on marine resources (9.4.3.4, 30.6.2.1, Table 30-2).

National Adaptation Programmes of Action (NAPA) for least developed countries (LDCs) are designed to be flexible, action-oriented and country-driven (UNFCCC, 2009). Key preparatory steps include the synthesis of available information on vulnerability and impacts via extensive public participation (see Chapter 14). The NAPA process has assisted least-developed countries to assess climate sensitive sectors and prioritize projects to address the most urgent adaptation issues (Lal et al., 2012; UNFCCC, 2012). Integrating NAPAs with other socio-economic programs can help develop resilience. However, although many countries have linked their NAPAs with development programs, Hardee and Mutunga (2010) argue that they have had limited success in aligning the NAPA priorities with existing national priorities such as population growth. To this end, scaling up and institutionalization of the NAPA process has commenced. Under the Cancun Adaptation Framework, a process was established that enables LDCs to formulate and implement National Adaptation Plans (NAPs) building upon the NAPA experience (UNFCCC, 2013). The NAP's main objectives are to identify vulnerabilities, medium- and long-term adaptation needs and to develop and implement strategies and programmes to address those needs and also to mainstream climate change risks. The NAPs are also an opportunity to align with other global initiatives such as the Millennium Development Goals and Hyogo Framework for Action.

Many developed countries are developing adaptation strategy documents at different scales of governance (European Environmental Agency, 2013). Biesbroek et al. (2010) analysed National Adaptation Strategies (NAS) of nine European nations, examining their decision making aspects and finding both 'top-down' and 'bottom-up' (delegation of authorities to local governments) approaches. Dissemination of information on weather, climate, impacts, vulnerability and scenarios was found to be a critical element for adaptation decision making.

Climate risk is being increasingly factored into existing decision-making processes (15.2.1). For example, learning from the 2003 heat waves that killed some 35,000 people across Europe, many European countries have implemented health-watch warning systems (Alcamo et al., 2007; WHO, 2008). Vietnam has initiated large-scale mangrove restoration and rehabilitation programs with the support of international institutions to protect coastal settlements and aquaculture industry (World Resources Institute et al., 2011). The Tsho Rolpa glacier lake in Nepal was at the risk of outburst due to glacial melt (Adger et al., 2007) so the Government of Nepal introduced both short- and long-term measures to prevent the outburst flood event (World Resources Institute et al., 2011). In many ways, local government is at the coal face of adaptation decision making (Pelling et al., 2008; Measham et al., 2011; Roberts et al., 2012). Municipal governments are incorporating climate change adaptation planning within municipal planning instruments, including energy and water system design, disaster risk reduction and sustainability plans (Ford and Berrang-Ford, 2011; Rosenzweig et al., 2011). In human health, two main areas of benefit are occurring through improvements in current health patterns being exacerbated by changing climate and in reducing pollutants associated with co-pollutants of greenhouse gas emissions (11.7, 11.9). Climate is being increasingly recognised as a component of human conflict and insecurity, so is becoming a factor in governance arrangements affecting security and peace building programs (12.5).

Details of adaptation planning within urban and rural settlements are addressed in Chapters 8 and 9, respectively. In urban settlements, adaptations are occurring in areas of energy, water, transport, housing and green infrastructure (8.3.3) but opportunities for broader integration into planning and the urban economy are largely being missed (8.4). The overall status of adaptation implementation is assessed in Chapter 15. Although there is a rapidly growing list of adaptation plans being generated at multiple scales, an evaluation of adaptation plans from Australia, United Kingdom and the United States suggests they are under-developed (Berrang Ford et al., 2011). These plans reflect a preference for capacity building over the delivery of specific vulnerability-reduction measures, indicating that current adaptation planning is still informal and ad hoc (Preston et al., 2011; Bierbaum et al., 2013). Capacity barriers have hampered the transition from planning to implementation, so only a small number of jurisdictions have been successful at implementing adaptation measures (15.2). However, there has been growth in community-based adaptation initiatives (Baer and Risbey, 2009; Rudiak-Gould, 2011; 15.1, 15.2, 15.5, 15.6)

Various enabling factors for implementation have been identified in stakeholder engagement processes. Such factors include access to resources, sharing observations, language specific information and ICT tools (e.g., wireless sensor networks, geographic information systems and Web-based tools) that increase local awareness, allowing for good public understanding of stresses, risks and trade-offs (15.4.2). These factors allow new strategies to be explored, evaluated and implemented (Shepherd et al., 2006; Hewitt et al., 2013). Enabling factors also include customized impact and vulnerability assessments for communities of interest and local practitioners who would serve as champions for adaptation planning, and the existence of local social influences/networks and capacity that enable long term strategic planning and mainstreaming (Gardner et al., 2009; Cohen, 2010). These factors are further discussed in Chapters 15 and 16. Local government officials often lack training on climate change adaptation and require capacity to be built in a number of areas. To assist this process, guidebooks have been produced, framing the process of adaptation planning as both a team-building and project management exercise, activities that are already part of usual practice (Snover et al., 2007; Bizikova et al., 2008; ICLEI Oceania, 2008; CARE International in Vietnam, 2009; Ayers et al., 2012). Practitioner engagement in decision ‘games’ can offer another training resource (Black et al., 2012).

2.5. Linking Adaptation with Mitigation and Sustainable Development

2.5.1. Assessing Synergies and Trade-offs with Mitigation

Capacities to adapt to and mitigate climate change are broadly similar. Opportunities for synergies are particularly relevant for the agriculture, forestry, urban infrastructure, energy and water sectors (Chapters 3, 4, 7–10). The IPCC AR4 (Klein et al., 2007) concluded that a lack of information made it difficult to assess these synergies. Assessing the synergies and trade-offs that face both adaptation and mitigation is an important goal of the new IPCC scenario process (Kriegler et al., 2012; O'Neill et al., 2013). These synergies and trade-offs between adaptation and mitigation are illustrated in Figure 2-4. The negatives associated with ‘adaptive emissions’ or ‘new vulnerabilities’ arising from mitigation do not necessarily mean that such measures should not be contemplated, but they do need to be assessed within a larger portfolio of actions where losses and gains have been sufficiently well quantified (19.7). Limits of adaptation emphasise the different reach of adaptation and mitigation in managing climate risks (16.6, 19.7.5).

Mitigation can affect, for example, the water (3.7.2.1), terrestrial and freshwater ecosystems (4.4.4, 19.3.2.2), agriculture (19.3.2.2, 19.4.1) and livelihoods and poverty (13.3.1) sectors and will in turn be affected by the water sector (3.7.3.2), terrestrial ecosystems (4.3.3.1, 4.2.4.1). Adaptation actions for agriculture generally tend to reduce emissions (7.5.1.4). Potential losses of human security associated with climate policy are discussed in 12.5.2 and 19.4.2.2. Recent literature on potential interactions between mitigation and adaptation is reviewed in Sections 16.4.3, 19.7.1–5. Chapter 20 discusses the relationship between adaptation, mitigation, and sustainable development including sustainable risk management (20.3.3).

[INSERT FIGURE 2-4 HERE
Figure 2-4: Examples of adaptation (A) – mitigation (M) trade-offs and synergies (adapted from Cohen and Waddell, 2009). The upper right quadrant (sustainable win-win) illustrates synergies in which actions enable the achievement of both adaptation and mitigation goals. The lower left quadrant (unsustainable) shows the opposite condition. The upper left (adaptive emissions) and lower right (new vulnerabilities) quadrants illustrate trade-offs that can result from actions within particular local-regional circumstances.]

2.5.2. Linkage with Sustainable Development – Resilience

The idea that climate change response and sustainable development should be integrated within a more holistic decision framework was assessed in IPCC AR4 (Robinson et al., 2006; Klein et al., 2007; Yohe et al., 2007). Practical aspects of this integration are being tested as decision makers endeavour to incorporate adaptation measures within official long-term development plans (15.3.3). A typical example is the engagement of researchers and practitioners (planners, engineers, water managers, etc.) in scenario-based exercises to build local capacity to plan for a wide range of climate outcomes (Bizikova et al., 2010). Development can yield adaptation co-benefits if climate change is factored into its design (17.2.7.2, 20.3, 20.4).

Resilience is the capacity to change in order to maintain the same identity (see Glossary) and can be assessed through participatory research (Tyler and Moench, 2012) or through system modelling. Chapter 20 examines climate-resilient pathways, which are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development while meeting the goals of the UNFCCC (Box 20-1). An example of resilience assessment at the landscape scale is in the Arctic, where local sources of important productivity and biodiversity are being mapped and their future capacity in supporting larger ecoregions under climate change is being assessed (Christie and Sommerkorn, 2012). An industry example covers the resilience analysis of supply chains, specifically petrochemical supply chains exposed to a hurricane in south-eastern United States (Vugrin et al., 2011). For urban areas, Leichenko (2011) categorize four types of urban resilience studies: i) urban ecological resilience, ii) urban hazards and disaster risk reduction, iii) resilience of urban and regional economies, and iv) urban governance and institutions. Boyd et al. (2008) promote resilience as a way of guiding future urbanization that would be better ‘climatized’. The Asian Cities Climate Change Resilience Network is applying a resilience planning framework, with attention given to the role of agents and institutions (Tyler and Moench, 2012).

Adaptive capacity is seen as an important component of resilience on a range of scales (Sections 2.1.1, 2.2.3, 2.3.4, 2.4.2, 20.3). Local cases, such as King County (Seattle) USA, illustrate the importance of researcher–practitioner collaboration for knowledge exchange (Snover et al., 2007) and iterative and reflexive processes that enable local ownership, and adjustment to new information and evaluation of actions taken (Saavedra and Budd, 2009). However, in regions with high and chronic poverty, coupled with low awareness of global change drivers, adaptation as a process is not well understood and tools that enable anticipatory learning are lacking (Tschakert and Dietrich, 2010).

The normative concept of sustainable adaptation has been proposed to manage adaptation’s unintended consequences (Eriksen et al., 2011). It considers effects on social justice and environmental integrity, challenging current (unsustainable) development paths rather than seeking adjustments within them. This concept recognizes the role of multiple stressors in vulnerability, the importance of values in affecting adaptation outcomes (Section 2.2.1), and potential feedbacks between local and global processes. Little is known about the long-term effects of adaptation on livelihoods and poverty (13.3.2) although focussing on poverty alleviation as part of adaptation is thought to build capacity (13.4.1, 13.4.2).

The Hyogo Framework for Action on disaster risk reduction considers climate change as an underlying risk factor, and promotes the integration of risk reduction and climate change adaptation (UNISDR, 2007; 2011; 15.3.2). Social development is being integrated with disaster risk management in order to enhance adaptive capacity and address the structural causes of poverty, vulnerability and exposure.. In small island states, this integration is being enabled through focused institutional coordination, greater stakeholder engagement and promotion of community-based adaptation and resilience-building projects (UNISDR, 2012b). Similar initiatives are underway in urban areas (UNISDR, 2012a; 15.3.2, 15.3.3, 15.5 and Chapter 24, Box CC-TC).

Resilience is also being explored as an outcome of social contracts that underpin governance. O'Brien et al. (2009) use examples from Norway, New Zealand and Canada to illustrate how resilience thinking on climate does not easily fit into existing social contracts, and that new types of arrangements may better serve the goals of resilience and sustainable development within the context of climate change. Chapter 20 describes climate-resilient development pathways as being an explicit objective of long-term planning and decision making and considers the need for transformational adaptation aiming to achieve sustainable development (20.5).

2.5.3. Transformation – How Do We Make Decisions Involving Transformation?

Much of the existing adaptation literature examines gradual adjustment or accommodation to change. But a growing literature highlights the importance of transformative adaptation (14.3.5, 16.4.2), both in the context of a world where global temperature raise above 2°C (Kates et al., 2012; PIK, 2012) and in the context of climate resilient pathways that manage risk through combinations of adaptation and mitigation (20.5).

In concluding this chapter, we therefore reflect on some emerging, though still sparse literature that examines such transformational adaptation, how it differs from incremental adaptation (O'Brien, 2012; Park et al., 2012), and how it might occur in specific sectors and systems (Rickards and Howden, 2012). This early literature suggests that many themes raised in this chapter may prove important to transformational adaptation, including: iterative risk management with a broad view of risk, adaptive management, robustness and resilience and deliberation (McGray et al., 2007; Leary et al., 2008; Hallegatte, 2009; Tschakert and Dietrich, 2010; Hallegatte et al., 2011; Stafford Smith et al., 2011). For instance, Irvin and Stansbury (2004) identify situations where participatory processes may be most effective for bringing about positive social and environmental change. Recently, Park et al. (2012) have proposed the Adaptation Action Cycles concept as a means to delineate incremental and transformative adaptation and the role of learning in the decision-making process. Similarly to the learning process called 'triple-loop' that considers a situation, its drivers plus the underlying frames and values that provide the situation context (Argyris and Schön, 1978; Peschl, 2007; Hargrove, 2008), transformational adaptation may involve decision makers questioning deep underlying principles (Flood and Romm, 1996; Pelling et al., 2008) and seeking changes in institutions, such as legal and regulatory structures underlying environmental and natural resource management (Craig, 2010 ; Ruhl, 2010a), as well as in cultural values (O'Brien, 2012; O'Brien et al., 2013).

Frequently Asked Questions

FAQ 2-1: What constitutes a good (climate) decision? *[to be inserted after Section 2.1.1]*
No universal criterion exists for a good decision, including a good climate-related decision. Seemingly reasonable decisions can turn out badly, and seemingly unreasonable decisions can turn out well. However, findings from decision theory, risk governance, ethical reasoning and related fields offer general principles that can help improve the quality of decisions made.

Good decisions tend to emerge from processes in which people are explicit about their goals; consider a range of alternative options for pursuing their goals; use the best available science to understand the potential consequences of their actions; carefully consider the trade-offs; contemplate the decision from a wide range of views and vantages, including those who are not represented but may be affected; and follow agreed-upon rules and norms that enhance the legitimacy of the process for all those concerned. A good decision will be implementable within constraints such as current systems and processes, resources, knowledge and institutional frameworks. It will have a given lifetime over which it is expected to be effective, and a process to track its effectiveness. It will have defined and measurable criteria for success, in that monitoring and review is able to judge whether measures of success are being met, or whether those measures, or the decision itself, need to be revisited.

A good climate decision requires information on climate, its impacts, potential risks and vulnerability to be integrated into an existing or proposed decision-making context. This may require a dialogue between users and specialists to jointly ascertain how a specific task can best be undertaken within a given context with the current state of scientific knowledge. This dialogue may be facilitated by individuals, often known as knowledge brokers or extension agents, and boundary organizations, who bridge the gap between research and practice. Climate services are boundary organizations that provide and facilitate knowledge about climate, climate change and climate impacts for planning, decision making and general societal understanding of the climate system.

FAQ 2.2: Which is the best method for climate change decision-making/assessing adaptation?
[to be inserted in Section 2.3.4]
No single method suits all contexts, but the overall approach used and recommended by the IPCC is iterative risk management. The International Standards Organization defines risk as *the effect of uncertainty on objectives*. Within the climate change context, risk can be defined as the potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk management is a general framework that includes alternative approaches, methodologies, methods and tools. Although the risk management concept is very flexible, some methodologies are quite prescriptive; for example, legislated emergency management guidelines and fiduciary risk. At the operational level, there is no single definition of risk that applies to all situations. This gives rise to much confusion about what risk is and what it can be used for.

Simple climate risks can be assessed and managed by the standard methodology of making up the 'adaptation deficit' between current practices and projected risks. Where climate is one of several or more influences on risk, a wide range of methodologies can be used. Such assessments need to be context-sensitive, involve those who are affected by the decision (or their representatives), use both expert and practitioner knowledge, and need to map a clear pathway between knowledge generation, decision-making and action.

FAQ 2.3: Is climate change decision-making different from other kinds of decision-making?
[to be inserted after Section 2.4.3]
Climate-related decisions have similarities and differences with decisions concerning other long-term, high consequence issues. Commonalities include the usefulness of a broad risk framework and the need to consider uncertain projections of various biophysical and socioeconomic conditions. However, climate change includes longer time-horizons and affects a broader range of human and earth systems as compared to many other sources of risk. Climate change impact, adaptation and vulnerability assessments offer a specific platform for exploring long term future scenarios in which climate change is considered along with other projected changes of relevance to long term planning.

In many situations, climate change may lead to non-marginal and irreversible outcomes, which pose challenges to conventional tools of economic and environmental policy. In addition, the realization that future climate may differ significantly from previous experience is still relatively new for many fields of practice (e.g., food production, natural resources management, natural hazards management, insurance, public health services and urban planning).

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Nature of IAV assessments	Biophysical conditions	Socio-economic conditions
Stationarity and extrapolation	Continuation of current trends, no change in statistical properties	No change from current conditions
Transitional	Scenario-based projections of future biophysical conditions	No change from current conditions, sometimes sensitivity analysis with alternate futures
Coupled and interactive	Scenario-based projections of future biophysical conditions	Alternative futures from scenarios/storylines consistent with biophysical projections, sometimes with dynamic response

Table 2-1: Nature of published IAV assessments.

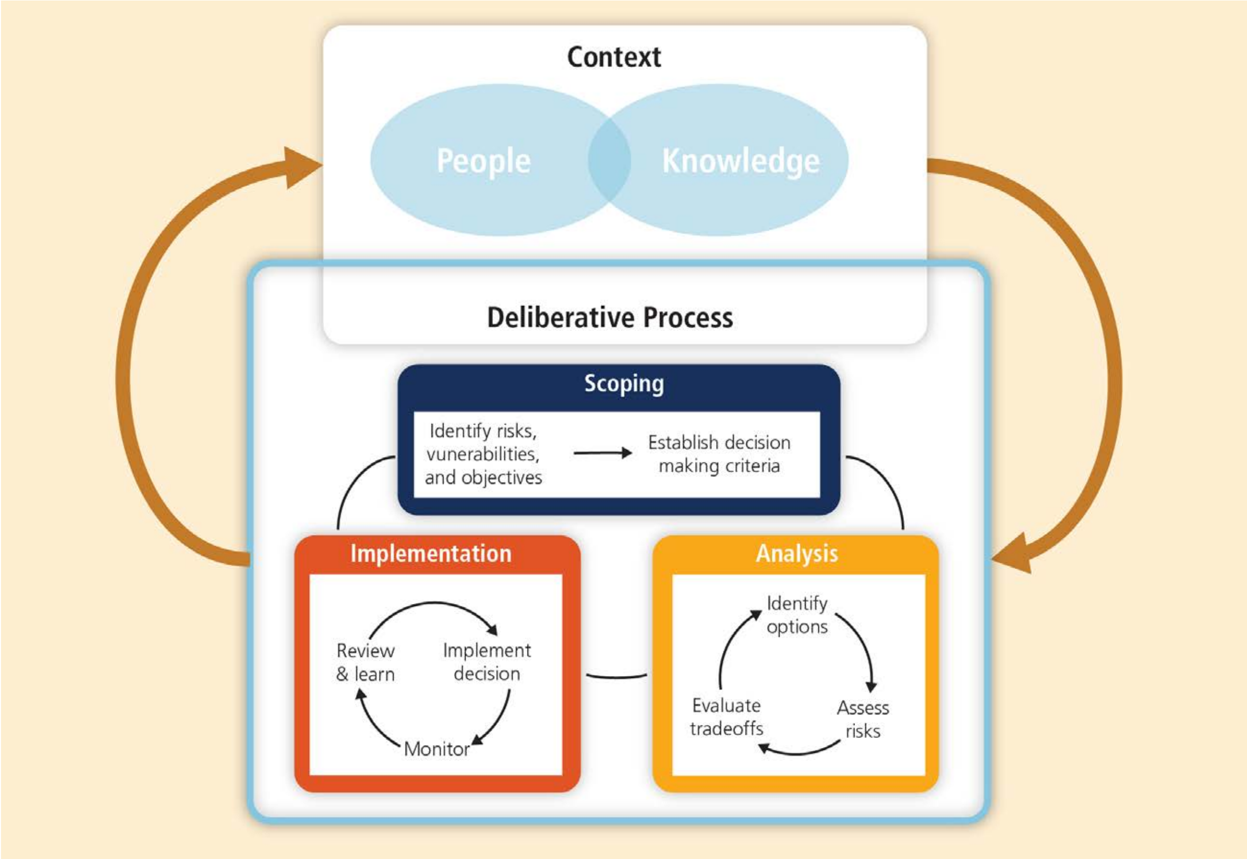
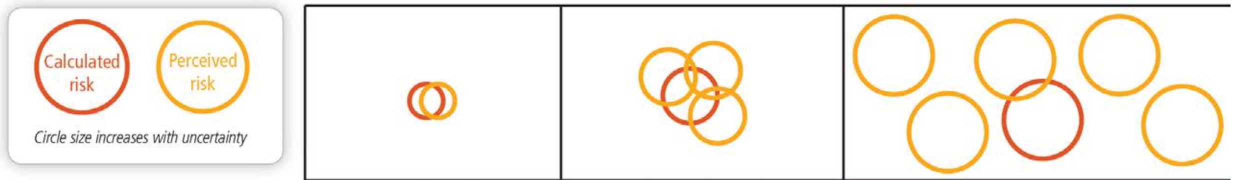


Figure 2-1: Iterative risk management framework depicting the assessment process, and indicating multiple feedbacks within the system and extending to the overall context. Adapted from Willows and Connell (2003).



Characteristics of decision making	Simple risk	Complicated risk	Complex risk
Methodology	Linear, cause and effect	Top down and/or bottom up, iterative	Iterative and/or adaptive, ongoing and systemic
Approach	Analytic and technical	Collaborative process with technical input	Process driven. Frame and model multiple drivers and valued outcomes
Stakeholder strategy	Communication	Collaboration	Deliberation, creating shared understanding and ownership
Mental models	Common model	Negotiated and shared	Contested initially and negotiated over project
Values and outcomes	Widely accepted	Negotiated over project by user perspectives and calculated risk	Contested initially and negotiated over project
Monitoring	Straightforward	With review and trigger points	As real-time as possible, adaptive with management feedback and trigger points

Figure 2-2: Hierarchy of simple, complicated, and complex risks, showing how perceived risks multiply and become less connected with calculated risk with increasing complexity. Also shown are major characteristics of assessment methods for each level of complexity.

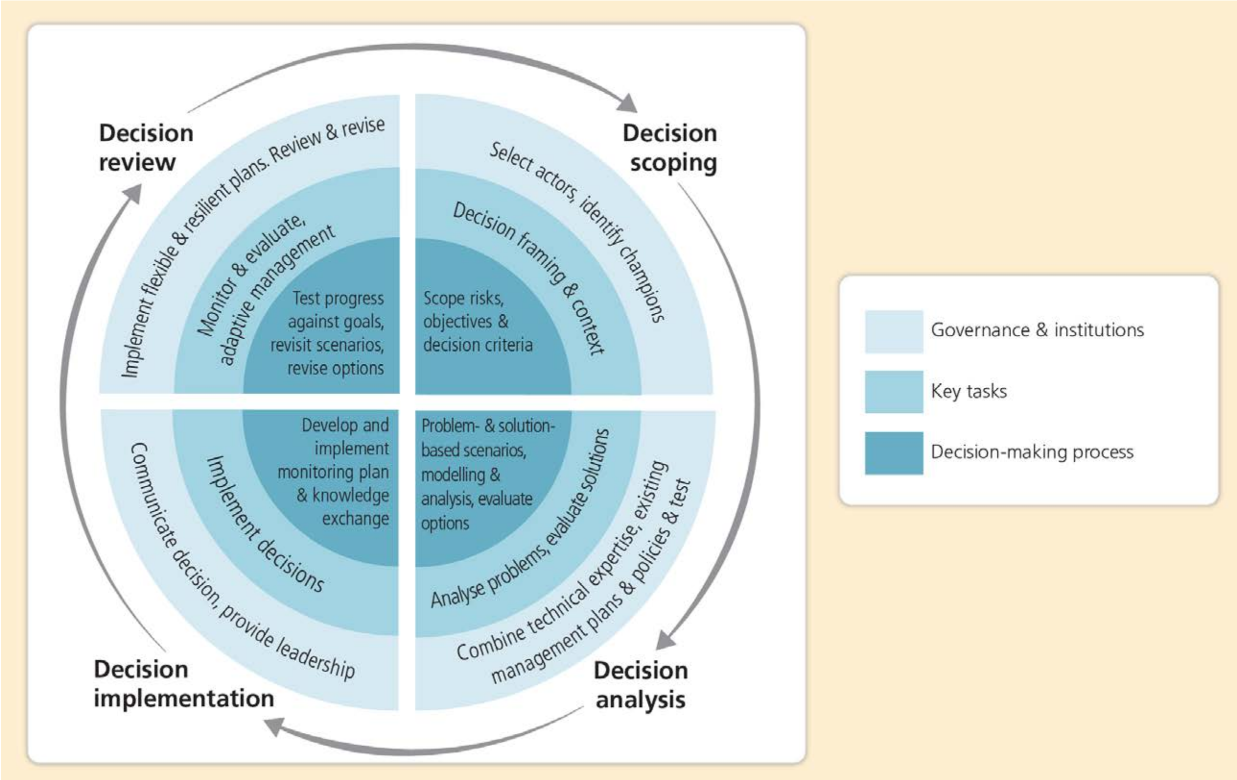


Figure 2-3. Four-stage process of decision making. Note that while adaptive management is located in the decision review quadrant here, when applied it will influence the entire process.

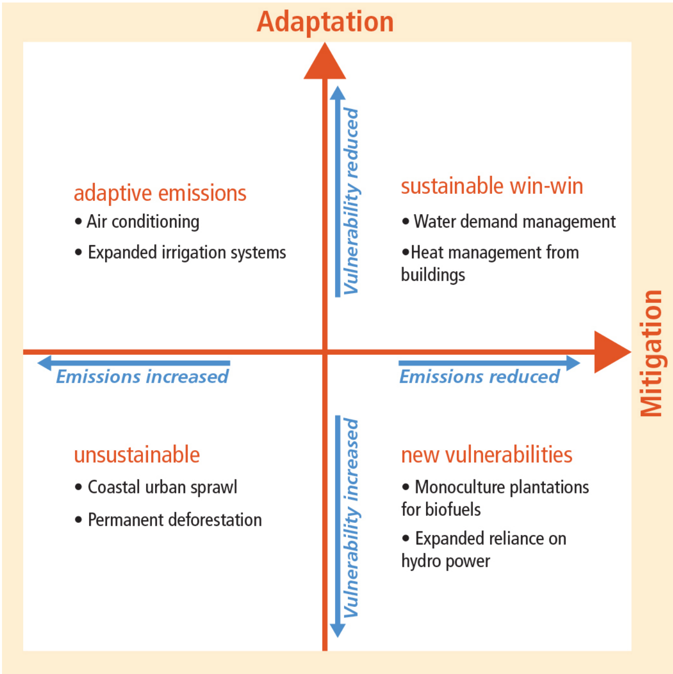


Figure 2-4: Examples of adaptation (A) – mitigation (M) trade-offs and synergies (adapted from Cohen and Waddell, 2009). The upper right quadrant (sustainable win-win) illustrates synergies in which actions enable the achievement of both adaptation and mitigation goals. The lower left quadrant (unsustainable) shows the opposite condition. The upper left (adaptive emissions) and lower right (new vulnerabilities) quadrants illustrate trade-offs that can result from actions within particular local-regional circumstances.

Chapter 3. Freshwater Resources

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Contents

Executive Summary

Key risks at the global scale

Freshwater-related risks of climate change increase significantly with increasing greenhouse gas emissions (*high agreement, robust evidence*) [3.4; 3.5]. Modelling studies since AR4, with large but better quantified uncertainties, have demonstrated clear differences between global futures with higher emissions, which have stronger adverse impacts, and those with lower emissions, which cause less damage and cost less to adapt to [Table 3-2]. Each degree of warming is projected to decrease renewable water resources by at least 20% for an additional 7% of the global population. By the end of the 21st century, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6) [Table 3-2; 3.4.8].

Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*high agreement, robust evidence*) [3.4; 3.5]. This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy and food security [3.5.1; 3.5.2; Box CC-WE]. In contrast, water resources are projected to increase at high latitudes. Proportional changes are typically one to three times greater for runoff than for precipitation. The effects on water resources and irrigation requirements of changes in vegetation due to increasing greenhouse-gas concentrations and climate change remain uncertain [Box CC-VW].

So far there are no widespread observations of changes in flood magnitude and frequency due to anthropogenic climate change, but projections imply variations in the frequency of floods (*medium agreement,*

***limited evidence*).** Flood hazards are projected to increase in parts of south, southeast and northeast Asia, tropical Africa, and South America (*medium agreement, limited evidence*). Since the mid-20th century, socio-economic losses from flooding have increased mainly due to greater exposure and vulnerability (*high confidence*). Global flood risk will increase in the future partly due to climate change (*medium agreement, limited evidence*) [3.2.7; 3.4.8].

Climate change is *likely* to increase the frequency of meteorological droughts (less rainfall) and agricultural droughts (less soil moisture) in presently dry regions by the end of this century under the RCP8.5 scenario (*medium confidence*) [WGI Ch12]. This is *likely* to increase the frequency of short hydrological droughts (less surface water and groundwater) in these regions (*medium agreement, medium evidence*) [3.4.8]. Projected changes in the frequency of droughts longer than 12 months are more uncertain, because these depend on accumulated precipitation over long periods. There is no evidence that surface water and groundwater drought frequency has changed over the last few decades, although impacts of drought have increased mostly due to increased water demand [3.5.1].

Climate change negatively impacts freshwater ecosystems by changing streamflow and water quality (*high agreement, medium evidence*). Quantitative responses are known in only a few cases. Except in areas with intensive irrigation, the streamflow-mediated ecological impacts of climate change are expected to be stronger than historical impacts due to anthropogenic alteration of flow regimes by water withdrawals and the construction of reservoirs [Box CC-RF; 3.5.2.4].

Climate change is projected to reduce raw water quality, posing risks to drinking water quality even with conventional treatment (*high agreement, medium evidence*). The sources of the risks are increased temperature, increases in sediment, nutrient and pollutant loadings due to heavy rainfall, reduced dilution of pollutants during droughts, and disruption of treatment facilities during floods [3.2.5; Figure 3-2; 3.4.6; 3.5.2.3].

In regions with snowfall, climate change has altered observed streamflow seasonality, and increasing alterations due to climate change are projected (*high agreement, robust evidence*) [Table 3-1; 3.2.3; 3.2.7; 3.4.5; 3.4.6; 26.2.2]. Except in very cold regions, warming in the last decades has reduced the spring maximum snow depth and brought forward the spring maximum of snowmelt discharge; smaller snowmelt floods, increased winter flows and reduced summer low flows have all been observed. River ice in Arctic rivers has been observed to break up earlier [3.2.3; 28.2.1.1].

Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*high agreement, robust evidence*). Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments [3.4.3].

There is little or no observational evidence yet that soil erosion and sediment loads have been altered significantly due to changing climate (*medium agreement, limited evidence*). However, increases in heavy rainfall and temperature are projected to change soil erosion and sediment yield, although the extent of these changes is highly uncertain and depends on rainfall seasonality, land cover, and soil management practices [3.2.6; 3.4.7].

Adaptation, mitigation, and sustainable development

Of the global cost of water-sector adaptation, most is necessary in developing countries where there are many opportunities for anticipatory adaptation (*high agreement, medium evidence*). There is limited published information on the water-sector costs of adaptation at the local level [3.6.1; 3.6.3].

An adaptive approach to water management can address uncertainty due to climate change (*high agreement, limited evidence*). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible and low-regret solutions that are resilient to uncertainty. Barriers to progress include lack of human and institutional capacity, financial resources, awareness, and communication [3.6.1; 3.6.2; 3.6.4].

Reliability of water supply, which is expected to suffer from increased variability of surface water availability, may be enhanced by increased groundwater abstractions (*high agreement, limited evidence*). This adaptation to climate change is limited in regions where renewable groundwater resources decrease due to climate change [3.4.5; 3.4.8; 3.5.1].

Some measures to reduce greenhouse gas emissions imply risks for freshwater systems (*high agreement, medium evidence*). If irrigated, bioenergy crops make water demands that other mitigation measures do not. Hydropower has negative impacts on freshwater ecosystems which can be reduced by appropriate management. Carbon capture and storage can decrease groundwater quality. In some regions, afforestation can reduce renewable water resources but also flood risk and soil erosion [3.7.2.1; Box CC-WE].

3.1. Introduction

Changes in the hydrological cycle due to climate change can lead to diverse impacts and risks, and they are conditioned by and interact with non-climatic drivers of change and water-management responses (Figure 3-1). Water is the agent that delivers many of the impacts of climate change to society, for example to the energy, agriculture, and transport sectors. Even though water moves through the hydrological cycle, it is a locally variable resource, and vulnerabilities to water-related hazards such as floods and droughts differ between regions. Anthropogenic climate change is one of many stressors of water resources. Non-climatic drivers such as population increase, economic development, urbanization, and land-use or natural geomorphic changes also challenge the sustainability of resources by decreasing water supply or increasing demand. In this context, adaptation to climate change in the water sector can contribute to improving the availability of water.

[INSERT FIGURE 3-1 HERE
Figure 3-1: Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water-management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).]

The key messages with *high* or *very high confidence* from the Working Group II Fourth Assessment Report (AR4; IPCC, 2007) in respect to freshwater resources were:

- The observed and projected impacts of climate change on freshwater systems and their management are mainly due to increases in temperature and sea level, local changes of precipitation, and changes in the variability of those quantities.
- Semi-arid and arid areas are particularly exposed.
- Warmer water, more intense precipitation, and longer periods of low flow reduce water quality, with impacts on ecosystems, human health, and reliability and operating costs of water services.
- Climate change affects water-management infrastructure and practice.
- Adaptation and risk-management practices have been developed for the water sector in some countries and regions.
- The negative impacts of climate change on freshwater systems outweigh its benefits.

This chapter assesses hydrological changes due to climate change, mainly based on research published since AR4. Current gaps in research and data are summarized in Section 3.8. For further information on observed trends in the water cycle, please see Chapter 2 of the Working Group I (WGI) contribution to this assessment. See WGI Chapter 4 for freshwater in cold regions and WGI Chapter 10 for detection and attribution, Chapter 11 for near-term projections, and Chapter 12 for long-term projections of climate change. In this Working Group II contribution, impacts on aquatic ecosystems are discussed in Chapter 4 (see also Section 3.5.2.4). Chapter 7 describes the impacts of climate change on food production (see also Section 3.5.2.1 for the impact of hydrological changes on the agricultural sector). The health effects of changes in water quality and quantity are covered in Chapter 11, and regional vulnerabilities related to freshwater in Chapters 21-30. Sections 3.2.7, 3.4.8 and 3.6.3 discuss impact costs and adaptation costs related to water resources; these costs are assessed more broadly in Chapter 10.

3.2. Observed Hydrological Changes due to Climate Change

3.2.1. Detection and Attribution

A documented hydrological change is not necessarily due to anthropogenic climate change. Detection entails showing, usually statistically, that part of the documented change is not due to natural variability of the water cycle (Chapter 18; WGI Chapter 10). For robust attribution to climatic change, all the drivers of the hydrological change must be identified, with confidence levels assigned to their contributions. Human contributions such as water withdrawals, land-use change and pollution mean that this is usually difficult. Nevertheless, many hydrological impacts can be attributed confidently to their climatic drivers (Table 3-1). End-to-end attribution, from human climate-altering activities to impacts on freshwater resources, is not attempted in most studies, because it requires experiments with climate models in which the external natural and anthropogenic forcing is “switched off”. However climate models do not currently simulate the water cycle at fine enough resolution for attribution of most catchment-scale hydrological impacts to anthropogenic climate change. Until climate models and impact models become better integrated, it is necessary to rely heavily on multi-step attribution, in which hydrological changes are shown to result from climatic changes that may in turn result partly from human activities.

[INSERT TABLE 3-1 HERE
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, not all of which are necessarily anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.
1: Gerten *et al*. (2008), Piao *et al.* (2010), Alkama *et al.* (2011); 2: Piao *et al*. (2010); 3: Shiklomanov *et al*. (2007); 4: Hidalgo *et al*. (2009); 5: Collins (2008); 6: Baraer *et al*. (2012); 7: Rosenzweig *et al*. (2007); 8: Min *et al*. (2011); 9: Pall *et al*. (2011); 10: Aguilera and Murillo (2009); 11: Jeelani (2008); 12: Evans *et al*. (2005); 13: Marcé *et al*. (2010); 14: Pednekar *et al*. (2005); 15: Paerl *et al*. (2006); 16: Tibby and Tiller (2007).]

Extreme hydrological events, such as floods, prompt speculation about whether they are “caused” by climate change. Climate change can indeed alter the probability of a particular event. However, to estimate the alteration reliably it is necessary to quantify uncertainties due to natural variability in the changed and the unchanged climates, and also – because of the need for model simulations – uncertainties due to limited ability to simulate the climate.

The probability or risk of the extreme event can be measured by recording the fraction of events beyond some threshold magnitude. Call this fraction r_{ctrl} in the simulated actual climate and r_{expt} in the simulated climate in which there is no anthropogenic forcing, and suppose there are many paired instances of r_{ctrl} and r_{expt}, with the ratio of risks in each pair given by $F = r_{expt}/r_{ctrl}$. The distribution of risk ratios F describes the likelihood that the climate change has altered the risk. Several thousand pairs of such simulations were run to estimate the risk ratio for the floods in England and Wales in autumn 2000 (Pall *et al.*, 2011). Each pair started from a unique initial state that differed slightly from a common reference state, and was obtained with a seasonal-forecast model driven by patterns of attributable warming found beforehand from four climate-model simulations of the 20th century. The forecast model was coupled to a model of basin-scale runoff and channel-scale hydraulics. It is not probable that such exercises will become routine for assessing single-event risks in, for example, the insurance industry, because the necessary amount of computation was so formidable. Nevertheless, the result was compelling: in each of the four sets of simulation pairs, the risk increased greatly on average in the runs forced by anthropogenic greenhouse radiation. In aggregate, the most probable amount of increase was two- to three-fold, and at most a few percent of the simulation pairs suggested that anthropogenic forcing actually decreased the risk. This summary is worded carefully: the thousands of simulation pairs were needed for quantifying the uncertainties, which led unavoidably to a spread of likelihoods, and thus to statements about uncertainty about risk that are themselves uncertain.

3.2.2. Precipitation, Evapotranspiration, Soil Moisture, Permafrost, and Glaciers

Global trends in precipitation from several different datasets during 1901-2005 are statistically insignificant (Bates *et al*., 2008; WGI Chapter 2). According to regional observations, most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Arndt *et al*., 2010) and certain trends in total and extreme precipitation amounts are observed (WGI Chapter 2). Most regional changes in precipitation are attributed either to internal variability of the atmospheric circulation or to global warming (Lambert *et al*., 2004; Stott *et al*., 2010). It was estimated that the 20th-century anthropogenic forcing contributed significantly to observed changes in global and regional precipitation (Zhang *et al*., 2007). Changes in snowfall amounts are indeterminate, as for precipitation; however, consistent with observed warming, shorter snowfall seasons are observed over most of the Northern Hemisphere, with snowmelt seasons starting earlier (Takala *et al*., 2009). In Norway, increased temperature at lower altitudes has reduced the snow water equivalent (Skaugen *et al*., 2012).

Steady decreases since the 1960s of global and regional actual evapotranspiration and pan evaporation have been attributed to changes in precipitation, in diurnal temperature range, aerosol concentration, (net) solar radiation, vapour pressure deficit, and wind speed (Fu *et al*., 2009; McVicar *et al*., 2010; Miralles *et al*., 2011; Wang A. *et al*., 2011). Regional downward and upward trends in soil moisture content have been calculated for China from 1950 to 2006, where longer, more severe and more frequent soil moisture droughts have been experienced over 37% of the land area (Wang A. *et al*., 2011). This is supported by detected increases since the 1960s in dry days and a prolongation of dry periods (Fischer *et al.*, 2013; Gemmer *et al*., 2011), and can be attributed to increases in warm days and warm periods (Fischer *et al.*, 2011).

Decreases in the extent of permafrost and increases in its average temperature are widely observed, for example in some regions of the Arctic and Eurasia (WGI Chapter 4) and the Andes (Rabassa, 2009). Active layer depth and permafrost degradation are closely dependent on soil ice content. In steep terrain, slope stability is highly affected by changes in permafrost (Harris *et al*., 2009). The release of GHGs (greenhouse gases) due to permafrost degradation can have unprecedented impacts on the climate, but these processes are not well represented in global climate models yet (Grosse *et al*., 2011). In most parts of the world glaciers are losing mass (Gardner *et al.*, 2013). For example, almost all glaciers in the tropical Andes have been shrinking rapidly since the 1980s (Rabassa, 2009; Rabatel *et al.*, 2013); similarly, Himalayan glaciers are losing mass at present (Bolch *et al.*, 2012).

3.2.3. Streamflow

Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature since the 1950s. In Europe, streamflow (1962-2004) decreased in the south and east and generally increased elsewhere (Stahl *et al*., 2010; 2012), particularly in northern latitudes (Wilson *et al*., 2010). In North America (1951-2002), increases were observed in the Mississippi basin and decreases in the US Pacific Northwest and southern Atlantic-Gulf regions (Kalra *et al*., 2008). In China, a decrease in streamflow in the Yellow River (1960-2000) is consistent with a reduction of 12% in summer and autumn precipitation, whereas the Yangtze shows a small increase in annual streamflow driven by an increase in monsoon rains (Piao *et al*., 2010; see Table 3-1). These and other stream flow trends must be interpreted with caution (Jones, 2011) because of confounding factors such as land-use changes (Zhang and Schilling, 2006), irrigation (Kustu *et al*., 2010) and urbanization (Wang and Cai, 2010).

In a global analysis of simulated streamflows (1948-2004), about one-third of the top 200 rivers (including the Congo, Mississippi, Yenisei, Paraná, Ganges, Columbia, Uruguay and Niger) showed significant trends in discharge; 45 recorded decreases and only 19 recorded increases (Dai *et al*., 2009). Decreasing trends in low and mid latitudes are consistent with recent drying and warming in West Africa, southern Europe, south and east Asia, eastern Australia, western Canada and the USA and northern South America (Dai, 2013). The contribution to observed streamflow changes due to decreased stomatal opening of many plant species at higher CO_2 concentration remains disputed (Box CC-VW).

In regions with seasonal snow storage, warming since the 1970s has led to earlier spring discharge maxima (*high agreement, robust evidence*) and has increased winter flows because more winter precipitation falls as rain instead of snow (Clow, 2010; Korhonen and Kuusisto, 2010; Tan *et al*., 2011). There is *robust evidence* of earlier breakup of river ice in Arctic rivers (de Rham *et al*., 2008; Smith, 2000). Where streamflow is lower in summer, decrease in snow storage has exacerbated summer dryness (Cayan *et al*., 2001; Knowles *et al*., 2006).

3.2.4. Groundwater

Attribution of observed changes in groundwater level, storage or discharge to climatic changes is difficult due to additional influences of land use changes and groundwater abstractions (Stoll *et al*., 2011). Observed trends are largely attributable to these additional influences. The extent to which groundwater abstractions have already been affected by climate change is not known. Both detection of changes in groundwater systems and attribution of those changes to climatic changes are rare, due to a lack of appropriate observation wells and a small number of studies. Observed decreases of the discharge of groundwater-fed springs in Kashmir (India) since the 1980s were attributed to observed precipitation decreases (Jeelani, 2008; Table 3-1). A model-based assessment of observed decreases of groundwater levels in four overexploited karst aquifers in Spain led to the conclusion that groundwater recharge not only decreased strongly during the 20th century due to the decreasing precipitation but that groundwater recharge as a fraction of observed precipitation declined progressively, possibly indicating an increase in evapotranspiration (Aguilera and Murillo, 2009; Table 3-1).

3.2.5. Water Quality

Most observed changes of water quality due to climate change (Table 3-1; Figure 3-2) are known from isolated studies, mostly of rivers or lakes in high-income countries, of a small number of variables. In addition, even though some studies extend over as many as 80 years, most are short-term. For lakes and reservoirs, the most frequently reported change is more intense eutrophication and algal blooms at higher temperatures, or shorter hydraulic retention times and higher nutrient loads resulting from increased storm runoff (*high agreement, medium to robust evidence*). Greater runoff results in greater loads of salts, faecal coliforms, pathogens and heavy metals (Boxall *et al*., 2009; Paerl *et al.*, 2006; Pednekar *et al.*, 2005; Tibby and Tiller, 2007) (*medium to high agreement, robust evidence*, depending on the pollutant). In some cases there are associated impacts on health. For instance, hospital admissions for gastrointestinal illness in elderly people increased by 10% when turbidity increased in the raw water of a drinking water plant even when treated using conventional procedures (Schwartz *et al*., 2000). However, positive impacts were also reported. For example, the risk of eutrophication was reduced when nutrients were flushed from lakes and estuaries by more frequent storms and hurricanes (Paerl and Huisman, 2008). For rivers, all reported impacts on water quality were negative. Greater runoff, instead of diluting pollution, swept more pollutants from the soil into watercourses (*medium to high agreement, robust evidence*) (Benítez-Gilabert *et al*., 2010; Boxall *et al*., 2009; Gascuel-Odoux *et al.*, 2010; Howden *et al*., 2010; Loos *et al*., 2009; Macleod *et al*., 2012; Saarinen *et al*., 2010; Tetzlaff *et al.*, 2010). Increased organic matter content impaired the quality of conventionally treated drinking water (Weatherhead and Howden, 2009). In streams in semiarid and arid areas, temperature changes had a stronger influence on the increase of organic matter, nitrates and phosphorus than precipitation changes (Benítez-Gilabert *et al.*, 2010; Chang, 2004; Ozaki *et al.*, 2003) (*medium agreement, limited evidence*). Studies of impacts on groundwater quality are limited and mostly report elevated concentrations of faecal coliforms during the rainy season or after extreme rain events (*high agreement, medium evidence*), with varying response times (Auld *et al*., 2004; Curriero *et al*., 2001; Jean *et al*., 2006; Seidu *et al*., 2013; Tumwine *et al*., 2002; 2003). Given the widespread use of groundwater for municipal supply and minimal or lacking treatment of drinking water in poor regions, increased pollution is a source of concern (Jean *et al.*, 2006; Seidu *et al*., 2013). Another concern is the nonlinearity (except for temperature) of relationships between water quality and climatic variables (*medium agreement, limited evidence*). In general, the linkages between observed effects on water quality and climate should be interpreted cautiously and at the local level, considering the type of water body, the pollutant of concern, the hydrological regime and the many other possible sources of pollution (*high confidence*, Benítez-Gilabert *et al*., 2010; Howden *et al*., 2010; Kundzewicz and Krysanova, 2010; Senhorst and Zwolsman, 2005; Ventela *et al*., 2011; Whitehead *et al*., 2009a).

[INSERT FIGURE 3-2 HERE
Figure 3-2: Observations of the impacts of climate on water quality.]

3.2.6. Soil Erosion and Sediment Load

Precipitation extremes in many regions have increased since 1950 (Seneviratne *et al*., 2012), which suggests an increase in rainfall erosivity that would enhance soil erosion and stream sediment loads. A warmer climate may affect soil moisture, litter cover and biomass production, and can bring about a shift in winter precipitation from snow to more erosive rainfall (Kundzewicz *et al*., 2007) or, in semiarid regions, an increase in wildfires with subsequent rainfall leading to intense erosive events (Bussi *et al*., 2013; Nyman *et al*., 2011). The effects of climate change on soil erosion and sediment load are frequently obscured by human agricultural and management activities (Walling, 2009).

Only few studies have isolated the contribution of climate change to observed trends in soil erosion and sediment load. In the Yellow River basin, where soil erosion results mostly from heavy rainfall, reduced precipitation (~10%) contributed about 30% to a total reduction in stream sediment loads reaching the sea during 2000-2005, compared to 1950-1968, with the remaining 70% attributable to sediment trapping in reservoirs and soil conservation measures (Miao *et al*., 2011; Wang *et al*., 2007). Dai *et al*. (2008), analyzing the decrease in sediment load of the Yangtze River over 1956-2002, found that climate change was responsible for an increase of about 3±2%; most of the decline in its lower reaches was due to dam construction (Three Gorges Dam) and soil conservation measures.

Potential impacts of climate change on soil erosion and sediment production are of concern in regions with pronounced glacier retreat (Walling, 2009). Glacial rivers are expected to discharge more meltwater, which may increase sediment loads. However, the *limited evidence* is inconclusive for a global diagnosis of sediment load changes; there are both decreasing (e.g. Iceland, Lawler *et al*., 2003) and increasing trends (Patagonia, Fernandez *et al*., 2011). So far, there is no clear evidence that the frequency or magnitude of shallow landslides have changed over past decades (Huggel *et al*., 2012), even in regions with relatively complete event records (e.g. Switzerland, Hilker *et al*., 2009). Increased landslide impacts (measured by casualties or losses) in south and southeast Asia, where landslides are predominantly triggered by monsoon and tropical cyclone activity, are largely attributed to population growth leading to increased exposure (Petley, 2012).

In summary, there is *low agreement* and *limited evidence* that anthropogenic climate change has made a significant contribution to soil erosion, sediment loads and landslides. The available records are limited in space and time, and evidence suggests that, in most cases, the impacts of land-use and land-cover changes are more significant than those of climate change.

3.2.7. Extreme Hydrological Events and Their Impacts

There is *low confidence*, due to *limited evidence*, that anthropogenic climate change has affected the frequency and magnitude of floods at global scale (Kundzewicz *et al*., 2013). The strength of the evidence is limited mainly by lack of long-term records from unmanaged catchments. Moreover, in the attribution of detected changes it is difficult to distinguish the roles of climate and human activities (Section 3.2.1). However, recent detection of trends in extreme precipitation and discharge in some catchments implies greater risks of flooding at regional scale (*medium confidence*). More locations show increases in heavy precipitation than decreases (Seneviratne *et al*., 2012). Flood-damage costs worldwide have been increasing since the 1970s, although this is partly due to increasing exposure of people and assets (Handmer *et al*., 2012).

There is no strong evidence for trends in observed flooding in the USA (Hirsch and Ryberg, 2012), Europe (Benito and Machado, 2012; Hannaford and Hall, 2012; Mudelsee *et al*., 2003; Stahl *et al*., 2010), South America, and Africa (Conway *et al*., 2009). However, at smaller spatial scales, an increase in annual maximum discharge has been detected in parts of northwestern Europe (Giuntoli *et al*., 2012; Hattermann *et al*., 2012; Petrow and Merz, 2009), while a decrease was observed in southern France (Giuntoli *et al*., 2012). Flood discharges in the lower Yangtze basin increased over the last 40 years (Jiang *et al*., 2008; Zhang *et al*., 2009), and both upward and downward trends were identified in four basins in the northwestern Himalaya (Bhutiyani *et al*., 2008). In Australia, only 30% of 491 gauge stations showed trends at the 10% significance level, with decreasing magnitudes in southern regions and increasing magnitudes in the northern regions (Ishak *et al*., 2010). In Arctic rivers dominated by a snowmelt regime, there is no general trend in flood magnitude and frequency (Shiklomanov *et al*., 2007). In Nordic countries, significant changes since the mid-20th century are mostly towards earlier seasonal flood peaks, but flood magnitudes show contrasting trends, driven by temperature and precipitation, in basins with and without glaciers: increasing peaks in the former and decreasing peaks in the latter (Dahlke *et al*., 2012; Wilson *et al*., 2010). Significant trends at almost one fifth of 160 stations in Canada were reported, most of them decreases in snowmelt-flood magnitudes (Cunderlik and Ouarda, 2009). Similar decreases were found for spring and annual maximum flows (Burn *et al*., 2010).

Attribution has been addressed by Hattermann *et al*. (2012), who identified parallel trends in precipitation extremes and flooding in Germany, which for the increasing winter floods are explainable in terms of increasing frequency and persistence of circulation patterns favourable to flooding (Petrow *et al*., 2009). It is *very likely* that the observed intensification of heavy precipitation is largely anthropogenic (Min *et al.*, 2011; see also Section 3.2.1).

Socio-economic losses from flooding are increasing (*high confidence*), although attribution to anthropogenic climate change is established only seldom (Pall *et al.*, 2011). Reported flood damages (adjusted for inflation) have increased from an average of 7 billion US$ per year in the 1980s to about 24 billion US$ per year in 2011 (Munich Re, 2012; Kundzewicz *et al*., 2013). Economic, including insured, flood disaster losses are higher in developed countries, while fatality rates and economic losses expressed as a proportion of gross domestic product are higher in developing countries. Since 1980, the annual number of flood-related deaths has been in the thousands, with over 95% in developing countries and 75% in southern, southeastern and eastern Asia (Handmer *et al*., 2012). There is *high confidence* (*high agreement*, *medium evidence*) that greater exposure of people and assets, and societal factors related to population and economic growth, contributed to the increased losses (Handmer *et al*., 2012; Kundzewicz *et al*., 2013). When damage records are normalized for changes in exposure and vulnerability (Bouwer, 2011), most studies find no contribution of flooding trends to the trend in losses (Barredo, 2009; Benito and Machado, 2012; Hilker *et al*., 2009), although there are exceptions (Chang *et al*., 2009; Jiang *et al*., 2005).

Assessments of observed changes in 'drought' depend on the definition of drought (meteorological, agricultural or hydrological) and the chosen drought index (e.g. consecutive dry days, Standardised Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardised Runoff Index (SRI); see Seneviratne *et al.*, 2012). Meteorological (rainfall) and agricultural (soil moisture) droughts have become more frequent since 1950 (Seneviratne *et al*., 2012) in some regions, including southern Europe and western Africa, but in others (including the southern USA; Chen *et al*., 2012) there is no evidence of change in frequency (WGI Chapter 2).

Very few studies have considered variations over time in hydrological (streamflow) drought, largely because there are few long records from catchments without direct human interventions. A trend was found towards lower summer minimum flows for 1962–2004 in small catchments in southern and eastern Europe were found, but there was no clear trend in northern or western Europe (Stahl *et al*., 2010). Models can reproduce observed patterns of drought occurrence (e.g. Prudhomme *et al*., 2011), but as with climate models their outputs can be very divergent. In simulations of drought at the global scale in 1963–2000 with an ensemble of hydrological models, strong correlations were noted between ENSO (El Niño-Southern Oscillation) events and hydrological droughts, and – particularly in dry regions – low correlations between meteorological and hydrological droughts, which suggests that hydrological droughts cannot necessarily be inferred from rainfall deficits (van Huijgevoort *et al*., 2013).

3.3. Drivers of Change for Freshwater Resources

3.3.1. Climatic Drivers

Precipitation and potential evaporation are the main climatic drivers controlling freshwater resources. Precipitation is strongly related to atmospheric water-vapor content, because saturation specific humidity depends on temperature: warmer air can hold much more water vapor. Temperature has increased in recent decades while surface and tropospheric relative humidity have changed little (WGI Chapter 2). Among other climatic drivers are atmospheric carbon dioxide, which affects plant transpiration (Box CC-VW), and deposited black carbon and dust, both of which, even in very small concentrations, enhance melting of snow and ice by reducing the surface albedo.

Uncertainty in the climatic drivers is due mainly to internal variability of the atmospheric system, inaccurate modelling of the atmospheric response to external forcing, and the external forcing itself as described by the Representative Concentration Pathways (RCPs; Section 1.1.3 in Chapter 1). Internal variability and variation between models account for all of the uncertainty in precipitation in the first few decades of the 21st century in CMIP (Coupled Model Intercomparison Project) Phase 3 projections (Hawkins and Sutton, 2011). The contribution of internal variability diminishes progressively. By no later than mid-century, most of the uncertainty in precipitation is due to discrepancies between models, and divergent scenarios never contribute more than one third of the uncertainty. In contrast, the uncertainty in temperature (WGI Chapter 11) is due mostly to divergent scenarios.

CMIP5 simulations of the water cycle during the 21st century (WGI Chapter 12), with further constraints added here from 20th-century observations, can be summarized as follows:

- Surface temperature, which affects the vapor-carrying capacity of the atmosphere and the ratio of snowfall to precipitation, increases non-uniformly, but by about 1.5 times more over land than over ocean (*very high confidence*).
- Warming is greatest over the Arctic (*very high confidence*), implying latitudinally variable changes in snowmelt and glacier mass budgets.
- Less precipitation falls as snow and snow cover decreases in extent and duration (*high confidence*). In the coldest regions, however, increased winter snowfall outweighs increased summer snowmelt.
- Wet regions and seasons become wetter and dry regions and seasons become drier (*high confidence*), although one observational analysis (Sun *et al.*, 2012) is discordant; moreover the models tend to underestimate observed trends in precipitation (Noake *et al.*, 2012) and its observed sensitivity to temperature (Liu *et al.*, 2012).
- Global mean precipitation increases in a warmer world (*virtually certain*), but with substantial variations, including some decreases, from region to region. Precipitation tends to decrease in subtropical latitudes, particularly in the Mediterranean, Mexico and central America and parts of Australia, and to increase elsewhere, notably at high northern latitudes and in India and parts of central Asia (*likely* to *very likely*; WGI Chapter 12, Figure 12-41). However, precipitation changes generally become statistically significant only when temperature rises by at least 1.4°C, and in many regions projected 21st-century changes lie within the range of late-20th-century natural variability (Mahlstein *et al.*, 2012).
- Changes in evaporation have patterns similar to those of changes in precipitation, with moderate increases almost everywhere, especially at higher northern latitudes (Figure 12-25 in WGI Chapter 12). Scenario-dependent decreases of soil moisture are widespread, particularly in central and southern Europe, southwestern North America, Amazonia and southern Africa (*medium to high confidence*; Figure 12-23 and Section 12.4.5.3 in WGI Chapter 12).

More intense extreme precipitation events are expected (IPCC, 2012). One proposed reason is the projected increase in specific humidity: intense convective precipitation in short periods (less than 1 hour) tends to “empty” the water vapor from the atmospheric column (Berg *et al.*, 2013; Utsumi *et al.*, 2011). Annual maxima of daily precipitation that are observed to have 20-year return periods in 1986-2005 are projected to have shorter return periods in 2081-2100: about 14 years for RCP2.6, 11 years for RCP4.5 and 6 years for RCP8.5 (Kharin *et al.*, 2013). Unlike annual mean precipitation, for which the simulated sensitivity to warming is typically 1.5-2.5% K^{-1}, the 20-year return amount of daily precipitation typically increases at 4-10% K^{-1}. Agreement between model-simulated extremes and reanalysis extremes is good in the extra-tropics but poor in the tropics, where there is *robust evidence* of greater sensitivity (10±4% K^{-1}, O'Gorman, 2012). In spite of the intrinsic uncertainty of sampling infrequent events, variation between models is the dominant contributor to uncertainty. Model-simulated changes in the incidence of meteorological (rainfall) droughts vary widely, so that there is at best *medium confidence* in projections (Seneviratne *et al.*, 2012). Regions where droughts are projected to become longer and more frequent include the Mediterranean, central Europe, central North America and southern Africa.

3.3.2. Non-Climatic Drivers

In addition to impacts of climate change, the future of freshwater systems will be impacted strongly by demographic, socio-economic and technological changes, including lifestyle changes. These change both exposure to hazard and requirements for water resources. A wide range of socio-economic futures can produce similar climate changes (van Vuuren *et al*., 2012), meaning that certain projected hydrological changes (Section 3.4) can occur under a wide range of future demographic, social, economic and ecological conditions. Similarly the same future socio-economic conditions can be associated with a range of different climate futures.

Changing land use is expected to affect freshwater systems strongly in the future. For example, increasing urbanization may increase flood hazards and decrease groundwater recharge. Of particular importance for freshwater systems is future agricultural land use, especially irrigation, which accounts for about 90% of global water consumption and severely impacts freshwater availability for humans and ecosystems (Döll, 2009). Due mainly to population and economic growth but also to climate change, irrigation may significantly increase in the future. The share of irrigation from groundwater is expected to increase due to increased variability of surface water supply caused by climate change (Taylor R. *et al*., 2013a).

3.4. Projected Hydrological Changes

3.4.1. Methodological Developments in Hydrological Impact Assessment

Most recent studies of the potential impact of climate change on hydrological characteristics have used a small number of climate scenarios. An increasing number has used larger ensembles of regional or global models (e.g. Arnell, 2011; Arnell and Gosling, 2013; Bae *et al*., 2011; Chiew *et al*., 2009; Gosling *et al*., 2010; Jackson *et al*., 2011; Kling *et al*., 2012; Olsson *et al*., 2011). Some studies have developed "probability distributions" of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke *et al*., 2009b; Christierson *et al*., 2012; Liu *et al*., 2013; Manning *et al*., 2009). These studies conclude that the relative weightings given are typically less important in determining the distribution of future impacts than the initial selection of climate models considered. Very few impact studies (Dankers *et al*., 2013; Hanasaki *et al*., 2013; Portmann *et al.*, 2013; Schewe *et al*., 2013) have so far used scenarios based on CMIP5 climate models, and these have only used a small subset.

Most assessments have used a hydrological model with the "delta method" to create scenarios, which applies projected changes in climate derived from a climate model either to an observed baseline or with a stochastic weather generator. Several approaches to the construction of scenarios at the catchment scale have been developed (Fowler *et al*., 2007), including dynamical downscaling using regional climate models and a variety of statistical approaches (e.g. Fu *et al*., 2013). Systematic evaluations of different methods have demonstrated that estimated impacts can be very dependent on the approach used to downscale climate model data, and the range in projected change between downscaling approaches can be as large as the range between different climate models (Chen J. *et al*., 2011; Quintana Segui *et al*., 2010). An increasing number of studies (e.g. Fowler and Kilsby, 2007; Hagemann *et al*., 2011; Kling *et al*., 2012; Teutschbein and Seibert, 2012; Veijalainen *et al*., 2012; Weiland *et al*., 2012a) have run hydrological models with bias-corrected input from regional or global climate model output (Piani *et al*., 2010; van Pelt *et al*., 2009; Yang *et al*., 2010), rather than by applying changes to an observed baseline. The range between different bias correction methods can be as large as the range between climate models (Hagemann *et al*., 2011), although this is not always the case (Chen C. *et al*., 2011; Muerth *et al*., 2013). Some studies (e.g. Falloon and Betts, 2006; 2010; Hirabayashi *et al*., 2008; Nakaegawa *et al*., 2013) have examined changes in global-scale river runoff as simulated directly by a high-resolution climate model, rather than by an "off-line" hydrological model. Assessments of the ability of climate models directly to simulate current river flow regimes (Falloon *et al*., 2011; Weiland *et al*., 2012b) show that performance largely depends on simulated precipitation and is better for large basins, but the limited evidence suggests that direct estimates of change are smaller than off-line estimates (Hagemann *et al*., 2013).

The effects of hydrological model parameter uncertainty on simulated runoff changes are typically small when compared with the range from a large number of climate scenarios (Arnell, 2011; Cloke *et al*., 2010; Lawrence and Haddeland, 2011; Steele-Dunne *et al*., 2008; Vaze *et al*., 2010). However, the effects of hydrological model structural uncertainty on projected changes can be substantial (Dankers *et al*., 2013; Hagemann *et al*., 2013; Schewe *et al*., 2013), due to differences in the representation of evaporation and snowmelt processes. In some regions (e.g. high latitudes; Hagemann et al., 2013) with reductions in precipitation (Schewe *et al*., 2013)), hydrological model uncertainty can be greater than climate model uncertainty – although this is based on small numbers of climate models. Much of the difference in projected changes in evaporation is due to the use of different empirical formulations (Milly and Dunne, 2011). In a study in southeast Australia, the effects of hydrological model uncertainty were small compared with climate model uncertainty, but all the hydrological models used the same potential evaporation data (Teng *et al.*, 2012).

Among other approaches to impact assessment, an inverse technique (Cunderlik and Simonovic, 2007) starts by identifying the hydrological changes which would be critical for a system and then uses a hydrological model to determine the meteorological conditions which trigger those changes; the future likelihood of these conditions is estimated by inspecting climate model output, as in a catchment study in Turkey (Fujihara *et al*., 2008a; 2008b). Another approach constructs response surfaces relating sensitivity of a hydrological indicator to changes in climate. Several studies have used a water-energy balance framework (based on Budyko's hypothesis and formula) to characterise the sensitivity of average annual runoff to changes in precipitation and evaporation (Donohue *et al*., 2011; Renner and Bernhofer, 2012; Renner *et al*., 2012). A response surface showing change in flood magnitudes was constructed by running a hydrological model with systematically-varying changes in climate (Prudhomme *et al*., 2010). This approach show the sensitivity of a system to change, and also allows rapid assessment of impacts under specific climate scenarios which can be plotted on the response surface.

3.4.2. Evapotranspiration, Soil Moisture and Permafrost

Based on global and regional climate models as well as physical principles, potential evapotranspiration over most land areas is *very likely* to increase in a warmer climate, thereby accelerating the hydrologic cycle (WGI Chapter 12). Long-term projections of actual evapotranspiration are uncertain in both magnitude and sign. They are affected not only by rising temperatures but also by changing net radiation and soil moisture, decreases in bulk canopy conductance associated with rising CO_2 concentrations, and vegetation changes related to climate change (Box CC-VW; Katul and Novick, 2009). Projections of the response of potential evapotranspiration to a warming climate are also uncertain. Based on six different methodologies, an increase in potential evapotranspiration was associated with global warming (Kingston *et al*., 2009). Regionally, increases are projected in southern Europe, Central America, southern Africa and Siberia (Seneviratne *et al.*, 2010). The accompanying decrease in soil moisture increases the risk of extreme hot days (Hirschi *et al.*, 2011; Seneviratne *et al.*, 2006) and heat waves. For a range of scenarios, soil-moisture droughts lasting 4–6 months double in extent and frequency, and droughts longer than 12 months become three times more common, between the mid-20th century and the end of the 21st century (Sheffield and Wood, 2008). Because of strong natural variability, the generally monotonic projected increases are statistically indistinguishable from current climate.

Changes consistent with warming are also evident in the freshwater systems and permafrost of northern regions. The area of permafrost is projected to continue to decline over the first half of the 21st century in all emissions scenarios (Figure 4-18 in WGI Chapter 4). Under RCP2.6, permafrost area is projected to stabilize at near 20% less than the 20th century area, and then begin to increase slightly.

3.4.3. Glaciers

All projections for the 21st century (WGI Chapter 13) show continued mass loss from glaciers. In glacierized catchments, runoff reaches an annual maximum in summer. As the glaciers shrink, their relative contribution decreases and the annual runoff peak shifts towards spring (e.g. Huss, 2011). This shift is expected with *very high confidence* in most regions, although not, for example, in the eastern Himalaya where the monsoon and the melt season coincide. The relative importance of high-summer glacier meltwater can be substantial, for example contributing 25% of August discharge in basins draining the European Alps, with area ~10^5 km^2 and only 1% glacier cover (Huss, 2011). Glacier meltwater also increases in importance during droughts and heat waves (Koboltschnig *et al*., 2007).

If the warming rate is constant, and if, as expected, ice melting per unit area increases and total ice-covered area decreases, the total annual yield passes through a broad maximum: "peak meltwater". Peak-meltwater dates have been projected between 2010 and 2050 (parts of China, Xie *et al.*, 2006); 2010–2040 (European Alps, Huss, 2011); and mid- to late-century (glaciers in Norway and Iceland, Jóhannesson *et al.*, 2012). Note that the peak can only be dated relative to a specified reference date. Declining yields relative to various dates in the past have been detected in some observational studies (Table 3-1); that is, a peak has been passed already. There is *medium confidence* that the peak response to 20th- and 21st-century warming will fall within the 21st century in many inhabited glacierized basins, where at present society is benefitting from a transitory "meltwater dividend". Variable forcing leads to complex variations of both the melting rate and the extent of ice, which depend on each other.

If they are in equilibrium, glaciers reduce the interannual variability of water resources by storing water during cold or wet years and releasing it during warm years (Viviroli *et al.*, 2011). As glaciers shrink, however, their diminishing influence may make the water supply less dependable.

_____ START BOX 3-1 HERE _____

Box 3-1. Case Study: Himalayan Glaciers

The total freshwater resource in the Himalayan glaciers of Bhutan, China, India, Nepal and Pakistan is known only roughly; estimates range from 2100 to 5800 Gt (Bolch *et al*., 2012). Their mass budgets have been negative on average for the past five decades. The loss rate may have become greater after about 1995, but it has not been greater in the Himalaya than elsewhere. A recent large-scale measurement, highlighted in Figure 3-3, is the first well-resolved, region-wide measurement of any component of the Himalayan water balance. It suggests strongly that the conventional measurements, mostly on small, accessible glaciers, are not regionally representative.

[INSERT FIGURE 3-3 HERE
Figure 3-3: All published glacier mass balance measurements from the Himalaya (based on Bolch *et al*., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements). Region-wide measurement (Kääb *et al*., 2012) was by satellite laser altimetry. Global average (WGI Chapter 4) is shown as a 1-sigma confidence region.]

Glacier mass changes for 2006-2100 were projected by simulating the response of a glacier model to CMIP5 projections from 14 general circulation models (GCMs) (Radić *et al*., 2013). Results for the Himalaya range between 2% gain and 29% loss to 2035; to 2100, the range of losses is 15-78% under RCP4.5. The model-mean loss to 2100 is 45% under RCP4.5 and 68% under RCP8.5 (*medium confidence*). It is *virtually certain* that these projections are more reliable than an earlier erroneous assessment (Cruz *et al*., 2007) of complete disappearance by 2035.

At the catchment scale, projections do not yet present a detailed region-wide picture. However the GCM-forced simulations of Immerzeel *et al.* (2013) in Kashmir and eastern Nepal show runoff increasing throughout the century. Peak ice meltwater is reached in mid- to late-century, but increased precipitation over-compensates for the loss of ice.

The growing atmospheric burden of anthropogenic black carbon implies reduced glacier albedo, and measurements in eastern Nepal by Yasunari *et al*. (2010) suggest that this could yield 70-200 mm/year of additional meltwater. Deposited soot may outweigh the greenhouse effect as a radiative forcing agent for snowmelt (Qian *et al*., 2011).

The hazard due to moraine-dammed ice-marginal lakes continues to increase. In the western Himalaya, they are small and stable in size, while in Nepal and Bhutan they are more numerous and larger, and most are growing (Gardelle *et al*., 2011). There has been little progress on the predictability of dam failure but, of five dams that have failed since 1980, all had frontal slopes steeper than 10° before failure and much gentler slopes afterwards (Fujita *et al*., 2013). This is a promising tool for evaluating the hazard in detail.

The relative importance of Himalayan glacier meltwater decreases downstream, being greatest where the runoff enters dry regions in the west and becoming negligible in the monsoon-dominated east (Kaser *et al*., 2010). In the mountains, however, dependence on and vulnerability to glacier meltwater are of serious concern when measured per head of population.

_____ END BOX 3-1 HERE _____

3.4.4. Runoff and Streamflow

Many of the spatial gaps identified in AR4 have been filled to a very large extent by catchment-scale studies of the potential impacts of climate change on streamflow. The projected impacts in a catchment depend on the sensitivity of the catchment to change in climatic characteristics and on the projected change in the magnitude and seasonal distribution of precipitation, temperature and evaporation. Catchment sensitivity is largely a function of the ratio of runoff to precipitation: the smaller the ratio, the greater the sensitivity. Proportional changes in average annual runoff are typically between one and three times as large as proportional changes in average annual precipitation (Tang and Lettenmaier, 2012).

Projected scenario-dependent changes in runoff at the global scale, mostly from CMIP3 simulations, exhibit a number of consistent patterns (e.g. Arnell and Gosling, 2013; Döll and Zhang, 2010; Fung *et al*., 2011; Hirabayashi *et al*., 2008; Murray *et al*., 2012; Nakaegawa *et al*., 2013; Okazaki *et al*., 2012; Schewe *et al*., 2013; Tang and Lettenmaier, 2012; Weiland *et al*., 2012a). Average annual runoff is projected to increase at high latitudes and in the wet tropics, and to decrease in most dry tropical regions. However, for some regions there is very considerable uncertainty in the magnitude and direction of change, specifically in China, south Asia and large parts of South America. Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation, particularly across south Asia. Figure 3-4 shows the average percentage change in average annual runoff for an increase in global average temperature of 2°C above the 1980-2010 mean, averaged across five CMIP5 climate models and 11 hydrological models. The pattern of change in Figure 3-4 is different in some regions from the pattern shown in WGI Chapter 12 (Figure 12-24), largely because it is based on fewer climate models.

[INSERT FIGURE 3-4 HERE
Figure 3-4: Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 4 GCMs and 11 global hydrological models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe *et al*., 2013).]

The seasonal distribution of change in streamflow varies primarily with the seasonal distribution of change in precipitation, which in turn varies between scenarios. Figure 3-5 illustrates this variability, showing the percentage change in monthly average runoff in a set of catchments from different regions using scenarios from seven climate models, all scaled to represent a 2°C increase in global mean temperature above the 1961-1990 mean. One of the climate models is separately highlighted, and for that model the figure also shows changes with a 4°C rise in temperature. In the Mitano catchment in Uganda, for example, there is a non-linear relationship between amount of climate change and hydrological response. Incorporating uncertainty in hydrological model structure (Section 3.4.1) would increase further the range in projected impacts at the catchment scale.

[INSERT FIGURE 3-5 HERE
Figure 3-5: Change in mean monthly runoff across seven climate models in seven catchments, with a 2ºC increase in global mean temperature above 1961-1990 (Arnell, 2011; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011; Xu *et al*., 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2ºC increase (dotted line) and a 4ºC increase (solid line).]

There is a much more consistent pattern of future seasonal change in areas currently influenced by snowfall and snowmelt. A global analysis (Adam *et al*., 2009) with multiple climate scenarios shows a consistent shift to earlier peak flows, except in some regions areas where increases in precipitation are sufficient to result in increased, rather than decreased snow accumulation during winter. The greatest changes are found near the boundaries of regions which currently experience considerable snowfall, where the marginal effect on snowfall and snowmelt of higher temperatures is greatest.

3.4.5. Groundwater

While the relation between groundwater and climate change was rarely investigated before 2007, the number of studies and review papers (Green *et al*., 2011; Taylor R. *et al*., 2013a) has increased significantly since then. Ensemble studies, relying on between four and twenty climate models, of the impact of climate change on groundwater recharge and partially also on groundwater levels were done for the globe (Portmann *et al*., 2013), all of Australia (Crosbie *et al*., 2013a), the German Danube basin (Barthel *et al*., 2010), aquifers in Belgium and England (Goderniaux *et al*., 2011; Jackson *et al*., 2011), the Pacific coast of the USA and Canada (Allen *et al*., 2010) and the semi-arid High Plains aquifer of the USA (Crosbie *et al*., 2013b; Ng *et al*., 2010). With three exceptions, simulations were run under only one GHG emissions scenario. The range over the climate models of projected groundwater changes was large, from significant decreases to significant increases for the individual study areas, and the range of percentage changes of projected groundwater recharge mostly exceeded the range of projected precipitation changes. The uncertainties in projected groundwater recharge that originate in the hydrological models have not yet been explored. There are only a few studies of the impacts on groundwater of vegetation changes in response to climate change and CO_2 increase (Box CC-VW). Nor are there any studies on the impact of climate-driven changes of land use on groundwater recharge, even though projected increases in precipitation and streamflow variability due to climate change are expected to lead to increased groundwater abstraction (Taylor R. *et al*., 2013a), lowering groundwater levels and storage.

Under any particular climate scenario, the areas where total runoff (sum of surface runoff and groundwater recharge) is projected to increase (or decrease) roughly coincide with the areas where groundwater recharge and thus renewable groundwater resources are projected to increase (or decrease) (Kundzewicz and Döll, 2009). Changes in precipitation intensity affect the fraction of total runoff that recharges groundwater. Increased precipitation intensity may decrease groundwater recharge due to exceedance of the infiltration capacity (typically in humid areas), or may increase it due to faster percolation through the root zone and thus reduced evapotranspiration (typically in semi-arid areas) (Liu, 2011; Taylor R. *et al*., 2013b). The sensitivity of groundwater recharge and levels to climate change is diminished by perennial vegetation, fine-grained soils and aquitards, and is enhanced by annual cropping, sandy soils and unconfined (water-table) aquifers (Crosbie *et al*., 2013b; van Roosmalen *et al*., 2007). The sensitivity of groundwater recharge change to precipitation change was found to be highest for low groundwater recharge and lowest for high groundwater recharge, the ratio of recharge change to precipitation change ranging from 1.5 to 6.0 in the semi-arid High Plains aquifer (Crosbie *et al*., 2013b). Decreasing snowfall may lead to lower groundwater recharge even if precipitation remains constant; at sites in the southwestern USA, snowmelt provides at least 40-70% of groundwater recharge, although only 25-50% of average annual precipitation falls as snow (Earman *et al*., 2006).

Climate change affects coastal groundwater not only through changes in groundwater recharge but also through sea-level rise which, together with the rate of groundwater pumping, determines the location of the saltwater/freshwater interface. While most confined aquifers are expected to be unaffected by sea-level rise, unconfined aquifers are expected to suffer from saltwater intrusion (Werner *et al*., 2012). The volume available for freshwater storage is reduced if the water table cannot rise freely as the sea level rises (Masterson and Garabedian, 2007; Werner *et al*., 2012). This happens where land surfaces are low-lying, for example on many coral islands and in deltas, but also where groundwater discharges to streams. If the difference between the groundwater table and sea level is decreased by 1 meter, the thickness of the unconfined freshwater layer decreases by roughly 40 meter (Ghyben-Herzberg relation). Deltas are also affected by storm surges that drive salt water into stream channels, contaminating the underlying fresh groundwater from above (Masterson and Garabedian, 2007). In three modeling studies, the impact of sea-level rise on groundwater levels was found to be restricted to areas within 10 km from the coast (Carneiro *et al*., 2010; Oude Essink *et al*., 2010; Yechieli *et al*., 2010). Salt water intrusion due to sea-level rise is mostly a very slow process that may take several centuries to reach equilibrium (Webb and Howard, 2011). Even small rates of groundwater pumping from coastal aquifers are expected to lead to stronger salinization of the groundwater than sea-level rise during the 21st century (Ferguson and Gleeson, 2012; Loaiciga *et al*., 2012).

Changes in groundwater recharge also affect streamflow. In the Mitano basin in Uganda, mean global temperature increases of 4°C or more with respect to 1961-1990 are projected to decrease groundwater outflow to the river so much that the spring discharge peak disappears and the river flow regime changes from bimodal to unimodal (one seasonal peak only) (Kingston and Taylor, 2010; Figure 3-5). Changing groundwater tables affect land-surface energy fluxes, including evaporation, and thus feed back on the climate system, in particular in semi-arid areas where the groundwater table is within 2-10 meter of the surface (Ferguson and Maxwell, 2010; Jiang *et al*., 2009).

3.4.6. Water Quality

Climate change affects the quality of water through a complex set of natural and anthropogenic mechanisms working concurrently in parallel and in series. Projections under climate-change scenarios are difficult, both to perform and interpret, because they require not only integration of the climate models with those used to analyze the transportation and transformation of pollutants in water, soil, and air but also the establishment of a proper baseline (Andersen *et al*., 2006; Arheimer *et al*., 2005; Bonte and Zwolsman, 2010; Ducharne, 2008; Marshall and Randhir, 2008; Rehana and Mujumdar, 2012; Towler *et al*., 2010; Trolle *et al*., 2011; Wilby *et al*., 2006). The models have different spatial scales and have to be adapted and calibrated to local conditions for which adequate and appropriate information is needed. In consequence, there are few projections of the impacts of climate change on water quality; where available, their uncertainty is high. It is evident, however, that water-quality projections depend strongly on (a) local conditions; (b) climatic and environmental assumptions; and (c) the current or reference pollution state (Bonte and Zwolsman, 2010; Chang, 2004; Kundzewicz and Krysanova, 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011; Whitehead *et al*., 2009a; 2009b). Most projections suggest that future negative impacts will be similar in kind to those already observed in response to change and variability in air and water temperature, precipitation and storm runoff, and to many confounding anthropogenic factors (Chang, 2004; Whitehead *et al*., 2009a). This holds for natural and artificial reservoirs (Bonte and Zwolsman, 2010; Brikowski, 2008; Ducharne, 2008; Loos *et al*., 2009; Marshall and Randhir, 2008; Qin *et al*., 2010; Sahoo *et al*., 2010; Trolle *et al*., 2011), rivers (Andersen *et al*., 2006; Bowes *et al*., 2012; Whitehead *et al*., 2009a; 2009b) and groundwater (Butscher and Huggenberger, 2009; Rozemeijer *et al*., 2009).

3.4.7. Soil Erosion and Sediment Load

Heavy rainfalls are *likely* to become more intense and frequent during the 21st century in many parts of the world (Seneviratne *et al*., 2012; WGI Chapter 11), which may lead to more intense soil erosion even if the total rainfall does not increase. At the global scale, soil erosion simulated assuming doubled CO_2 is projected to increase about 14% by the 2090s, compared to the 1980s (9% attributed to climate change and 5% to land use change), with increases by as much as 40-50% in Australia and Africa (Yang *et al*., 2003). The largest increases are expected in semiarid areas, where a single event may contribute 40% of total annual erosion (Bussi *et al*., 2013). In agricultural lands in temperate regions, soil erosion may respond to more intense erosion in complex non-linear ways; for instance in the UK a 10% increase in winter rainfall (i.e. during early growing season) could increase annual erosion of arable land by up to 150% (Favis-Mortlock and Boardman, 1995), while in Austria a simulation for 2010–2099 projected a decrease of rainfall by 10-14% in erosion-sensitive months and thus a decline in soil erosion by 11-24% (Scholz *et al*., 2008). Land management practices are critical for mitigating soil erosion under projected climate change. In China's Loess Plateau, four GCMs coupled to an erosion model show soil erosion increasing by 5-195% during 2010-2039 under conventional tillage, for three emission scenarios (A2, B2 and GGa), whereas under conservation tillage they show decreases of 26-77% (Li *et al*., 2011).

Climate change will also affect the sediment load in rivers by altering water discharge and land cover. For example, an increase in water discharge of 11-14% in two Danish rivers under the SRES A2 emission scenario was projected to increase the annual suspended sediment load by 9–16% during 2071-2100 (Thodsen *et al*., 2008). Increases in total precipitation, increased runoff from glaciers, permafrost degradation, and the shift of precipitation from snow to rain will further increase soil erosion and sediment loads in colder regions (Lu *et al*., 2010). In a major headwater basin of the Ganges River, increased precipitation and glacier runoff are projected to increase sediment yield by 26% by 2050 (Neupane and White, 2010). In the tropics, the intensity of cyclones is projected to increase 2-11% by 2100, which may increase soil erosion and landslides (Knutson *et al*., 2010).

In summary, projected increases in heavy rainfall and temperature will lead to changes in soil erosion and sediment load, but due to the non-linear dependence of soil erosion on rainfall rate and its strong dependence on land cover there is *low confidence* in projected changes in erosion rates. At the end of the 21st century, the impact of climate change on soil erosion is expected to be twice the impact of land-use change (Yang *et al*., 2003), although management practices may mitigate the problem at catchment scale.

3.4.8. Extreme Hydrological Events (Floods and Droughts)

The SREX report (Seneviratne *et al*., 2012) recognized that projected increases in temperature and heavy precipitation imply regional-scale changes in flood frequency and intensity, but with *low confidence* because these projections were obtained from a single GCM. Global flood projections based on multiple CMIP5 GCM simulations coupled with global hydrology and land surface models (Dankers *et al*., 2013; Hirabayashi *et al*., 2013) show flood hazards increasing over about half of the globe, but with great variability at the catchment scale. Projections of increased flood hazard are consistent for parts of south and southeast Asia, tropical Africa, northeast Eurasia, and South America (Figure 3-6), while decreases are projected in parts of northern and eastern Europe, Anatolia, central Asia, central North America, and southern South America. This spatial pattern resembles closely that described by Seneviratne *et al.* (2012), but the latest projections justify *medium confidence* despite new appreciation of the large uncertainty due to variation between climate models and their coupling to hydrological models.

[INSERT FIGURE 3-6 HERE
Figure 3-6: a) Multi-model median return period (years) in the 2080s for the 20th-century 100-year flood (Hirabayashi *et al*., 2013), based on one hydrological model driven by 11 CMIP5 GCMs under RCP8.5. At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi *et al*., 2013). Left: ensemble means of historical (black thick line) and future simulations (coloured thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: maximum and minimum (whiskers), mean (horizontal thick lines within each bar), ±1 standarddeviation (box) and projections of each GCM (coloured symbols) averaged over the 21st century. The impact of 21st-century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4-14 times as compared to the 20th century [4±3 (RCP2.6), 7±5 (RCP4.5), 7±6 (RCP6.0) and 14±10 (RCP8.5) times, or 0.1% to 0.4-1.2% of the global population in 2005)]. Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7-25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.]

There have been several assessments of the potential effect of climate change on meteorological droughts (less rainfall) and agricultural droughts (drier soil) (e.g. WGI Chapter 12; Orlowsky and Seneviratne, 2013; Vidal *et al*., 2012), but few on hydrological droughts, either in terms of river runoff or groundwater levels. Many catchment-scale studies (Section 3.4.4) consider changes in indicators of low river flow (such as the flow exceeded 95% of the time), but these indicators do not necessarily characterise 'drought' as they define neither duration nor spatial extent, and are not necessarily particularly extreme or rare. In an ensemble comparison under SRES A1B of the proportion of the land surface exhibiting significant projected changes in hydrological drought frequency to the proportions exhibiting significant changes in meteorological and agricultural drought frequency, 18-30% of the land surface (excluding cold areas) experienced a significant increase in the frequency of 3-month hydrological droughts, whilst approximately 15-45% saw a decrease (Taylor I. *et al*., 2013). This is a smaller area with increased frequency, and a larger area with decreased frequency, than for meteorological and agricultural droughts, and is understandable because river flows reflect the accumulation of rainfall over time. Flows during dry periods may be sustained by earlier rainfall. For example at the catchment scale in the Pacific Northwest (Jung and Chang, 2012), short hydrological droughts are projected to increase in frequency whilst longer droughts remain unchanged because, although dry spells last longer, winter rainfall increases.

The impacts of floods and droughts are projected to increase even when the hazard remains constant, due to increased exposure and vulnerability (Kundzewicz *et al*., 2013). Projected flood damages vary greatly between models and from region to region, with the largest losses in Asia. Projections from 21 GCMs under SRES A1B of the population exposed by 2050 to a doubling of flood frequency range from 31 to 449 million people, and the change in risk varies between -9 and +376% (Arnell and Gosling, 2013). Studies of projected flood damages are mainly focussed in Europe, the USA and Australia (Bouwer, 2013; Handmer *et al*., 2012). In Europe, the annual damage (€6.4 billion) and number of people exposed (200,000) in 1961-1990 are expected to increase about twofold by the 2080s under scenario B2 and about three times under scenario A2 (Feyen *et al*., 2012). Drought impacts at continental and smaller scales are difficult to assess because they will vary greatly with the local hydrological setting and water-management practices (Handmer *et al*., 2012). More frequent droughts due to climate change may challenge existing water management systems (Kim *et al*., 2009); together with an increase of population, this may place at risk even the domestic supply in parts of Africa (MacDonald *et al*., 2009).

3.5. Projected Impacts, Vulnerabilities, and Risks

In general, projections of freshwater-related impacts, vulnerabilities and risks caused by climate change are evaluated by comparison to historical conditions. Such projections are helpful for understanding human impact on nature and for supporting adaptation to climate change. However, for supporting decisions on climate mitigation, it is more helpful to compare the different hydrological changes that are projected under different future GHG emissions scenarios, or different amounts of global mean temperature rise. One objective of such projections is to quantify what may happen under current water-resources management practice, and another is to indicate what actions may be needed to avoid undesirable outcomes (Oki and Kanae, 2006). The studies compiled in Table 3-2 illustrate the benefits of reducing GHG emissions for the Earth's freshwater systems. Emissions scenarios are rather similar until the 2050s. Their impacts, and thus the benefits of mitigation, tend to become more clearly marked by the end of the 21st century. For example, the fraction of the world population exposed to a 20th century 100-year flood is projected to be, at the end of the 21st century, three times higher per year for RCP8.5 than for RCP2.6 (Hirabayashi *et al*., 2013). Each degree of global warming (up to 2.7°C above pre-industrial levels; Schewe *et al.*, 2013) is projected to decrease renewable water resources by at least 20% for an additional 7% of the world population. The number of people with significantly decreased access to renewable groundwater resources is projected to be roughly 50% higher under RCP8.5 than under RCP2.6 (Portmann *et al*., 2013). The percentage of global population living in river basins with new or aggravated water scarcity is projected to increase with global warming, from 8% at 2°C to 13% at 5°C (Gerten *et al.*, 2013).

[INSERT TABLE 3-2 HERE
Table 3-2: Effects of different GHG emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the SRES scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. RCP8.5 is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the CMIP5 model

mean) over different reference periods, typically since pre-industrial. GW is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2080s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2080s, while in RCP2.6, GW stays below 1.8°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase.]

3.5.1. Availability of Water Resources

Approximately 80% of the world's population already suffers serious threats to its water security, as measured by indicators including water availability, water demand and pollution (Vörösmarty *et al*., 2010). Climate change can alter the availability of water and therefore threaten water security.

Global-scale analyses so far have concentrated on measures of resource availability rather than the multi-dimensional indices used in Vörösmarty *et al*. (2010). All have simulated future river flows or groundwater recharge using global-scale hydrological models. Some have assessed future availability based on runoff per capita (Arnell *et al*., 2011; Arnell *et al*., 2013; Fung *et al*., 2011; Gerten *et al*., 2013; Gosling and Arnell, 2013; Hayashi *et al*., 2010; Murray *et al*., 2012; Schewe *et al*., 2013), whilst others have projected future human withdrawals and characterized availability by the ratio of withdrawals to availability from runoff or recharge (Arnell *et al*., 2011; Gosling and Arnell, 2013; Hanasaki *et al*., 2013). A groundwater vulnerability index was constructed which combined future reductions of renewable groundwater resources with water scarcity, dependence on groundwater and the Human Development Index (Figure 3-7) (Döll, 2009). There are several key conclusions from this set of studies. First, the spatial distribution of the impacts of climate change on resource availability varies considerably between climate models, and strongly with the pattern of projected rainfall change. There is strong consistency in projections of reduced availability around the Mediterranean and parts of southern Africa, but much greater variation in projections for south and east Asia. Second, some water-stressed areas see increased runoff in the future (Section 3.4.4), and therefore less exposure to water-resources stress. Third, over the next few decades and for increases in global mean temperature of less than around 2^{o}C above pre-industrial, changes in population will generally have a greater effect on changes in resource availability than will climate change. Climate change would, however, regionally exacerbate or offset the effects of population pressures. Fourth, estimates of future water availability are sensitive not only to climate and population projections and population assumptions, but also to the choice of hydrological impact model (Schewe *et al*., 2013) and to the adopted measure of stress or scarcity. As an indication of the potential magnitude of the impact of climate change, Schewe *et al*. (2013) estimated that approximately 8% of the global population would see a severe reduction in water resources (a reduction in runoff either greater than 20% or more than the standard deviation of current annual runoff) with a 1^{o}C rise in global mean temperature (compared to the 1990s), rising to 14% at 2^{o}C and 17% at 3^{o}C; the spread across climate and hydrological models was, however, large.

[INSERT FIGURE 3-7 HERE
Figure 3-7: Human vulnerability to climate-change induced decreases of renewable groundwater resources by the 2050s. Lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961-1990 (Döll, 2009)]

Under climate change, reliable surface water supply is expected to decrease due to increased variability of river flow that is due in turn to increased precipitation variability and decreased snow and ice storage. Under these circumstances, it might be beneficial to take advantage of the storage capacity of groundwater and to increase groundwater withdrawals (Kundzewicz and Döll, 2009). However, this option is only sustainable where, over the long term, withdrawals remain well below recharge, while care must also be taken to avoid excessive reduction of groundwater outflow to rivers. Therefore, groundwater cannot be expected to ease freshwater stress where climate change is projected to decrease groundwater recharge and thus renewable groundwater resources (Kundzewicz and Döll, 2009). The percentage of projected global population (SSP2 population scenario) that will suffer from a decrease of renewable groundwater resources of more than 10% between the 1980s and the 2080s was computed to range from 24% (mean based on five GCMs, range 11-39%) for RCP2.6 to 38% (range 27-50%) for RCP8.5 (Portmann *et al*., 2013; Table 3-2). The land area affected by decreases of groundwater resources increases linearly with global mean temperature rise between 0°C and 3°C. For each degree of global mean temperature rise, an additional 4% of the global land area is projected to suffer a groundwater resources decrease of more than 30%, and an additional 1% to suffer a decrease of more than 70% (Portmann *et al*., 2013).

3.5.2. Water Uses

3.5.2.1. Agriculture

Water demand and use for food and livestock feed production is governed not only by crop management and its efficiency, but also by the balance between atmospheric moisture deficit and soil water supply. Thus, changes in climate (precipitation, temperature, radiation) will affect the water demand of crops grown in both irrigated and rainfed systems. Using projections from 19 CMIP3 GCMs forced by SRES A2 emissions to drive a global vegetation and hydrology model, climate change by the 2080s would hardly alter the global irrigation water demand of major crops in areas currently equipped for irrigation (Konzmann *et al.*, 2013). However, there is *high confidence* that irrigation demand will increase significantly in many areas (by more than 40% across Europe, the USA and parts of Asia). Other regions – including major irrigated areas in India, Pakistan and southeastern China – might experience a slight decrease in irrigation demand, due for example to higher precipitation, but only under some climate change scenarios (also see Biemans *et al.*, 2013). Using seven global hydrological models but a limited set of CMIP5 projections, Wada *et al.* (2013) suggested a global increase in irrigation demand by the 2080s (ensemble average 7–21% depending on emissions scenario), with a pronounced regional pattern, a large inter-model spread, and possible seasonal shifts in crop water demand and consumption. By contrast, based on projections from two GCMs and two emissions scenarios, a slight global decrease in crop water deficits was suggested in both irrigated and rainfed areas by the 2080s, which can partly be explained by a smaller difference between daily maximum and minimum temperatures (Zhang and Cai, 2013). As in other studies, region-to-region variations were very heterogeneous.

Where poor soil is not a limiting factor, physiological and structural crop responses to elevated atmospheric CO_2 concentration (CO_2 fertilization) might partly cancel out the adverse effects of climate change, potentially reducing global irrigation water demand (Konzmann *et al.*, 2013; Box CC-VW). However, even in this optimistic case, increases in irrigation water demand by >20% are still projected under most scenarios for some regions, such as southern Europe. In general, future irrigation demand is projected to exceed local water availability in many places (Wada *et al.*, 2013). The water demand to produce a given amount of food on either irrigated or rainfed cropland will increase in many regions due to climate change alone (Gerten *et al.*, 2011, projections from 17 CMIP3 GCMs, SRES A2 emissions), but this increase might be moderated by concurrent increases in crop water productivity due to CO_2 effects, i.e. decreases in per-calorie water demand. The CO_2 effects may thus lessen the global number of people suffering water scarcity; nonetheless, the effect of anticipated population growth is *likely* to exceed those of climate and CO_2 change on agricultural water demand, use, and scarcity (Gerten *et al.*, 2011).

Rainfed agriculture is vulnerable to increasing precipitation variability. Differences in yield and yield variability between rainfed and irrigated land may increase with changes in climate and its variability (e.g. Finger *et al.*, 2011). Less irrigation water might be required for paddy rice cultivation in monsoon regions where rainfall is projected to increase and the crop growth period to become shorter (Yoo *et al*., 2013). Water demand for rainfed crops could be reduced by better management (Brauman *et al.*, 2013), but unmitigated climate change may counteract such efforts, as shown in a global modelling study (Rost *et al.*, 2009). In some regions, expansion of irrigated areas or increases of irrigation efficiencies may overcome climate change impacts on agricultural water demand and use (McDonald and Girvetz, 2013).

3.5.2.2. Energy Production

Hydroelectric and thermal power plants, and the irrigation of bioenergy crops (Box CC-WE), require large amounts of water. This section assesses the impact of hydrological changes (as described in Section 3.4) on hydroelectric and thermal power production. The impacts of changes in energy production due to climate change mitigation efforts are discussed in Section 3.7.2.1, while the economic implications of the impact of climate change on thermal power and hydropower production as well as adaptation options are assessed in Chapter 10.

Climate change affects hydropower generation through changes in the mean annual streamflow, shifts of seasonal flows and increases of streamflow variability (including floods and droughts) as well as by increased evaporation from reservoirs and changes in sediment fluxes. Therefore, the impact of climate change on a specific hydropower plant will depend on the local change of these hydrological characteristics, as well as on the type of hydropower plant and on the (seasonal) energy demand, which will itself be affected by climate change (Golombek *et al*., 2012). Run-of-river power plants are more susceptible to increased flow variability than plants at dams. Projections of future hydropower generation are subject to the uncertainty of projected precipitation and streamflow. For example, projections to the 2080s of hydropower generation in the Pacific Northwest of the USA range from a decrease of 25% to an increase of 10% depending on the climate model (Markoff and Cullen, 2008). Based on an ensemble of 11 GCMs, hydropower generation at the Aswan High Dam (Egypt) was computed to remain constant until the 2050s but to decrease, following the downward trend of mean annual river discharge, to 90% (ensemble mean) of current mean annual production under both SRES B1 and A2 (Beyene *et al*., 2010; Table 3-2). In snow-dominated basins, increased discharge in winter, smaller and earlier spring floods and reduced discharge in summer have already been observed (Section 3.2.5) and there is *high confidence* that these trends will continue. In regions with high electricity demands for heating, this makes the annual hydrograph more similar to seasonal variations in electricity demand, reducing required reservoir capacities and providing opportunities for operating dams and power stations to the benefit of riverine ecosystems (Golombek *et al*., 2012; Renofalt *et al*., 2010). In regions with high electricity demand for summertime cooling, however, this seasonal streamflow shift is detrimental. In general, climate change requires adaptation of operating rules (Minville *et al*., 2009; Raje and Mujumdar, 2010) which may, however, be constrained by reservoir capacity. In California, for example, high-elevation hydropower systems with little storage, which rely on storage in the snowpack, are projected to yield less hydropower due to the increased occurrence of spills, unless precipitation increases significantly (Madani and Lund, 2010). Storage capacity expansion would help increase hydropower generation but might not be cost-effective (Madani and Lund, 2010).

Regarding water availability for cooling of thermal power plants, the number of days with a reduced useable capacity is projected to increase in Europe and the USA, due to increases in stream temperatures and the incidence of low flows (Flörke *et al*., 2012; van Vliet *et al*., 2012; Table 3-2). Warmer cooling water was computed to lower thermal power plant efficiency and thus electricity production by 1.5-3% in European countries by the 2080s under emissions scenario A1b (Golombek *et al*., 2012).

3.5.2.3. Municipal Services

Under climate change, water utilities are confronted by the following (Bates *et al*., 2008; Black and King, 2009; Bonte and Zwolsman, 2010; Brooks *et al*., 2009; Chakraborti *et al*., 2011; Christierson *et al*., 2012; Hall and Murphy, 2010; Jiménez, 2008; Major *et al*., 2011; Mukhopadhyay and Dutta, 2010; Qin *et al*., 2010; Thorne and Fenner, 2011; van Vliet and Zwolsman, 2008; Whitehead *et al*., 2009a):

- Higher ambient temperatures, which reduce snow and ice volumes and increase the evaporation rate from lakes, reservoirs and aquifers. These changes decrease natural storage of water and hence, unless precipitation increases, its availability. Moreover, higher ambient temperatures increase water demand, and with it the competition for the resource (*medium to high agreement, limited evidence*).
- Shifts in timing of river flows and possible more frequent or intense droughts, which increase the need for artificial water storage.
- Higher water temperatures, which encourage algal blooms and increase risks from cyanotoxins and natural organic matter in water sources, requiring additional or new treatment of drinking water (*high agreement, medium evidence*). On the positive side, biological water and wastewater treatment is more efficient when the water is warmer (Tchobanoglous *et al*., 2003).
- Possibly drier conditions, which increase pollutant concentrations. This is a concern especially for groundwater sources that are already of low quality, even when pollution is natural as in India and Bangladesh, North and Latin America and Africa; here arsenic, iron, manganese and fluorides are often a problem (Black and King, 2009).

- Increased storm runoff, which increases loads of pathogens, nutrients and suspended sediment.
- Sea-level rise, which increases the salinity of coastal aquifers, in particular where groundwater recharge is also expected to decrease.

Climate change also impacts water quality indirectly. For instance, at present many cities rely on water from forested catchments that requires very little treatment. More frequent and severe forest wildfires could seriously degrade water quality (Emelko *et al*., 2011; Smith *et al*., 2011).

Many drinking-water treatment plants – especially small ones – are not designed to handle the more extreme influent variations that are to be expected under climate change. These demand additional or even different infrastructure capable of operating for up to several months per year, which renders wastewater treatment very costly, notably in rural areas (Arnell *et al*., 2011; Zwolsman *et al*., 2010).

Sanitation technologies vary in their resilience to climate impacts (Howard *et al*., 2010). For sewage, three climatic conditions are of interest (NACWA, 2009; Zwolsman *et al*., 2010):

- Wet weather: heavier rainstorms mean increased amounts of water and wastewater in combined systems for short periods. Current designs, based on critical “design storms” defined through analysis of historical precipitation data, therefore need to be modified. New strategies to adapt to and mitigate urban floods need to be developed, considering not only climate change but also urban design, land use, the “heat island effect” and topography (Changnon, 1969).
- Dry weather: soil shrinks as it dries, causing water mains and sewers to crack and making them vulnerable to infiltration and exfiltration of water and wastewater. The combined effects of higher temperatures, increased pollutant concentrations, longer retention times, and sedimentation of solids may lead to increasing corrosion of sewers, shorter asset lifetimes, more drinking-water pollution and higher maintenance costs.
- Sea-level rise: intrusion of brackish or salty water into sewers necessitates processes that can handle saltier wastewater.

Increased storm runoff implies the need to treat additional wastewater when combined sewers are used, as storm runoff adds to sewage; in addition, the resulting mixture has a higher content of pathogens and pollutants. Under drier conditions higher concentrations of pollutants in wastewater, of any type, are to be expected and must be dealt with (Whitehead *et al*., 2009a; 2009b; Zwolsman *et al*., 2010). The cost may rule this out in low-income regions (Chakraborti *et al*., 2011; Jiménez, 2011). The disposal of wastewater or faecal sludge is a concern that is just beginning to be addressed in the literature (Seidu *et al*., 2013).

3.5.2.4. Freshwater Ecosystems

Freshwater ecosystems are comprised of biota (animals, plants and other organisms) and their abiotic environment in slow-flowing surface waters such as lakes, man-made reservoirs or wetlands; in fast-flowing surface waters such as rivers and creeks; and in the groundwater. They have suffered more strongly from human activities than have marine and terrestrial ecosystems. Between 1970 and 2000, populations of freshwater species included in the Living Planet Index declined on average by 50%, compared to 30% for marine and also for terrestrial species (Millennium Ecosystem Assessment, 2005). Climate change is an additional stressor of freshwater ecosystems, which it affects not only through increased water temperatures (discussed in Chapter 4.3.3.3) but also by altered streamflow regimes, river water levels, and extent and timing of inundation (Box CC-RF). Wetlands in dry environments are hotspots of biological diversity and productivity, and their biotas are at risk of extinction if runoff decreases and the wetland dries out (as described for Mediterranean-type temporary ponds by Zacharias and Zamparas, 2010). Freshwater ecosystems are also affected by water quality changes induced by climate change (Section 3.2.5), and by human adaptations to climate-change induced increases of streamflow variability and flood risk, such as the construction of dykes and dams (Ficke *et al*., 2007; Section 3.7.2).

3.5.2.5. Other Uses

In addition to direct impacts, vulnerabilities and risks in water-related sectors, indirect impacts of hydrological changes are expected for navigation, transportation, tourism, and urban planning (Badjeck *et al*., 2010; Beniston, 2012; Koetse and Rietveld, 2009; Pinter *et al*., 2006; Rabassa, 2009). Social and political problems can result from hydrological changes. For example, water scarcity and water overexploitation may increase the risks of violent conflicts and nation-state instability (Barnett and Adger, 2007; Buhaug *et al*., 2010; Burke *et al*. 2009; Hsiang *et al*., 2011). Snowline rise and glacier shrinkage are *very likely* to impact environmental, hydrological, geomorphological, heritage, and tourism resources in cold regions (Rabassa, 2009), as already observed for tourism in the European Alps (Beniston, 2012). While most impacts will be adverse, some might be beneficial.

3.6. Adaptation and Managing Risks

In the face of hydrological changes and freshwater-related impacts, vulnerability and risks due to climate change, there is need for adaptation and for increasing resilience. Managing the changing risks due to the impacts of climate change is the key to adaptation in the water sector (IPCC, 2012), and risk management should be part of decision making and the treatment of uncertainty (ISO, 2009). Even to exploit the positive impacts of climate change on freshwater systems, adaptation is generally required.

3.6.1. Options

There is growing agreement that an adaptive approach to water management can successfully address uncertainty due to climate change. Although there is *limited evidence* of the effectiveness of such an approach, the evidence is growing (Section 3.6.2). Many practices identified as adaptive were originally reactions to climate variability. Climate change provides many opportunities for “low-regret” solutions, capable of yielding social and/or economic benefits and adaptive both to variability and to change (Table 3-3). Adaptive techniques include scenario planning, experimental approaches that involve learning from experience, and the development of flexible solutions that are resilient to uncertainty. A programme of adaptation typically mixes “hard” infrastructural and “soft” institutional measures (Bates *et al*., 2008; Cooley, 2008; Mertz *et al*., 2009; Olhoff and Schaer, 2010; Sadoff and Muller, 2009; UNECE, 2009).

[INSERT TABLE 3-3 HERE
Table 3-3: Categories of climate change adaptation options for the management of freshwater resources.
A+M: may assist both adaptation and mitigation
(1)This includes water reuse, rain water harvesting, and desalination, among others.
With information from: Arkell (2011a; 2011b); Andrews (2009); Bahri (2009); Bowes *et al*. (2012); de Graaf and der Brugge (2010); Dembo (2010); Dillon and Jiménez (2008); Elliott *et al*. (2011); Emelko *et al*. (2011); Godfrey *et al*. (2010); Howard *et al*. (2010); Jiménez and Asano (2008); Jiménez (2011); Keller (2008); Kingsford (2011); Mackay and Last (2010); Major *et al*. (2011); Marsalek *et al*. (2006); McCafferty (2008); McGuckin (2008); Mogaka *et al*. (2006); Mukhopadhyay and Dutta (2010); Munasinghe (2009); NACWA (2009); OECD (2010); OFWAT (2009); Reiter (2009); Renofalt *et al*. (2010); Seah (2008); Sprenger *et al*. (2011); Thöle (2008); UNESCO (2011); UNHABITAT (2008); Vörösmarty *et al*. (2000); Wang X. *et al*. (2011); Whitehead *et al*. (2009b); Zwolsman *et al*. (2010)]

To avoid adaptation that goes wrong – “maladaptation” – scientific research results should be analyzed during planning. Low-regret solutions, such as those for which moderate investment clearly increases the capacity to cope with projected risks or for which the investment is justifiable under all or almost all plausible scenarios, should be considered explicitly. Involving all stakeholders, reshaping planning processes, coordinating the management of land and water resources, recognizing linkages between water quantity and quality, using surface water and groundwater conjunctively, and protecting and restoring natural systems, are examples of principles that can beneficially inform planning for adaptation (World Bank, 2007).

Integrated Water Resource Management continues to be a promising instrument for exploring adaptation to climate change. It can be joined with a Strategic Environmental Assessment to address broader considerations. Attention is currently increasing to "robust measures" (European Communities, 2009), which are measures that perform well under different future conditions and clearly optimize prevailing strategies (Sigel *et al.*, 2010). Barriers to adaptation are discussed in detail in Section 16.5 in Chapter 16. Barriers to adaptation in the freshwater sector include lack of human and institutional capacity, lack of financial resources, lack of awareness, and lack of communication (Browning-Aiken *et al*., 2007; Burton, 2008; Butscher and Huggenberger, 2009; Zwolsman *et al*., 2010). Institutional structures can be major barriers to adaptation (Bergsma *et al*., 2012; Engle and Lemos, 2010; Goulden *et al*., 2009; Huntjens *et al*., 2010; Stuart-Hill and Schulze, 2010; Wilby and Vaughan, 2011; Ziervogel *et al*., 2010); structures that promote participation of and collaboration between stakeholders tend to encourage adaptation. Some adaptation measures may not pass the test of workability in an uncertain future (Campbell *et al.*, 2008), and uncertainty (Section 3.6.2) can be another significant barrier.

Case studies of the potential effectiveness of adaptation measures are abundant. Changes in operating practices and infrastructure improvements could help California's water managers respond to changes in the volume and timing of supply (Connell-Buck *et al*., 2011; Medellin-Azuara *et al*., 2008). Other studies include evaluations of the effectiveness of different adaptation options in Washington state, USA (Miles *et al*., 2010) and the Murray-Darling basin, Australia (Pittock and Finlayson, 2011), and of two dike-heightening strategies in the Netherlands (Hoekstra and de Kok, 2008). Such studies have demonstrated that it is technically feasible in general to adapt to projected climate changes, but not all have considered how adaptation would be implemented.

3.6.2. Dealing with Uncertainty in Future Climate Change

One of the key challenges in factoring climate change into water resources management lies in the uncertainty. Some approaches (e.g. in England and Wales, Arnell, 2011) use a small set of climate scenarios to characterise the potential range of impacts on water resources and flooding. Others (e.g. Brekke *et al*., 2008; Christierson *et al*., 2012; Hall *et al*., 2012; Lopez *et al*., 2009) use very large numbers of scenarios to generate likelihood distributions of indicators of impact for use in risk assessment. However, it has been argued (Dessai *et al*., 2009; Hall, 2007; Stainforth *et al*., 2007) that attempts to construct probability distributions of impacts are misguided because of "deep" uncertainty, which arises because analysts do not know, or cannot agree upon, how the climate system and water-management systems may change, how models represent possible changes, or how to value the desirability of different outcomes. Stainforth *et al*. (2007) therefore argue that it is impossible in practice to construct robust quantitative probability distributions of climate change impacts, and that climate change uncertainty needs to be represented differently, for example by using fewer plausible scenarios and interpreting the outcomes of scenarios less quantitatively.

Some go further, arguing that climate models are not sufficiently robust or reliable to provide the basis for adaptation (Anagnostopoulos *et al*., 2010; Blöschl and Montanari, 2010; Koutsoyiannis *et al*., 2008; Wilby, 2010), because they are frequently biased and do not reproduce the temporal characteristics (specifically the persistence or "memory") often found in hydrological records. It has been argued (Lins and Cohn, 2011; Stakhiv, 2011) that existing water-resources planning methods are sufficiently robust to address the effects of climate change. This view of climate model performance has been challenged and is the subject of some debate (Huard, 2011; Koutsoyiannis *et al*., 2009; 2011); the critique also assumes that adaptation assessment procedures would only use climate scenarios derived directly from climate model simulations.

Addressing uncertainty in practice by quantifying it through some form of risk assessment, however, is only one way of dealing with uncertainty. A large and increasing literature recommends that water managers should move from the traditional "predict and provide" approach towards adaptive water management (Gersonius *et al*., 2013; Huntjens *et al*., 2012; Matthews and Wickel, 2009; Mysiak *et al*., 2009; Pahl-Wostl, 2007; Pahl-Wostl *et al*., 2008; Short *et al*., 2012) and the adoption of resilient or "no-regrets" approaches (Henriques and Spraggs, 2011; WWAP, 2009). Approaches that are resilient to uncertainty are not entirely technical (or supply-side), and participation and collaboration amongst all stakeholders are central to adaptive water management. However, whilst climate change is frequently cited as a key motive, there is very little published guidance on how to implement the adaptive water management approach. Some examples are given in Ludwig *et al*. (2009). The most comprehensive overview of adaptive water management which explicitly incorporates climate change and its uncertainty is the three-step framework of the US Water Utilities Climate Alliance (WUCA, 2010): system vulnerability assessment, utility planning using decision-support methods, and decision-making and implementation. Planning methods for decision support include classic decision analysis, traditional scenario planning and robust decision making (Lempert *et al*., 1996; 2006; Nassopoulos *et al*., 2012). The latter was applied by the Inland Empire Utilities Agency, supplying water to a region in southern California (Lempert and Groves, 2010). This led to the refinement of the company's water resource management plan, making it more robust to three particularly challenging aspects of climate change that were identified by the scenario analysis. Another framework, based on risk assessment, is the threshold-scenario framework of Freas *et al*. (2008).

3.6.3. Costs of Adaptation to Climate Change

Calculating the global cost of adaptation in the water sector is a difficult task and results are highly uncertain. Globally, to maintain water services at non-climate change levels to the year 2030 in more than 200 countries, total adaptation costs for additional infrastructure were estimated as US$531 billion, with US$451 billion (85%) required in developing countries, mainly in Asia and Africa (Kirshen, 2007). Including two further costs, for reservoir construction since the best locations have already been taken, and for unmet irrigation demands, total water-sector adaptation costs were estimated as US$225 billion, or US$11 billion per year (UNFCCC, 2007).

Average annual water-supply and flood-protection costs to 2050 for restoring service to non-climate change levels were estimated to be US$14.0 billion for a dry GCM projection of the SRES A2 scenario and US$19.7 billion for a wet GCM projection (World Bank, 2010; Ward *et al*., 2010). Annual urban infrastructure costs, primarily for wastewater treatment and urban drainage, were US$13.7 billion (dry) and US$27.5 billion (wet). Under both GCM projections for the A2 scenario, the water sector accounted for approximately 50% of total global adaptation cost, which was distributed regionally in the proportions: East Asia/Pacific, 20%; Europe/Central Asia, 10%; Latin America/Caribbean, 20%; Middle East/North Africa, 5%; South Asia, 20%; Sub-Saharan Africa, 20%.

Annual costs for adaptation to climate change in sub-Saharan Africa are estimated as US$1.1–2.7 billion for current urban water infrastructure, plus US$1.0–2.5 billion for new infrastructure to meet the 2015 Millennium Development Goals (Muller, 2007). These estimates assume a 30% reduction in stream flow and an increase of at least 40% in the unit cost of water. Annual estimates of adaptation costs for urban water storage are $0.15-0.5 billion for existing facilities and $0.55-1.5 billion for new developments. For wastewater treatment, the equivalent estimates are $0.1-0.2 billion and $0.075-0.2 billion. For the coterminous United States under "business as usual", over 45% of economic costs are due to water quality and environmental flow impacts, suggesting significant costs for wastewater treatment infrastructure (Henderson *et al.*, 2013).

3.6.4. Adaptation in Practice in the Water Sector

A number of water management agencies are beginning to factor climate change into processes and decisions (Kranz *et al*., 2010; Krysanova *et al*., 2010), with the amount of progress strongly influenced by institutional characteristics. Most of the work has involved developing methodologies to be used by water resources and flood managers (e.g. Rudberg *et al*., 2012), and therefore represents attempts to improve adaptive capacity. In England and Wales, for example, methodologies to gauge the effects of climate change on reliability of water supplies have evolved since the late 1990s (Arnell, 2011) and the strategic plans of water supply companies now generally allow for climate change. Brekke *et al*. (2009a) describe proposed changes to practices in the USA. Several studies report community-level activities to reduce exposure to current hydrological variability, regarded explicitly as a means of adapting to future climate change (e.g. Barrios *et al*., 2009; Gujja *et al*., 2009; Kashaigili *et al*., 2009; Yu *et al*., 2009).

[INSERT TABLE 3-4 HERE
Table 3-4: Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near-term (here assessed over 2030-2040), and longer term (here assessed over 2080-2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.]

3.7. Linkages with Other Sectors and Services

3.7.1. Impacts of Adaptation in Other Sectors on Freshwater Systems

Adaptation in other sectors such as agriculture, forestry and industry might have impacts on the freshwater system, and therefore needs to be considered while planning adaptation in the water sector (Jiang *et al.*, 2013). For example, better agricultural land management practices can also reduce erosion and sedimentation in river channels (Lu *et al.*, 2010), while controlled flooding of agricultural land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream (World Bank, 2007). A project designed for other purposes may also deliver increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component (World Bank, 2007; Falloon and Betts, 2010).

3.7.2. Climate Change Mitigation and Freshwater Systems

3.7.2.1. Impact of Climate Change Mitigation on Freshwater Systems

Many measures for climate change mitigation affect freshwater systems. Afforestation generally increases evapotranspiration and decreases total runoff (van Dijk and Keenan, 2007). Afforestation of areas deemed suitable according to the Clean Development Mechanism–Afforestation/Reforestation provisions of the Kyoto Protocol (7.5 million km^2) would lead to large and spatially-extensive decreases of long-term average runoff (Trabucco *et al*., 2008). On 80% of the area, runoff is computed to decline by more than 40%, while on 27% runoff decreases of 80-100% were computed, mostly in semi-arid areas (Trabucco *et al*., 2008). For example, economic incentives for carbon sequestration may encourage the expansion of *Pinus radiata* timber plantations in the Fynbos biome of South Africa, with negative consequences for water supply and biodiversity; afforestation is viable to the forestry industry only because it pays less than 1% of the actual cost of streamflow reduction caused by replacing Fynbos by the plantations (Chisholm, 2010). In general, afforestation has beneficial impacts on soil erosion, local flood risk, water quality (nitrogen, phosphorus, suspended sediments) and stream habitat quality (Trabucco *et al*., 2008; van Dijk and Keenan, 2007; Wilcock *et al*., 2008).

Irrigated bioenergy crops and hydropower can have negative impacts on freshwater systems (Jacobson, 2009). In the USA, water use for irrigating biofuel crops could increase from 2% of total water consumption in 2005 to 9% in 2030 (King *et al*., 2010). Irrigating some bioenergy crops may cost more than the energy thus gained. In dry parts of India, pumping from a depth of 60 meter for irrigating jatropha is estimated to consume more energy than that gained from the resulting higher crop yields (Gupta *et al*., 2010). For a biofuel scenario of the International Energy Agency, global consumptive irrigation water use for biofuel production is projected to increase from 0.5% of global renewable water resources in 2005 to 5.5% in 2030; biofuel production is projected to increase water consumption significantly in some countries (e.g. Germany, Italy and South Africa), and to exacerbate the already serious water scarcity in others (e.g. Spain and China) (Gerbens-Leenes *et al*., 2012). Conversion of native Caatinga forest into rainfed fields for biofuels in semi-arid northwestern Brazil may lead to a significant increase of groundwater recharge (Montenegro and Ragab, 2010), but there is a risk of soil salinization due to rising groundwater tables.

Hydropower generation leads to alteration of river flow regimes that negatively affect freshwater ecosystems, in particular biodiversity and abundance of riverine organisms (Döll and Zhang, 2010; Poff and Zimmerman, 2010), and to fragmentation of river channels by dams, with negative impacts on migratory species (Bourne *et al*., 2011). Hydropower operations often lead to discharge changes on hourly timescales that are detrimental to the downstream river ecosystem (Bruno *et al*., 2009; Zimmerman *et al*., 2010). However, release management and structural measures like fish ladders can mitigate these negative impacts somewhat (Williams, 2008). In tropical regions, the global warming potential of hydropower, due to methane emissions from man-made reservoirs, may exceed that of thermal power; based on observed emissions of a tropical reservoir, this might be the case where the ratio of hydropower generated to the surface area of the reservoir is less than 1 MW/km^2 (Gunkel, 2009).

CO_2 leakage to freshwater aquifers from saline aquifers used for carbon capture and storage (CCS) can lower pH by 1-2 units and increase concentrations of metals, uranium and barium (Little and Jackson, 2010). Pressure exerted by gas injection can push brines or brackish water into freshwater parts of the aquifer (Nicot, 2008). Displacement of brine into potable water was not considered in a screening methodology for CCS sites in the Netherlands (Ramírez *et al*., 2010). Another emergent freshwater-related risk of climate mitigation is increased natural gas extraction from low-permeability rocks. The required hydraulic fracturing process ("fracking") uses large amounts of water (a total of approximately 9,000-30,000 m^3 per well, mixed with a number of chemicals), of which a part returns to the surface (Rozell and Reaven, 2012). Fracking is suspected to lead to pollution of the overlying freshwater aquifer or surface waters, but appropriate observations and peer-reviewed studies are still lacking (Jackson *et al*., 2013). Densification of urban areas to reduce traffic emissions is in conflict with providing additional open space for inundation in case of floods (Hamin and Gurran, 2009).

3.7.2.2. Impact of Water Management on Climate Change Mitigation

A number of water management decisions affect GHG emissions. Water demand management has a significant impact on energy consumption because energy is required to pump and treat water, to heat it, and to treat wastewater. For example, water supply and water treatment were responsible for 1.4 % of total electricity consumption in Japan in 2008 (MLIT, 2011). In the USA, total water-related energy consumption was equivalent to 13% of total electricity production in 2005, with 70% for water heating, 14% for wastewater treatment and only 5% for pumping of irrigation water (Griffiths-Sattenspiel and Wilson, 2009). In China, where agriculture accounts for 62% of water withdrawals, groundwater pumping for irrigation accounted for only 0.6% of China's GHG emissions in 2006, a small fraction of the 17-20% share of agriculture as a whole (Wang *et al*., 2012). Where climate change reduces water resources in dry regions, desalination of seawater as an adaptation option is expected to increase GHG emissions if carbon-based fuels are used as energy source (McEvoy and Wilder, 2012).

In southeast Asia, emissions due to peatland drainage contribute 1.3-3.1% of current global CO_2 emissions from the combustion of fossil fuels (Hooijer *et al*., 2010), and peatland rewetting could substantially reduce net GHG emissions (Couwenberg *et al*., 2010). Climate change mitigation by conservation of wetlands will also benefit water quality and biodiversity (House *et al*., 2010). Irrigation can increase CO_2 storage in soils by reducing water stress and so enhancing biomass production. Irrigation in semi-arid California did not significantly increase soil organic carbon (Wu *et al*., 2008). Water management in rice paddies can reduce CH_4 emissions. If rice paddies are drained at least once during the growing season, with resulting increased water withdrawals, global CH_4 emissions from rice fields could be decreased by 4.1 Tg/year (16% around the year 2000), and N_2O emissions would not increase significantly (Yan *et al*., 2009).

3.8. Research and Data Gaps

Precipitation and river discharge are systematically observed, but data records are unevenly available and unevenly distributed geographically. Information on many other relevant variables, such as soil moisture, snow depth, groundwater depth and water quality, is particularly limited in developing countries. Relevant socio-economic data, such as rates of surface water and groundwater withdrawal by each sector, and information on already-implemented adaptations for stabilizing water supply, such as long-range diversions, are limited even in developed countries. In consequence, assessment capability is limited in general, and especially so in developing countries.

Modeling studies have shown that the adaptation of vegetation to changing climate may have large impacts on the partitioning of precipitation into evapotranspiration and runoff. This feedback should be investigated more thoroughly.

Relatively little is known about the economic aspects of climate-change impacts and adaptation options related to water resources. For example, regional damage curves need to be developed, relating the magnitudes of major water-related disasters (such as intense precipitation and surface soil dryness) to the expected costs.

There is a continuing, although narrowing, mismatch between the large scales resolved by climate models and the catchment scale at which water is managed and adaptations must be implemented. Improving the spatial resolution of regional and global climate models, and the accuracy of methods for downscaling their outputs, can produce information more relevant to water management, although the robustness of regional climate projections is still constrained by the realism of GCM simulations of large-scale drivers. More computing capacity is needed to address these problems with more ensemble simulations at high spatial resolution. More research is also needed into novel ways of combining different approaches to projection of plausible changes in relevant climate variables so as to provide robust information to water managers. Robust attribution to anthropogenic climate change of hydrological changes, particularly changes in the frequency of extreme events, is similarly demanding, and further study is required to develop rigorous attribution tools that require less computation. In addition, there is a difficulty to model and interpret results obtained from applying models at different scales and with different logics to follow the future changes on water quality. Morover, the establishment of a proper baseline to isolate the effects derived from climate change from those antropogenic caused is a major challenge.

Interactions among socio-ecological systems are not yet well considered in most impact assessments. Particularly, there are few studies on the impacts of mitigation and adaptation in other sectors on the water sector, and conversely. A valuable advance would be to couple hydrological models, or even the land-surface components of climate models, to data on water-management activities such as reservoir operations, irrigation and urban withdrawals from surface water or groundwater.

To support adaptation by increasing reliance on groundwater and on the coordinated and combined use of groundwater and surface water, ground-based data are needed in the form of a long-term program to monitor groundwater dynamics and stored groundwater volumes. Understanding of groundwater recharge and groundwater-surface water interactions, particularly by the assessment of experiences of conjunctive use of groundwater and surface water, needs to be better developed.

More studies are needed, especially in developing countries, on the impacts of climate change on water quality, and of vulnerability to and ways of adapting to those impacts.

Frequently Asked Questions

FAQ 3.1: How will climate change affect the frequency and severity of floods and droughts?
[to be placed in Section 3.4.9]
Climate change is projected to alter the frequency and magnitude of both floods and droughts. The impact is expected to vary from region to region. The few available studies suggest that flood hazards will increase over more than half of the globe, in particular in central and eastern Siberia, parts of south-east Asia including India, tropical Africa, and northern South America, but decreases are projected in parts of northern and eastern Europe, Anatolia, central and east Asia, central North America, and southern South America (*limited evidence, high agreement*).The frequency of floods in small river basins is *very likely* to increase, but that may not be true of larger watersheds because intense rain is usually confined to more limited areas. Spring snowmelt floods are *likely* to become smaller, both because less winter precipitation will fall as snow and because more snow will melt during thaws over the

course of the entire winter. Worldwide, the damage from floods will increase because more people and more assets will be in harm's way.

By the end of the 21st century meteorological droughts (less rainfall) and agricultural droughts (drier soil) are projected to become longer, or more frequent, or both, in some regions and some seasons, because of reduced rainfall or increased evaporation or both. But it is still uncertain what these rainfall and soil moisture deficits might mean for prolonged reductions of streamflow and lake and groundwater levels. Droughts are projected to intensify in southern Europe and the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil and southern Africa. In dry regions, more intense droughts will stress water-supply systems. In wetter regions, more intense seasonal droughts can be managed by current water-supply systems and by adaptation; for example, demand can be reduced by using water more efficiently, or supply can be increased by increasing the storage capacity in reservoirs.

FAQ 3.2: How will the availability of water resources be affected by climate change?
[to be placed in Section 3.5.1]
Climate models project decreases of renewable water resources in some regions and increases in others, albeit with large uncertainty in many places. Broadly, water resources are projected to decrease in many mid-latitude and dry subtropical regions, and to increase at high latitudes and in many humid mid-latitude regions (*high agreement, robust evidence)*. Even where increases are projected, there can be short-term shortages due to more variable streamflow (because of greater variability of precipitation), and seasonal reductions of water supply due to reduced snow and ice storage. Availability of clean water can also be reduced by negative impacts of climate change on water quality; for instance the quality of lakes used for water supply could be impaired by the presence of algae-producing toxins.

FAQ 3.3: How should water management be modified in the face of climate change?
[to be placed in Section 3.6.1]
Managers of water utilities and water resources have considerable experience in adapting their policies and practices to the weather. But in the face of climate change, long-term planning (over several decades) is needed for a future that is highly uncertain. A flexible portfolio of solutions that produces benefits regardless of the impacts of climate change ("low-regret" solutions) and that can be implemented adaptively, step by step, is valuable because it allows policies to evolve progressively, thus building on – rather than losing the value of – previous investments. Adaptive measures that may prove particularly effective include rainwater harvesting, conservation tillage, maintaining vegetation cover, planting trees in steeply-sloping fields, mini-terracing for soil and moisture conservation, improved pasture management, water re-use, desalination, and more efficient soil and irrigation-water management. Restoring and protecting freshwater habitats, and managing natural floodplains, are additional adaptive measures that are not usually part of conventional management practice.

FAQ 3.4: Does climate change imply only bad news about water resources?
[to be placed after Section 3.6]
There is good news as well as bad about water resources, but the good news is very often ambiguous. Water may become less scarce in regions that get more precipitation, but more precipitation will probably also increase flood risk; it may also raise the groundwater table, which could lead to damage to buildings and other infrastructure or to reduced agricultural productivity due to wet soils or soil salinization. More frequent storms reduce the risk of eutrophication and algal blooms in lakes and estuaries by flushing away nutrients, but increased storm runoff will carry more of those nutrients to the sea, exacerbating eutrophication in marine ecosystems, with possible adverse impacts as discussed in Chapter 30. Water and wastewater treatment yields better results under warmer conditions, as chemical and biological reactions needed for treatment perform in general better at higher temperatures. In many rivers fed by glaciers, there will be a "meltwater dividend" during some part of the 21st century, due to increasing rates of loss of glacier ice, but the continued shrinkage of the glaciers means that after several decades the total amount of meltwater that they yield will begin to decrease (*medium confidence*). An important point is that often impacts do not become "good news" unless investments are made to exploit them. For instance, where additional water is expected to become available, the infrastructure to capture that resource would need to be developed if it is not already in place.

Box CC-RF. Impact of Climate Change on Freshwater Ecosystems due to Altered River Flow Regimes

[Petra Döll (Germany), Stuart E. Bunn (Australia)]

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

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*medium confidence*) (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (SRES A2 emissions, HadCM3 climate model), 15% of the global land area may be negatively affected, by the 2050s, by a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased runoff during winter months (Renofalt *et al.*, 2010).

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

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

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (Section 3.2.3 in Chapter 3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

[INSERT FIGURE RF-1 HERE
Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out 10 months. Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and

reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.]

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase, when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

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

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16 and 38% of the total species richness in the three study regions in Ecuador, Europe and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

Box CC-RF References

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

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

Climate, vegetation and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e. by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric CO_2 concentrations. In addition, effects of climate change (e.g. higher temperature or altered precipitation) on vegetation structure, biomass production and plant distribution have an indirect influence on water flows. Rising CO_2 concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO_2 Enrichment (FACE), laboratory and modelling experiments (e.g. Leakey *et al.*, 2009; de Boer *et al.*, 2011; Reddy *et al.*, 2010). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, i.e. lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of C3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO_2-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species WUE ceased to increase after 1970 (Gagen *et al.*, 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan *et al.*, 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modelling study by Gedney *et al.*, 2006) or has increased in some regions due to the structural CO_2 effect (as assumed in models by Piao *et al.*, 2007;

Gerten *et al.*, 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2 change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 effects (McMahon *et al.*, 2010). Satellite observations analysed in Donohue *et al.* (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO_2 fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO_2 increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modelling studies, can suppress the CO_2 fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.* (2006) which suggested that the physiological CO_2 effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat *et al.* (2004). However, a more recent analysis based on a more complete dataset (Dai *et al.*, 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO_2 increase and land use change have contributed less (Piao *et al*., 2007; Gerten *et al*., 2008; Alkama *et al.*, 2011; Sterling *et al.*, 2013). Oliveira *et al.* (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

It is uncertain how vegetation responses to future increases in CO_2 and to climate change will modulate the impacts of climate change on freshwater flows. 21st century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO_2 effect is included in addition to climate change effects (Betts *et al.*, 2007; Murray *et al.*, 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten *et al.*, 2011; Wiltshire *et al.*, in press). In absolute terms, the isolated effect of CO_2 has been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were not in Nugent and Matthews, 2012). In a global model intercomparison study (Davie *et al.*, in press), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO_2 effects compared to simulations with constant CO_2 concentration (consistent with above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO_2, stomatal closure and plant growth is a source of uncertainty, as also suggested by Cao *et al.* (2009). Lower transpiration due to rising CO_2 concentration may also affect future regional climate change itself (Boucher *et al.*, 2009) and enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama *et al.*, 2010).

An application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO_2 rise, i.e. increasing WUE and either increasing or decreasing leaf area (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a site in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Using a large ensemble of climate change projections, Konzmann *et al.* (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO_2 effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader *et al.*, 2010). However, substantial CO_2-driven improvements will only be realized if proper management abates limitation of plant growth by nutrient availability or other factors.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).]

Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the atmosphere such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). One model in the study by Davie *et al.* (in press) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO_2 effects. As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011; Gerten *et al.*, in press), it remains a challenge to disentangle the individual effects of climate, CO_2 and land cover change on the water cycle.

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Box CC-WE: The Water-Energy-Food/Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between countries, regions and production systems. Energy technologies (e.g. biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber 2008; McMahon and Price, 2011; Macknick *et al*., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Asano et al., 2006; Khan and Hanjra, 2009; USEPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012) *(robust evidence, high agreement)*. Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Sung et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Sections 10.2.2 10.3.4, 25.7.4; van Vliet et al., 2012; Davies et al., 2013) *(robust evidence, high agreement)*. Water for biofuels, for example, under the IEA Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (WEC, 2010; Sattler et al., 2012) *(medium evidence, high agreement)*. Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) *(robust evidence, high agreement).*

Water may require significant amounts of energy for lifting, transport and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly– electricity use ($kWhr/m^3$ of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (Smit and Nasr, 1992; Jimenez, 1996; Wichelns et al., 2007; Raschid-Sally and Jayakody, 2008) *(medium confidence)*. More energy efficient treatment methods enable poor quality (“black”) wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita et al, 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) *(high confidence)*.

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) *(robust evidence, high agreement)*. Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (Sections 25.4.3 and 25.6.2, Box 25-10) *(medium evidence, high agreement)*. Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity and other factors (see Figure WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this report.

The interconnectivity of food/fiber, water, land use, energy and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel-food-land use-water-GHG mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type and use requirements, energy requirements and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use and climate change is increasingly recognized as critical to effective climate resilient pathway decision making *(medium evidence, high agreement)*, although tools to support local- and regional-scale assessments and decision-support remain very limited.

Box CC-WE References

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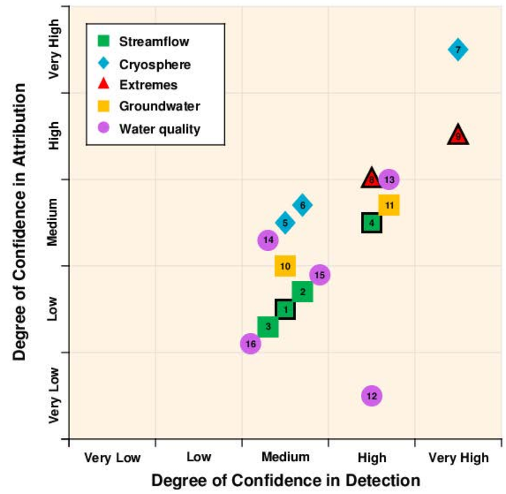
Table 3-1: Selected examples, mainly from Section 3.2, of the observation, detection and attribution of impacts of climate change on freshwater resources. Observed hydrological changes are attributed here to their climatic drivers, not all of which are necessarily anthropogenic; in the diagram, symbols with borders represent end-to-end attribution of the impact on resources to anthropogenic climate change.

1: Gerten *et al*. (2008), Piao *et al.* (2007), Alkama *et al.* (2011); 2: Piao *et al*. (2010); 3: Shiklomanov *et al*. (2007); 4: Hidalgo *et al*. (2009); 5: Collins (2008); 6: Baraer *et al*. (2012); 7: Rosenzweig *et al*. (2007); 8: Min *et al*. (2011); 9: Pall *et al*. (2011); 10: Aguilera and Murillo (2009); 11: Jeelani (2008); 12: Evans *et al*. (2005); 13: Marcé *et al*. (2010); 14: Pednekar *et al*. (2005); 15: Paerl *et al*. (2006); 16: Tibby and Tiller (2007).



Observed change	*Attributed to*	*Ref*
Changed runoff (global, 1960-1994)	Mainly climatic change, and to a lesser degree CO_2 increase and land-use change	1
Reduced runoff (Yellow River, China)	Increased temperature; only 35% of reduction attributable to human withdrawals	2
Earlier annual peak discharge (Russian Arctic, 1960-2001)	Increased temperature and earlier spring thaw	3
Earlier annual peak discharge (Columbia River, western USA, 1950-1999)	Anthropogenic warming	4
Glacier meltwater yield greater in 1910-1940 than in 1980-2000 (European Alps)	Glacier shrinkage forced by comparable warming rates in the two periods	5
Decreased dry-season discharge (Peru, 1950s-1990s)	Decreased glacier extent in the absence of a clear trend in precipitation	6
Disappearance of Chacaltaya Glacier, Bolivia (2009)	Ascent of freezing isotherm at 50 meters per decade, 1980s to 2000s	7
More intense extremes of precipitation (northern tropics and mid-latitudes, 1951-1999)	Anthropogenic greenhouse-gas emissions	8
Fraction of risk of flooding (England and Wales, autumn 2000)	Extreme precipitation attributable to anthropogenic greenhouse radiation	9
Decreased recharge of karst aquifers (Spain, 20th century)	Decreased precipitation, and possibly increased temperature; multiple confounding factors	10
Decreased groundwater recharge (Kashmir, 1985-2005)	Decreased winter precipitation	11
Increased dissolved organic carbon in upland lakes (UK, 1988-2004)	Increased temperature and precipitation; multiple confounding factors	12
Increased anoxia in a reservoir, moderated during ENSO (El Niño-Southern Oscillation) episodes (Spain, 1954-2007)	Decreased runoff due to decreased precipitation and increased evaporative demand	13
Variable faecal pollution in a saltwater wetland (California, 1969-2000)	Variable storm runoff; 70% of coliform variability attributable to variable precipitation	14
Nutrient flushing from swamps, reservoirs (North Carolina, 1970s-2002)	Hurricanes	15
Increased lake nutrient content (Victoria, Australia, 1984-2000)	Increased air and water temperature	16

Table 3-2: Effects of different GHG emissions scenarios on hydrological changes and freshwater-related impacts of climate change on humans and ecosystems. Among the SRES scenarios, GHG emissions are highest in A1f and A2, lower in A1 and B2, and lowest in B1. RCP8.5 is similar to A2, while the lower emissions scenarios RCP6.0 and RCP4.5 are similar to B1. RCP2.6 is a very low emissions scenario (Figure 1-4 and Section 1.1.3.1 in Chapter 1). The studies in the table give global warming (GW: global mean temperature rise, quantified as the CMIP5 model mean) over different reference periods, typically since pre-industrial. GW is projected to be, for RCP8.5, approximately 2°C in the 2040s and 4°C in the 2080s. For RCP6.0, GW is 2°C in the 2060s and 2.5°C in the 2080s, while in RCP2.6, GW stays below 1.8°C throughout the 21st century (Figure 1-4 in Chapter 1). Population scenario SSP2 assumes a medium population increase.

Type of hydrological change or impact	Description of indicator	Hydrological change or impact in different emissions scenarios or for different degrees of global warming (GW)	Reference
Decrease of renewable water resources, global scale	Percent of global population affected by a water resource decrease of more than 20% as compared to the 1990s (mean of 5 GCMs and 11 global hydrological models, population scenario SSP2)	Up to 2°C above the 1990s (GW 2.7°C) each degree of GW affects an additional 7%	Schewe *et al.* (2013)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a groundwater resource decrease of more than 10% by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	RCP2.6: 24% (11-39%) RCP4.5: 26% (23-32%) RCP6.0: 32% (18-45%) RCP8.5: 38% (27-50%)	Portmann *et al.* (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100-year flood discharge for the 1980s (mean and range of 5-11 GCMs, population constant at 2005 values)	RCP2.6: 0.4% (0.2-0.5%) RCP4.5: 0.6% (0.4-1.0%) RCP6.0: 0.7% (0.3-1.1%) RCP8.5: 1.2% (0.6-1.7%) GW 2°C: 0.5% (0.3-0.6%) GW 4°C: 1.2% (0.8-2.2%) 1980s: 0.1% (0.04-0.16%)	Hirabayashi *et al.* (2013)
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	RCP2.6: -0.2-1.6% RCP4.5: 1.9-2.8% RCP8.5: 6.7-10.0%	Hanasaki *et al.* (2013)
River flow regime shifts from perennial to intermittent and vice versa, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	SRES B2: 5.4-6.7% SRES A2: 6.3-7.0%	Döll and Müller Schmied (2012)
Water scarcity	Percent of global population living in countries with less than 1300 m^3/year of per-capita in the 2080s (mean of 17 GCMs, population constant at 2000 values)	No significant differences between SRES B1 and A2	Gerten *et al.* (2011)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 m^3/year of per-capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	GW 2°C: 8% GW 3.5°C: 11% GW 5°C: 13%	Gerten *et al.* (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 m^3/year of	For emissions scenarios with 2°C target, compared to SRES	Arnell *et al.* (2013)

	per-capita blue water resources) exposed to an increase in stress (1 GCM)	A1: 5-8% impact reduction in 2050 10-20% reduction in 2100	
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	GW 1.4°C: close to 0 almost everywhere GW 2.8°C: in western Australia 0.2-0.6, in central Australia 0.2-0.3, elsewhere close to 1	Crosbie *et al.* (2013a)
Change in groundwater recharge in East Anglia, UK	Percent change between baseline and future groundwater recharge, in %, by the 2050s (1 GCM)	SRES B1: -22% SRES A1f: -26%	Holman *et al.* (2009)
Change of river discharge, groundwater recharge and hydraulic head in groundwater in two regions of Denmark	Changes between the 1970s and the 2080s (1 regional climate model)	Differences between SRES B2 and A2 are very small compared to the changes between the 1970s and the 2080s in each scenario	van Roosmalen *et al.* (2007)
River flow regime shift for river in Uganda	Shift from bimodal to unimodal (1 GCM)	Occurs in scenarios with GW of at least 4.3°C but not for smaller GW	Kingston and Taylor (2010)
Agricultural (soil moisture) droughts in France	Mean duration, affected area and magnitude of short and long drought events throughout the 21st century (1 GCM)	Smaller increases over time for SRES B1 than for A2 and A1B	Vidal *et al.* (2012)
Salinization of artificial coastal freshwater lake IJsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg/liter), (2) Maximum duration of MAC exceedance (2050, 1 GCM)	Reference period 1997-2007 (GW 0.8°C): (1) 2.5%, (2) 103 days GW 1.8°C, no change in atmospheric circulation: (1) 3.1%, (2) 124 days GW 2.8°C and change in atmospheric circulation: (1) 14.3%, (2) 178 days	Bonte and Zwolsman (2010)
Decrease of hydropower production at Lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950-99 (11 GCMs)	SRES B1: 8% SRES A2: 7%	Beyene *et al.* (2010)
Reduction of usable capacity of thermal power plants in Europe and USA due to low river flow and excessive water temperature	Number of days per year with a capacity reduction of more than 50% (for existing power plants) (2031-2060, 3 GCMs)	Without climate change: 16 SRES B1: 22 SRES A2: 24	van Vliet *et al.* (2012)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006- €, (2) Expected annual population exposed (2080s, 2 GCMs)	SRES B2: (1) 14-15 billion €/year, (2) 440,000-470,000 people SRES A2: (1) 18-21 billion €/year, (2) 510,000-590,000 people Reference period: (1) 6.4 billion €/year, (2) 200,000 people	Feyen *et al.* (2012)

Table 3-3: Categories of climate change adaptation options for the management of freshwater resources.

OPTION	A+M
Institutional	
Support integrated water resources management, including the integrated management of land considering specifically negative and positive impacts of climate change	X
Promote synergy of water and energy savings and efficient use	X
Identify "low-regret policies" and build a portfolio of relevant solutions for adaptation	X
Increase resilience by forming water utility network working teams	
Build adaptive capacity	
Improve and share information	X
Adapt the legal framework to make it instrumental for addressing climate change impacts	X
Develop financial tools (credit, subsidies and public investment) for the sustainable management of water, and for considering poverty eradication and equity	
Design and operation	
Design and apply decision-making tools that consider uncertainty and fulfill multiple objectives	
Revise design criteria of water infrastructure to optimize flexibility, redundancy and robustness	
Ensure plans and services are robust, adaptable or modular, give good value, are maintainable, and have long-term benefits, especially in low-income countries	X
Operate water infrastructure so as to increase resilience to climate change for all users and sectors	
When and where water resources increase, alter dam operations to allow freshwater ecosystems to benefit	
Take advantage of hard and soft adaptation measures	X
Carry out programs to protect water resources in quantity and quality	
Increase resilience to climate change by diversifying water sources(1) and improving reservoir management	X
Reduce demand by controlling leaks, implementing water-saving programs, cascading and reusing water	X
Improve design and operation of sewers, sanitation and wastewater treatment infrastructure to cope with variations in influent quantity and quality	
Provide universal sanitation with technology locally adapted, and provide for proper disposal and reintegration of used water into the environment or for its reuse	
Reduce impact of natural disasters	
Implement monitoring and early warning systems	
Develop contingency plans	
Improve defenses and site selection for key infrastructure that is at risk of floods	
Design cities and rural settlements to be resilient to floods	
Seek and secure water from a diversity (spatially and source-type) of sources to reduce impacts of droughts and variability in water availability	
Promote both the reduction of water demand and the efficient use of water by all users	
Improve irrigation efficiency and reduce demand for irrigation water	X
Promote switching to more appropriate crops (drought-resistant, salt-resistant; low water demand)	X
Plant flood- or drought-resistant crop varieties	
Agricultural irrigation	
Reuse wastewater to irrigate crops and use soil for carbon sequestration	X
Industrial use	
When selecting alternative sources of energy, assess the need for water	X
Relocate water-thirsty industries and crops to water-rich areas	
Implement industrial water efficiency certifications	X

A+M: may assist both adaptation and mitigation
(1) This includes water reuse, rain water harvesting, and desalination, among others.

With information from: Arkell (2011a; 2011b); Andrews (2009); Bahri (2009); Bowes *et al*. (2012); de Graaf and der Brugge (2010); Dembo (2010); Dillon and Jiménez (2008); Elliott *et al*. (2011); Emelko *et al*. (2011); Godfrey *et al*. (2010); Howard *et al*. (2010); Jiménez and Asano (2008); Jiménez (2011); Keller (2008); Kingsford (2011); Mackay and Last (2010); Major *et al*. (2011); Marsalek *et al*. (2006); McCafferty (2008); McGuckin (2008); Mogaka *et al*. (2006); Mukhopadhyay and Dutta (2010); Munasinghe (2009); NACWA (2009); OECD (2010); OFWAT (2009); Reiter (2009); Renofalt *et al*. (2010); Seah (2008); Sprenger *et al*. (2011); Thöle (2008); UNESCO (2011); UNHABITAT (2008); Vörösmarty *et al*. (2000); Wang X. *et al*. (2011); Whitehead *et al*. (2009b); Zwolsman *et al*. (2010)

Table 3-4: Key risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three time frames: the present, near-term (here assessed over 2030-2040), and longer term (here assessed over 2080-2100). Sources: Xie et al., 2006; Döll, 2009; Kaser et al., 2010; Arnell et al., 2011; Huss, 2011; Jóhannesson et al., 2012; Seneviratne et al., 2012; Arnell and Gosling, 2013; Dankers et al., 2013; Gosling and Arnell, 2013; Hanasaki et al., 2013; Hirabayashi et al., 2013; Kundzewicz et al., 2013; Portmann et al., 2013; Radić et al., 2013; Schewe et al., 2013; WGI AR5 Chapter 13.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Flood risks associated with climate change increase with increasing greenhouse gas emissions (*high agreement, medium confidence*)	By 2100, the number of people exposed annually to a 20th-century 100-year flood is projected to be three times greater for very high emissions (RCP8.5) than for very low emissions (RCP2.6).		3.4.8	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Climate change is projected to reduce renewable water resources significantly in most dry subtropical regions (*high agreement, robust confidence*)	This will exacerbate competition for water among agriculture, ecosystems, settlements, industry and energy production, affecting regional water, energy and food security.		3.5.1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Because nearly all glaciers are too large for equilibrium with the present climate, there is a committed water-resources change during much of the 21st century, and changes beyond the committed change are expected due to continued warming; in glacier-fed rivers, total meltwater yields from stored glacier ice will increase in many regions during the next decades but decrease thereafter (*high agreement, robust confidence*)	Continued loss of glacier ice implies a shift of peak discharge from summer to spring, except in monsoonal catchments, and possibly a reduction of summer flows in the downstream parts of glacierized catchments.		3.4.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

Climatic drivers of impacts			Risk & potential for adaptation
Warming trend	Drying trend	Extreme precipitation	Potential for adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

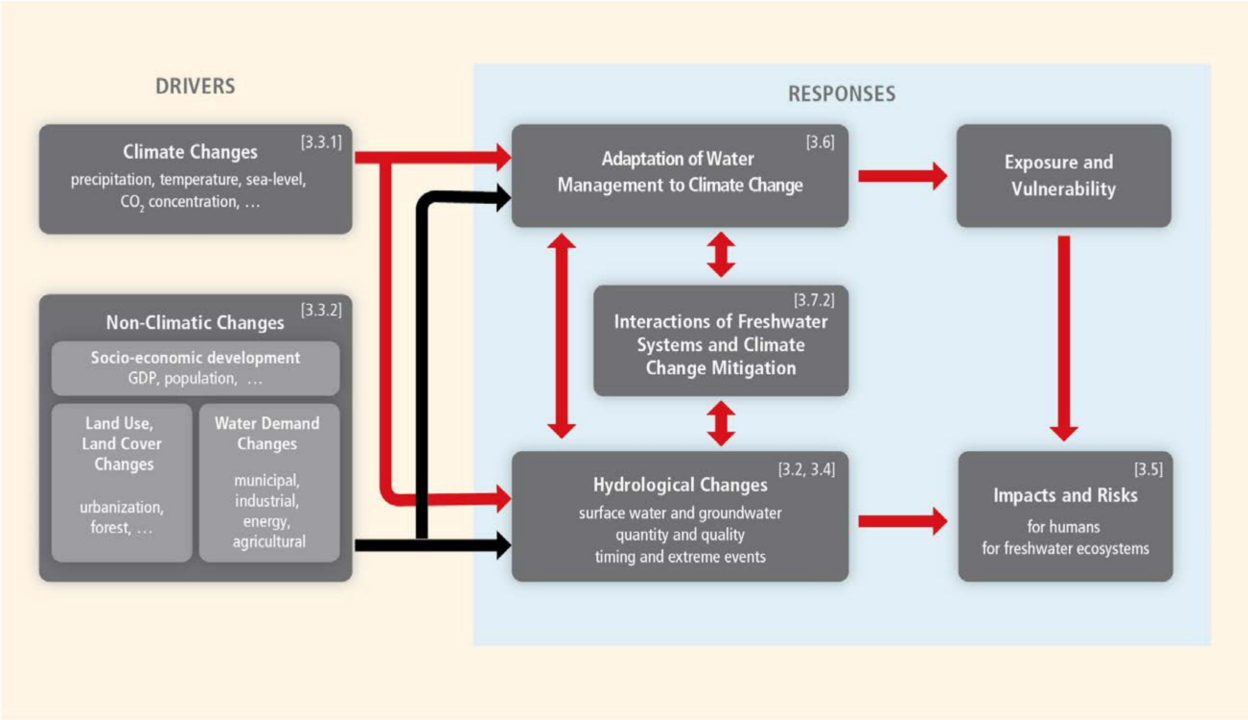
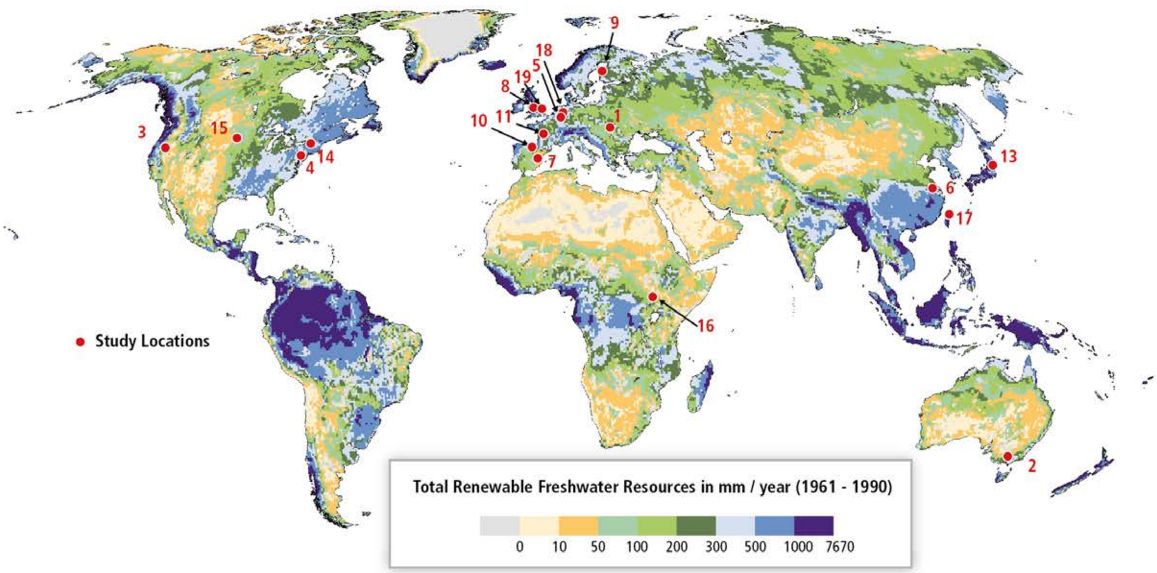


Figure 3-1: Framework (boxes) and linkages (arrows) for considering impacts of climatic and social changes on freshwater systems, and consequent impacts on and risks for humans and freshwater ecosystems. Both climatic (Section 3.3.1) and non-climatic (Section 3.3.2) drivers have changed natural freshwater systems (Section 3.2) and are expected to continue to do so (Section 3.4). They also stimulate adaptive measures (Section 3.6). Hydrological and water-management changes interact with each other and with measures to mitigate climate change (Section 3.7.2). Adaptive measures influence the exposure and vulnerability of human beings and ecosystems to water-related risks (Section 3.5).



#	Location	Study Period	Observation on water quality	Reference
1	Danube River, Bratislava, Slovakia	1926-2005	The water temperature is rising but the trend of the weighted long term average temperature values resulted close to zero because of the inter-annual distribution of the mean monthly discharge.	Pekarova et al., 2008
2	Purrumbete, Colac & Bullen Merri Lakes, Victoria, Australia	1984-2000	The increases in salinity and nutrient content were associated with the air temperature increase; salinity in addition was associated with variations in the effective precipitation.	Tibby and Tiller, 2007
3	Lake Tahoe, California and Nevada States, US	1970-2007	Thermal stability resulting from a higher ambient temperature decreased the dissolved oxygen content.	Sahoo et al., 2010
4	Neuse River Estuary, North Carolina, US	1979-2003	Intense storms and hurricanes flushed nutrients from the estuary reducing eutrophic conditions and the risk of algal blooms.	Paerl et al., 2006; Paerl and Huisman, 2008
5	River Meuse, western Europe	1976-2003	Increase of water temperature and the content of major elements and some heavy metals were associated with droughts. Algal blooms resulted from a higher nutrient content due to higher water temperature and longer residence time.	van Vliet and Zwolsman, 2008
6	Lake Taihu, Wuxi, Jiangsu, China	2007	The lake already suffering from periodic cyanobacterial blooms, was affected by a very intensive bloom in May 2007 attributed to an unusually warm spring and leading to the presence of Microcystis toxins in the water. This forced two million people to drink bottled water for at least one week.	Qin et al., 2010
7	Sau Reservoir, Spain	1964-2007	Stream flow variations were of greater significance than temperature increases in the depletion of dissolved oxygen.	Marcé et al., 2010
8	22 upland waters in UK	1988-2002	Dissolved organic matter increased due to temperature increase but also to rainfall variations, acid deposition, land-use, and CO_2 enrichment.	Evans et al., 2005
9	Coastal rivers from western Finland	1913-2007	Low pH values associated with higher rainfall and river discharge in an acid sulphate soil basin.	Saarinen et al., 2010
		1961-2007	Critical values of dissolved organic carbon associated with higher rainfall and river discharge.	
10	15 pristine mountain rivers, Northern Spain	1973-2005	For a semiarid area, a clear relationship between increases in air temperature and a higher nutrient and dissolved organic carbon content.	Benítez-Gilabert et al., 2010
11	30 coastal rivers and groundwater of Western France	1973-2007 (2-6 years)	Inter-annual variations in the nutrient content associated with air temperature, rainfall and management practices changes. These effects were not observed in groundwater because of the delay in response time and the depuration of soil on water.	Gascuel-Odoux et al., 2010
12	Girnock, Scotland	14 months	Higher risks of faecal pollution clearly related to rainfall during the wet period	Tetzlaff et al., 2010
13	27 rivers in Japan	1987-1995	Increases in organic matter and sediment and decreases in the dissolved oxygen content associated with increases in ambient temperature. Precipitation increases and variations associated with increase in the organic matter, sediments and chemical oxygen demand content in water.	Ozaki et al., 2003
14	Conestoga River Basin, Pennsylvania, US	1977-1997	Close association between annual loads of total nitrogen and annual precipitation increases.	Chang 2004
15	US	1948-1994	Increased rainfall and runoff associated with site-specific outbreaks of waterborne disease.	Curriero et al., 2001
16	Northern and Eastern Uganda	1999-2001, 2004, 2007	Elevated concentrations of faecal coliforms observed in groundwater-fed water supplies during the rainy season.	Tumwine et al. 2002, 2003; Taylor et al., 2009
17	Taiwan, China	1998	The probability of detecting cases of enterovirus infection was greater than 50% with rainfall rates >31 mm/h. The higher the rainfall rate, the higher the probability of an enterovirus epidemic.	Jean et al., 2006
18	Rhine Basin	1980-2001	Nutrient content in rivers followed seasonal variations in precipitation which were also linked to erosion within the basin.	Loos et al., 2009
19	River Thames, England	1868-2008	Higher nutrient contents were associated to changes in river runoff and land use.	Howden et al., 2010

Figure 3-2: Observations of the impacts of climate on water quality.

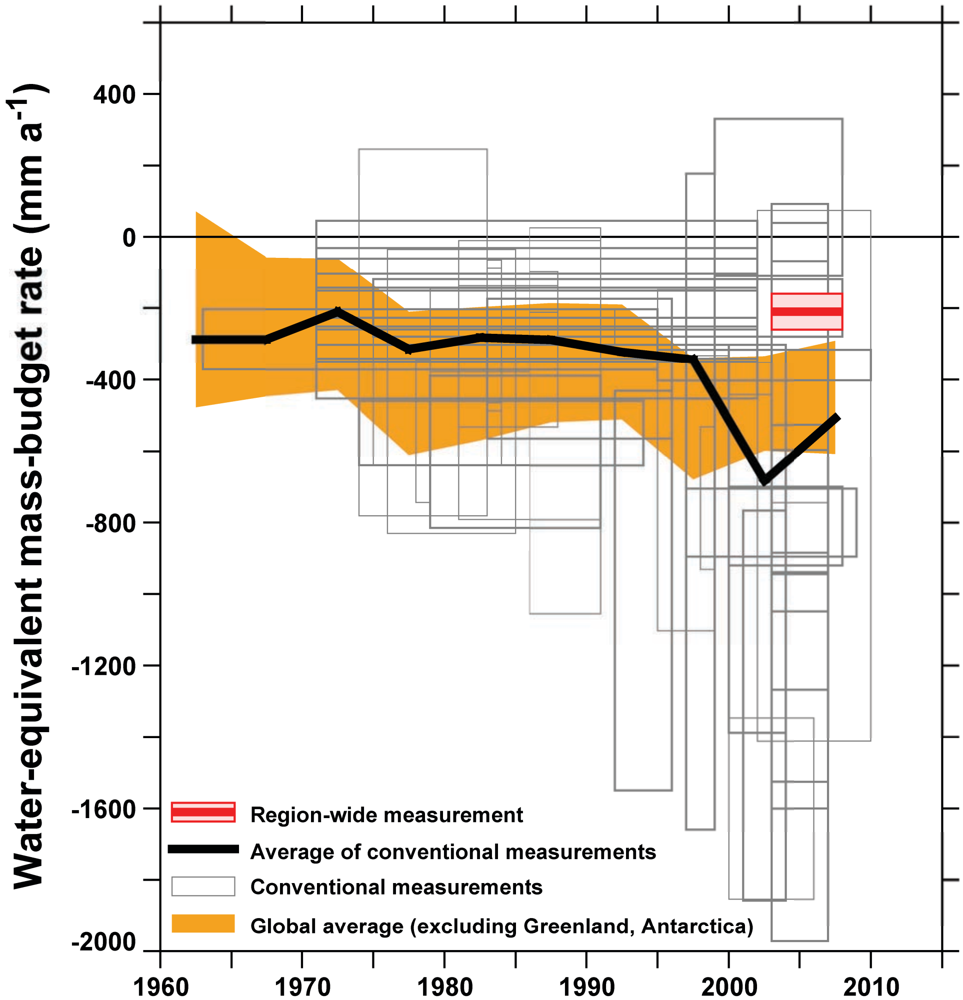


Figure 3-3: All published glacier mass balance measurements from the Himalaya (based on Bolch *et al*., 2012). To emphasize the variability of the raw information, each measurement is shown as a box of height ±1 standard deviation centred on the average balance (±1 standard error for multi-annual measurements). Region-wide measurement (Kääb *et al*., 2012) was by satellite laser altimetry. Global average (WGI Chapter 4) is shown as a 1-sigma confidence region.

[Illustration to be redrawn to conform to IPCC publication specifications.]

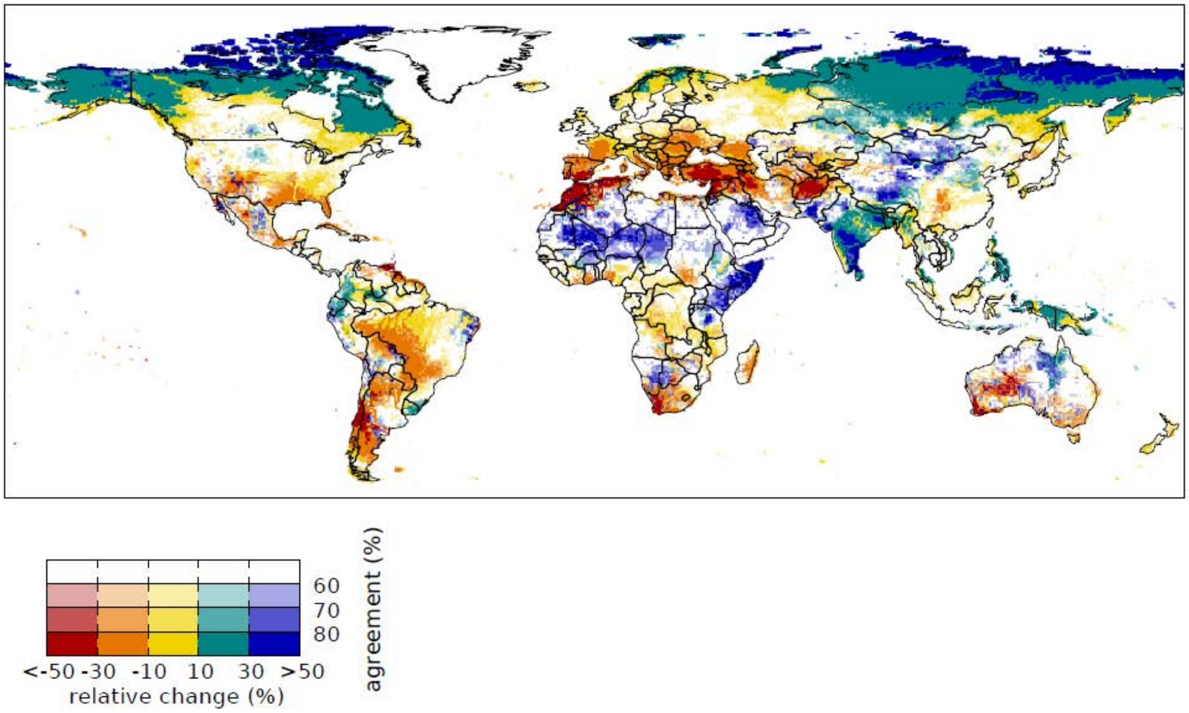


Figure 3-4: Percentage change of mean annual streamflow for a global mean temperature rise of 2°C above 1980–2010 (2.7°C above pre-industrial). Color hues show the multi-model mean change across 4 GCMs and 11 global hydrological models (GHMs), and saturation shows the agreement on the sign of change across all 55 GHM-GCM combinations (percentage of model runs agreeing on the sign of change) (Schewe *et al*., 2013).
[Illustration to be redrawn to conform to IPCC publication specifications.]

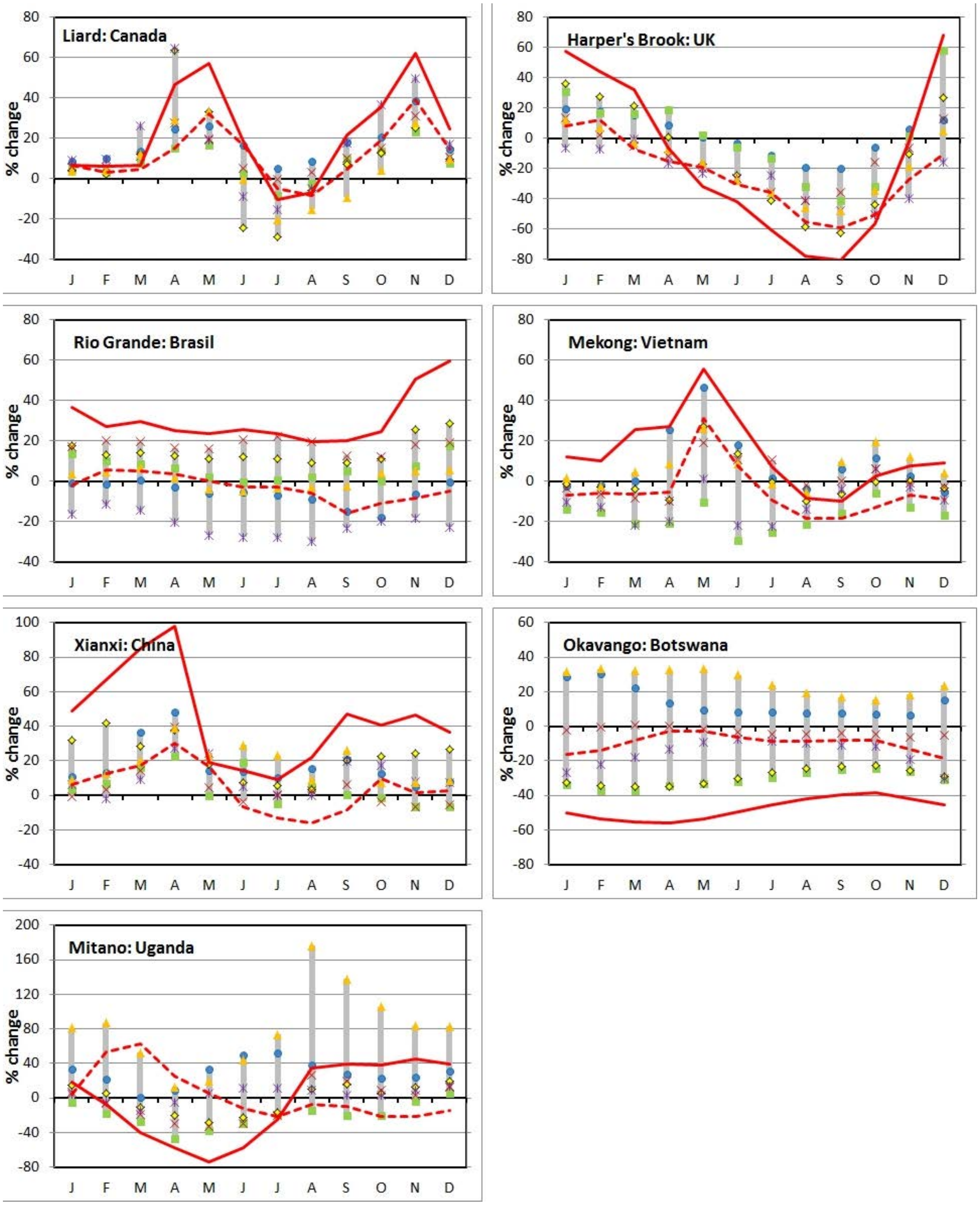
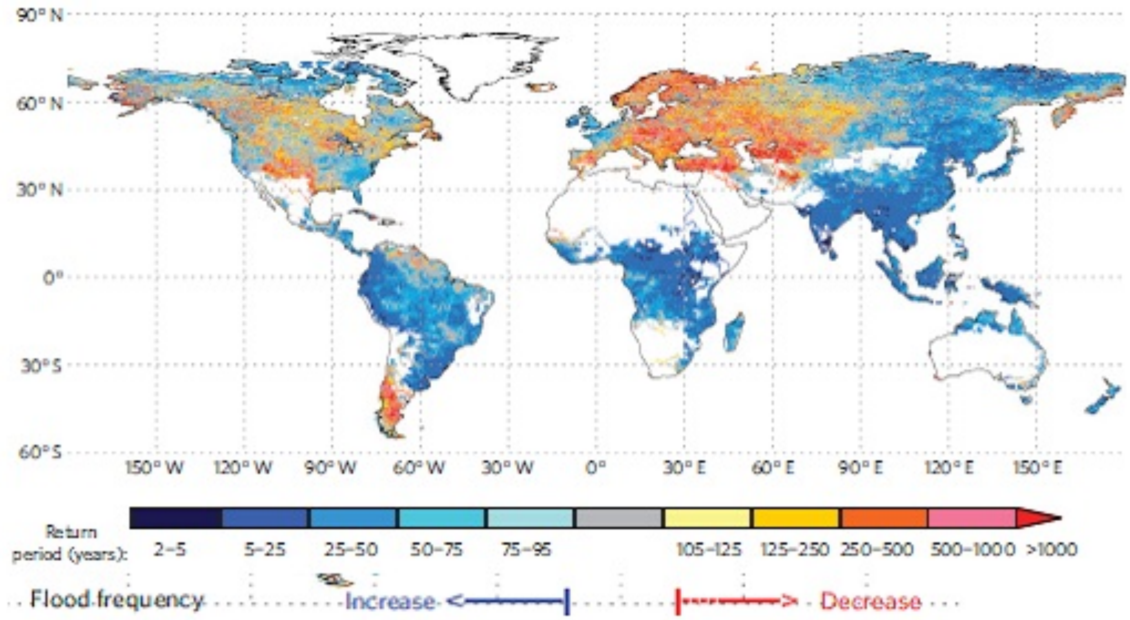


Figure 3-5: Change in mean monthly runoff across seven climate models in seven catchments, with a 2ºC increase in global mean temperature above 1961-1990 (Arnell, 2011; Hughes *et al*., 2011; Kingston and Taylor, 2010; Kingston *et al*., 2011; Nobrega *et al*., 2011; Thorne, 2011; Xu *et al*., 2011). One of the seven climate models (HadCM3) is highlighted separately, showing changes with both a 2ºC increase (dotted line) and a 4ºC increase (solid line). **[Illustration to be redrawn to conform to IPCC publication specifications.]**

a)



b)

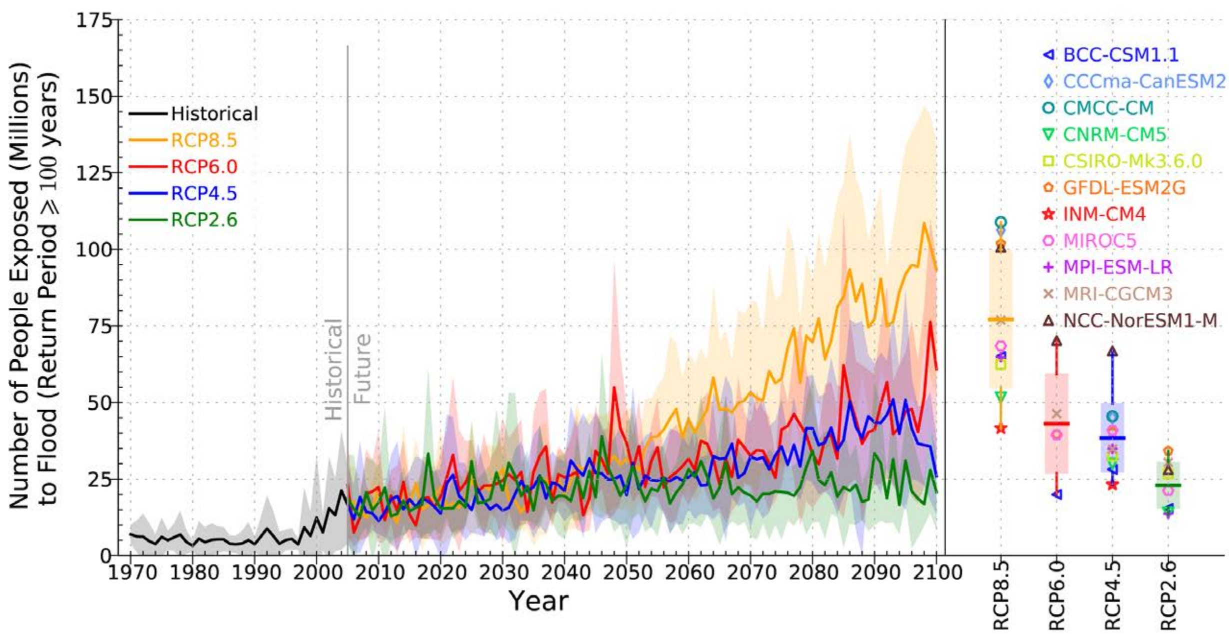


Figure 3-6: a) Multi-model median return period (years) in the 2080s for the 20th-century 100-year flood (Hirabayashi *et al*., 2013), based on one hydrological model driven by 11 CMIP5 GCMs under RCP8.5. At each location the magnitude of the 100-year flood was estimated by fitting a Gumbel distribution function to time series of simulated annual maximum daily discharge in 1971–2000, and the return period of that flood in 2071–2100 was estimated by fitting the same distribution to discharges simulated for that period. b) Global exposure to the 20th-century 100-year flood (or greater) in millions of people (Hirabayashi *et al*., 2013). Left: ensemble means of historical (black thick line) and future simulations (colored thick lines) for each scenario. Shading denotes ±1 standard deviation. Right: maximum and minimum (whiskers), mean (horizontal thick lines within each bar), ±1 standard deviation (box) and projections of each GCM (colored symbols) averaged over the 21st century. The

impact of 21st-century climate change is emphasized by fixing the population to that of 2005. Annual global flood exposure increases over the century by 4-14 times as compared to the 20th century [4±3 (RCP2.6), 7±5 (RCP4.5), 7±6 (RCP6.0) and 14±10 (RCP8.5) times, or 0.1% to 0.4-1.2% of the global population in 2005)]. Under a scenario of moderate population growth (UN, 2011), the global number of exposed people is projected to increase by a factor of 7-25, depending on the RCP, with strong increases in Asia and Africa due to high population growth.
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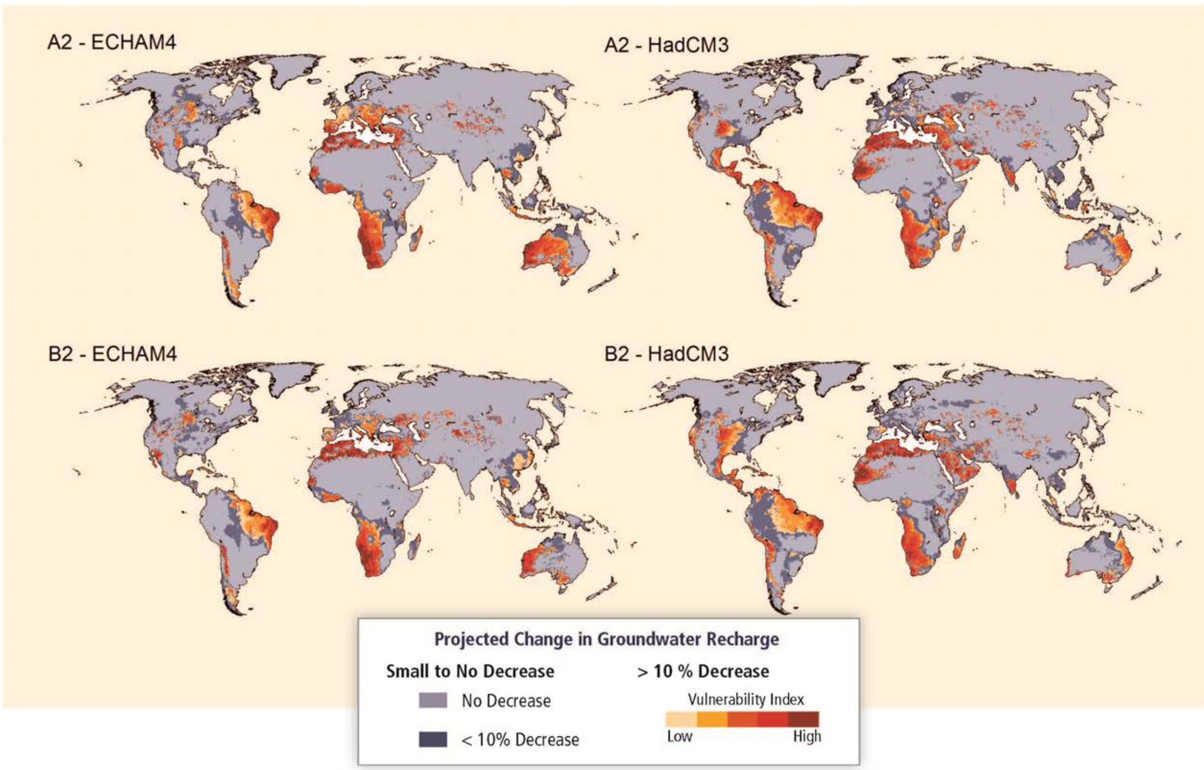

Figure 3-7: Human vulnerability to climate-change induced decreases of renewable groundwater resources by the 2050s. Lower (B2) and higher (A2) emissions pathways are interpreted by two global climate models. The higher the vulnerability index (computed by multiplying percentage decrease of groundwater recharge by a sensitivity index), the higher the vulnerability. The index is only defined for areas where groundwater recharge is projected to decrease by at least 10% relative to 1961-1990 (Döll, 2009).

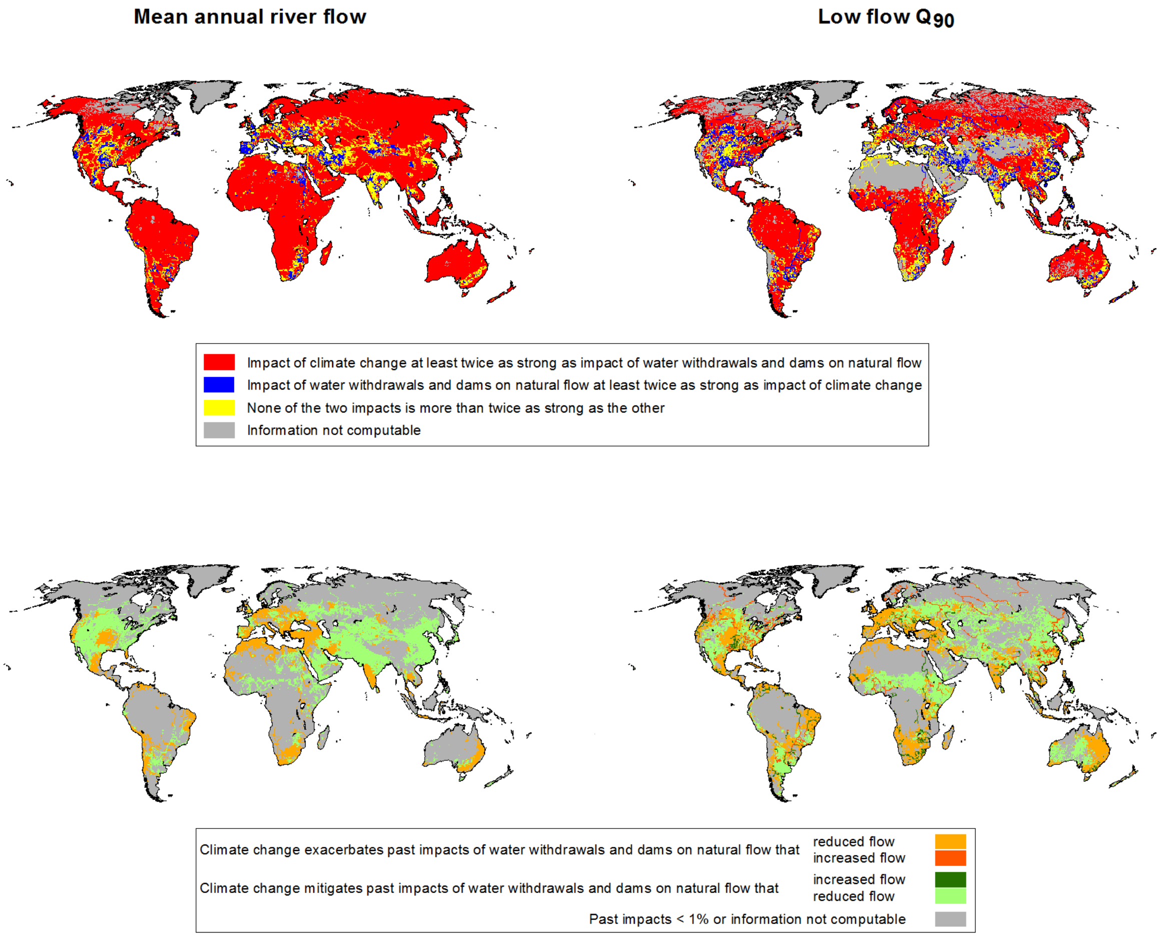

Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out 10 months. Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.
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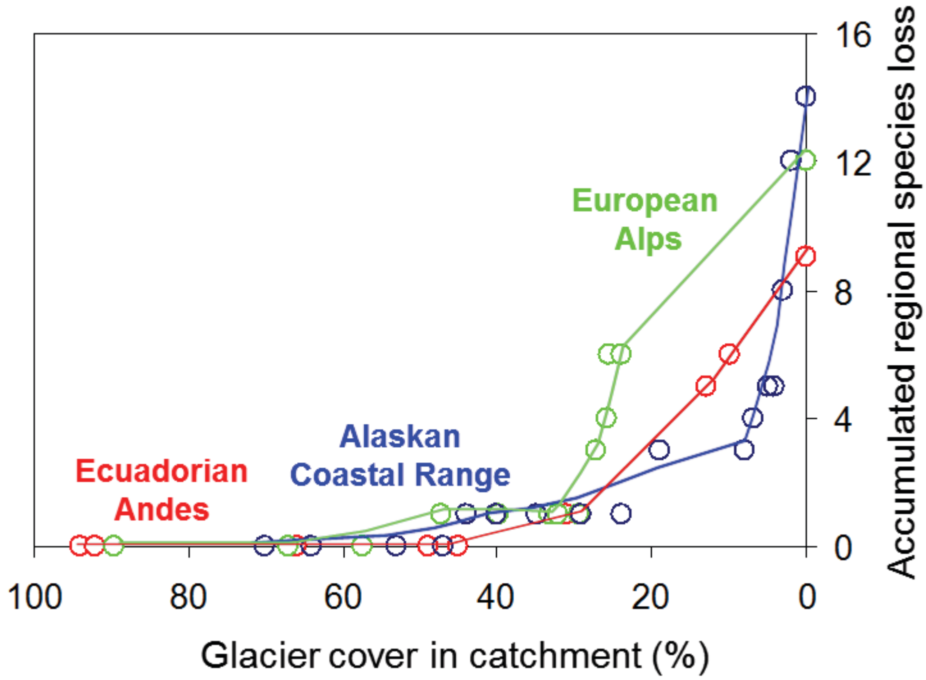

Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16 and 38% of the total species richness in the three study regions in Ecuador, Europe and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.

[Illustration to be redrawn to conform to IPCC publication specifications.]

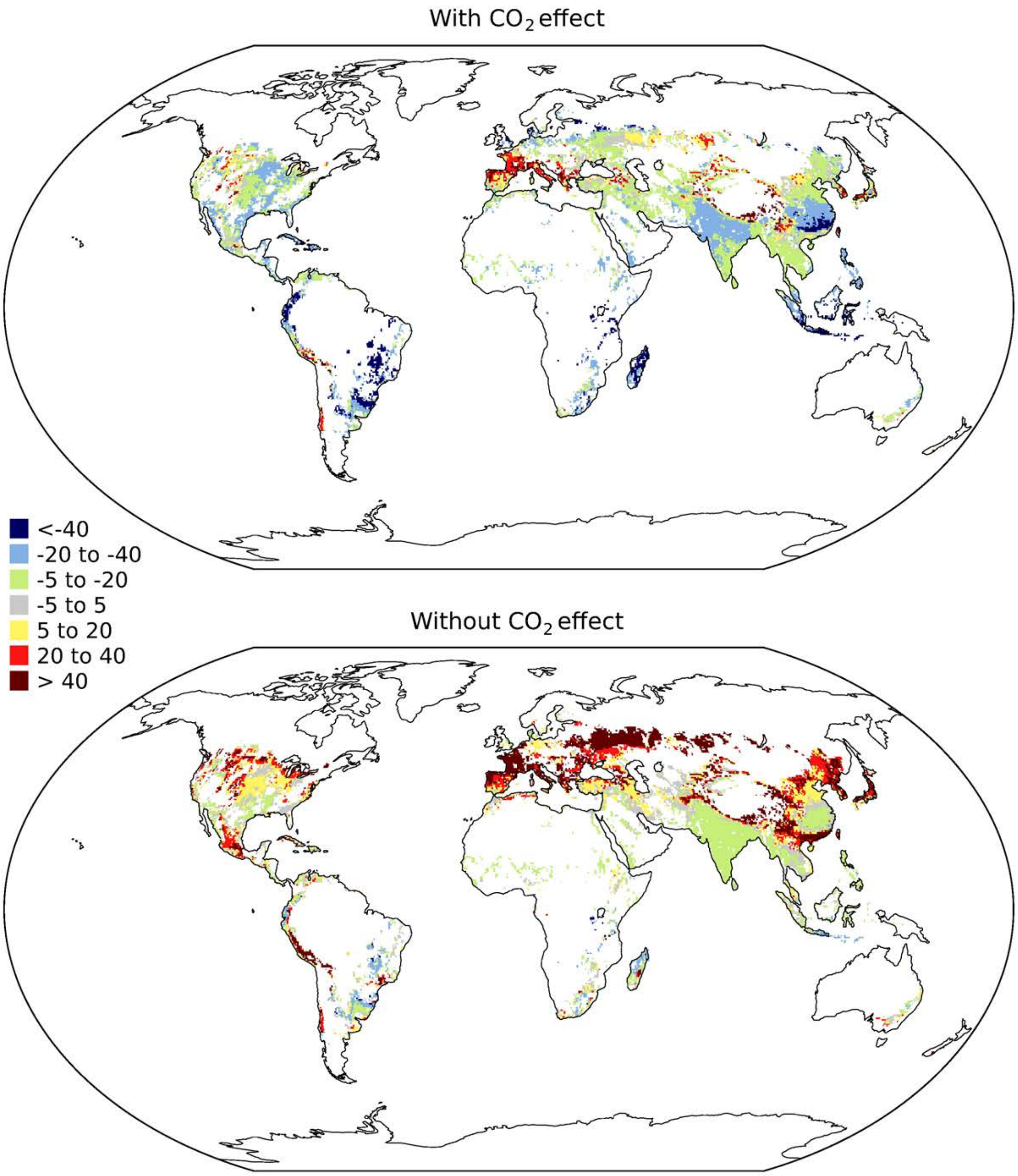

Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).
[Illustration to be redrawn to conform to IPCC publication specifications.]

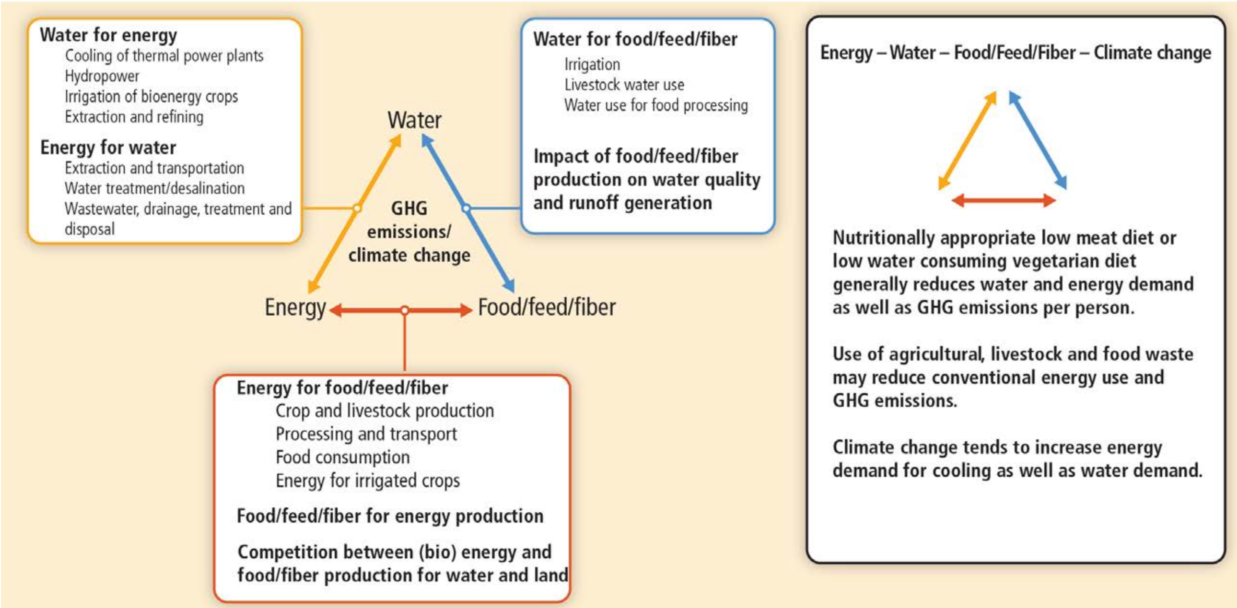

Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

Chapter 4. Terrestrial and Inland Water Systems

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Contents

Executive Summary

The planet's biota and ecosystem processes were strongly affected by past climate changes at rates of climate change lower than those projected during the 21st century under high warming scenarios (e.g., RCP8.5) (*high confidence*). Most ecosystems are vulnerable to climate change even at rates of climate change projected under low- to medium-range warming scenarios (e.g., RCP2.6 to RCP6.0). The paleoecological record shows that global climate changes comparable in magnitudes to those projected for the 21st century under all scenarios resulted in large-scale biome shifts and changes in community composition; and that for rates projected under RCP6 and 8.5, was associated with species extinctions in some groups (*high confidence*). [4.2.3]

Climate change is projected to be a powerful stressor on terrestrial and freshwater ecosystems in the second half of the 21st century, especially under high-warming scenarios such as RCP6.0 and RCP8.5 (*high confidence*). Direct human impacts such as land-use and land use change, pollution and water resource development will continue to dominate the threats to most freshwater (*high confidence*) and terrestrial (*medium confidence*) ecosystems globally over the next three decades. **Changing climate exacerbates other impacts on biodiversity (*high confidence*).** Ecosystem changes resulting from climate change may not be fully apparent for several decades, due to long response times in ecological systems (*medium confidence*). Model-based projections imply that under low to moderate warming scenarios (e.g., RCP2.6 to RCP6.0), direct land cover change will continue to dominate over (and conceal) climate-induced change as a driver of ecosystem change at the global scale; for higher climate change scenarios, some model projections imply climate-driven ecosystem changes sufficiently extensive to equal or exceed direct human impacts at the global scale (*medium confidence*). In high altitude and high latitude freshwater and terrestrial ecosystems, climate changes exceeding those projected under RCP2.6 will lead to major changes in species distributions and ecosystem function, especially in the second half of the 21st century (*high confidence*). [4.2.4, 4.3.2.5, 4.3.3, 4.3.3.1, 4.3.3.3, 4.4.1.1]

When terrestrial ecosystems are substantially altered (in terms of plant cover, biomass, phenology or plant group dominance), either through the effects of climate change or through other mechanisms such as conversion to agriculture or human settlement, the local, regional and global climates are also affected (*high confidence*). The feedbacks between terrestrial ecosystems and climate include, among other mechanisms, changes in surface albedo, evapotranspiration and greenhouse gas emissions and uptake. The physical effects on the climate can be opposite in direction to the greenhouse gas effects, and can materially alter the net outcome of the ecosystem change on the global climate (*high confidence*). The regions where the climate is affected may extend beyond the location of the ecosystem that has changed. [4.2.4.1, 4.3.3.4]

Rising water temperatures, due to global warming, will lead to shifts in freshwater species distributions and worsen water quality problems, especially in those systems experiencing high anthropogenic loading of nutrients (*high confidence*). Climate change-induced changes in precipitation will substantially alter ecologically important attributes of flow regimes in many rivers and wetlands and exacerbate impacts from human water use in developed river basins (*medium confidence*). [4.3.3.3, Box CC-RF]

Many plant and animal species have moved their ranges, altered their abundance and shifted their seasonal activities in response to observed climate change over recent decades (*high confidence*). They are doing so now in many regions and will continue to do so in response to projected future climate change (*high confidence*). The broad patterns of species and biome shifts towards the poles and higher in altitude in response to a warming climate are well established for periods thousands of years in the past (*very high confidence*). These general patterns of range shifts have also been observed over the last few decades in some well-studied species groups such as insects and birds and can be attributed to observed climatic changes (*high confidence*). Interactions between changing temperature, precipitation and land use can sometimes result in range shifts that are downhill or away from the poles. Certainty regarding past species movements in response to changing climate, coupled with projections from a variety of models and studies, provide *high confidence* that such species movements will be the norm with continued warming. Under all RCP climate change scenarios for the second half of the 21st century, with *high confidence*: a) community composition will change as a result of decreases in the abundances of some species and increases in others; b) the seasonal activity of many species will change differentially disrupting life cycles and interactions between species. Composition and seasonal change will both alter ecosystem function. **[**4.2.1, 4.2.3, 4.3.2, 4.3.2.1, 4.3.2.5, 4.3.3, 4.4.1.1]

Many species will be unable to move fast enough during the 21st century to track suitable climates under mid- and high-range rates of climate change (i.e., RCP 4.5, RCP 6.0 and RCP 8.5 scenarios) (*medium confidence*). The climate velocity (the rate of movement of the climate across the landscape) will exceed the maximum velocity at which many groups of organisms, in many situations, can disperse or migrate, except after mid-century in the RCP 2.6 scenario. Populations of species that cannot keep up with their climate niche will find themselves in unfavourable climates, unable to reach areas of potentially suitable climate. Species occupying extensive flat landscapes are particularly vulnerable because they must disperse over longer distances to keep pace with shifting climates than species in mountainous regions. Species with low dispersal capacity will also be especially vulnerable:

examples include many plants (especially trees), many amphibians and some small mammals. For example, the maximum observed and modelled dispersal and establishment rates for mid- and late-successional tree species are insufficient to track climate change except in mountainous areas, even at moderate projected rates of climate change. Barriers to dispersal, such as habitat fragmentation, prior occupation of habitat by competing species and human-made impediments such dams on rivers and urbanized areas on land, reduce the ability of species to migrate to more suitable climates (*high confidence*). Intentional and accidental anthropogenic transport can speed dispersal. [4.3.2.5, 4.3.3.3]

Large magnitudes of climate change will reduce the populations, vigour and viability of species with spatially-restricted populations, such as those confined to small and isolated habitats, mountaintops or mountain streams, even if the species has the biological capacity to move fast enough to track suitable climates (*high confidence*). The adverse effects on restricted populations are modest for low magnitudes of climate change (e.g., RCP 2.6) but very severe for the highest magnitudes of projected climate change (e.g., RCP 8.5). [4.3.2.5, 4.3.3.4, 4.3.4.1]

The capacity of many species to respond to climate change will be constrained by non-climate factors (*high confidence*), including but not limited to the simultaneous presence of inhospitable land-uses, habitat fragmentation and loss, competition with alien species, exposure to new pests and pathogens, nitrogen loading and tropospheric ozone. [4.2.4.6, 4.3.3.5, Figure 4-1]

The establishment, growth, spread and survival of populations of invasive alien species has increased (*high confidence*), but the ability to attribute alien species invasion to climate change is low in most cases. Some invasive alien species have traits that favour their survival and reproduction under changing climates. Future movement of species into areas where they were not present historically will continue to be mainly driven by increased dispersal opportunities associated with human activities and by increased disturbances from natural and anthropogenic events, in some cases facilitated and promoted by climate change. [4.2.4.6, Figure 4-4]

A large fraction of terrestrial and freshwater species face increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures, such as habitat modification, over-exploitation, pollution and invasive species (*high confidence*). The extinction risk is increased under all RCP scenarios, and the risk increases with both the magnitude and rate of climate change. While there is *medium confidence* that recent warming contributed to the extinction of many species of Central American amphibians, there is generally *very low confidence* that observed species extinctions can be attributed to recent climate change. Models project that the risk of species extinctions will increase in the future due to climate change, but there is *low agreement* concerning the fraction of species at increased risk, the regional and taxonomic focus for such extinctions and the timeframe over which extinctions could occur. Modelling studies and syntheses since the AR4 report broadly confirm that a large proportion of species are projected to be at increased risk of extinction at all but the lowest levels of climate warming (RCP2.6). Some aspects leading to uncertainty in the quantitative projections of extinction risks were not taken into account in previous models; as more realistic details are included, it has been shown that the extinction risks may be either under- or overestimated when based on simpler models. [4.3.2.5]

Terrestrial and freshwater ecosystems have sequestered about a quarter of the carbon dioxide emitted to the atmosphere by human activities in the past three decades (*high confidence*). The net fluxes out of the atmosphere and into plant biomass and soils show large year-to-year variability; as a result there is *low confidence* in the ability to determine whether the net rate at which carbon has been taken up by terrestrial ecosystems at the global scale has changed between the decades 1991-2000 and 2001-2010. There is *high confidence* that the factors causing the current increase in land carbon include the positive effects of rising CO_2 on plant productivity, a warming climate, nitrogen deposition and recovery from past disturbances, but *low confidence* regarding the relative contribution by each of these and other factors. [4.2.4.1, 4.2.4.2, 4.2.4.4, 4.3.2.2, 4.3.2.3, WGI AR5 Sections 6.3.1 and 6.3.2.6]

The natural carbon sink provided by terrestrial ecosystems is partially offset at the decadal timescale by carbon released through the conversion of natural ecosystems (principally forests) to farm and grazing land

and through ecosystem degradation (*high confidence*). Carbon stored in the terrestrial biosphere is vulnerable to loss back to the atmosphere as a result of the direct and indirect effects of climate change, deforestation and degradation (*high confidence*). The net transfer of carbon dioxide from the atmosphere to the land is projected to weaken during the 21st century (*medium confidence*). The direct effects of climate change on stored terrestrial carbon include high temperatures, drought and windstorms, indirect effects include increased risk of fires, pest and disease outbreaks. Experiments and modelling studies provide *medium confidence* that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate; and *high confidence* that low availability of nutrients, particularly nitrogen, will limit the response of many natural ecosystems to rising CO_2. There is *medium confidence* that other factors associated with global change, including high temperatures, rising ozone concentrations and in some places drought, decrease plant productivity by amounts comparable in magnitude to the enhancement by rising CO_2. There are few field-scale experiments on ecosystems at the highest CO_2 concentrations projected by RCP 8.5 for late in the century, and none of these include the effects of other potential confounding factors. [4.2.4, 4.2.4.1, 4.2.4.2, 4.2.4.3, 4.2.4.4, 4.3.2.2, 4.3.3.1, Box 4-3, Box CC-VW, WGI AR5 6.4.3.3]

Increases in the frequency or intensity of ecosystem disturbances such as droughts, wind-storms, fires and pest outbreaks have been detected in many parts of the world and in some cases are attributed to climate change (*medium confidence*). Changes in the ecosystem disturbance regime beyond the range of natural variability will alter the structure, composition and functioning of ecosystems (*high confidence*). Ecological theory and experimentation predicts that ecological change resulting from altered disturbance regimes will be manifested as relatively abrupt and spatially-patchy transitions in ecosystem structure, composition and function, rather than gradual and spatially-uniform shifts in location or abundance of species (*medium confidence*). [4.2.4.6, 4.3.3, 4.3.2.5, Box 4-3, Box 4-4, Figure 4-10]

Increased tree death has been observed in many places worldwide, and in some regions has been attributed to climate change (high confidence). In some places it is sufficiently intense and widespread as to result in forest dieback (*low confidence*). Forest dieback is a major environmental risk with potentially large impacts on climate, biodiversity, wood production, water quality, amenity and economic activity. In detailed regional studies in western and boreal North America, the tree mortality observed over the past few decades has been attributed to the effects of high temperatures and drought, or to changes in the distribution and abundance of insect pests and pathogens related, in part, to warming *(high confidence)***.** Tree mortality and associated forest dieback will become apparent in many regions sooner than previously anticipated (*medium confidence*). Earlier projections of increased tree growth and enhanced forest C sequestration due to increased growing season duration, rising CO_2 concentration and atmospheric N deposition, must be balanced by observations and projections of increasing tree mortality and forest loss due to fires and pest attacks. The consequences for the provision of timber and other wood products are projected to be highly variable between regions and products, depending on the balance of the positive *versus* negative effects of global change. [4.3.2, 4.3.3.1, 4.3.3.4, 4.3.3.5, 4.3.4, 4.3.4.2, Box 4-2, Box 4-3]

There is a high risk that the large magnitudes and high rates of climate change associated with low-mitigation climate scenarios (RCP4.5 and higher) will result within this century in abrupt and irreversible regional-scale change in the composition, structure and function of terrestrial and freshwater ecosystems, especially in the Amazon and Arctic, leading to substantial additional climate change (*medium confidence*). There are plausible mechanisms, supported by experimental evidence, observations, and model results, for the existence of ecosystem tipping points in both boreal-tundra Arctic systems and the rainforests of the Amazon basin. Continued climate change will transform the species composition, land cover, drainage and permafrost extent of the boreal-tundra system, leading to decreased albedo and the release of greenhouse gases (*medium confidence*). Adaptation measures will be unable to prevent substantial change in the boreal-arctic system (*high confidence*). Climate change alone is not projected to lead to abrupt widespread loss of forest cover in the Amazon during this century a (*medium confidence*), but a projected increase in severe drought episodes, together with land-use change and forest fire, would cause much of the Amazon forest to transform to less dense, drought- and fire-adapted ecosystems, and in doing so, put a large stock of biodiversity at elevated risk, while decreasing net carbon uptake from the atmosphere (*medium confidence*)**.** Large reductions in deforestation, as well as wider application of effective wildfire management, lower the risk of abrupt change in the Amazon, as well as the impacts of that change (*medium confidence*). [4.2.4.1, 4.3.3.1.1, 4.3.3.1.3, 4.3.3.4, Figure 4-8, Box 4-3, Box 4-4]

Management actions can reduce, but not eliminate, the risk of impacts to terrestrial and freshwater ecosystems due to climate change, as well as increase the inherent capacity of ecosystems and their species to adapt to a changing climate (*high confidence*). The capacity for natural adaptation by ecosystems and their constituent organisms is substantial, but for many ecosystems and species it will be insufficient to cope with projected rates and magnitudes of climate change in the 21st century without substantial loss of species and ecosystem services, under medium-range warming (e.g., RCP6.0) or high–range warming scenarios (e.g., RCP8.5) (*medium confidence*). The capacity for ecosystems to adapt to climate change can be increased by reducing the other stresses operating on them; reducing the rate and magnitude of climate change; reducing habitat fragmentation and increasing connectivity; maintaining a large pool of genetic diversity and functional evolutionary processes; assisted translocation of slow moving organisms or those whose migration is impeded, along with the species on which they depend; and manipulation of disturbance regimes to keep them within the ranges necessary for species persistence and sustained ecosystem functioning. [4.4, 4.4.1, 4.4.2]

Adaptation responses to climate change in the urban and agricultural sectors can have unintended negative outcomes for terrestrial and freshwater ecosystems (*medium confidence*). For example, adaptation responses to counter increased variability of water supply, such as building more and larger impoundments and increased water extraction, will in many cases worsen the direct effects of climate change in freshwater ecosystems**.** [4.3.3.3, 4.3.4.6]

Widespread transformation of terrestrial ecosystems in order to mitigate climate change, such as carbon sequestration through planting fast-growing tree species into ecosystems where they did not previously occur, or the conversion of previously uncultivated or non-degraded land to bioenergy plantations, will lead to negative impacts on ecosystems and biodiversity (*high confidence*). For example, the land use scenario accompanying the mitigation scenario RCP2.6 features a large expansion of biofuel production, displacing natural forest cover. [4.2.4.1, 4.4.4]

4.1. Past Assessments

The topics assessed in this chapter were last assessed by the IPCC in 2007, principally in the Working Group II report Chapters 3 (Freshwater resources and their management; Kundzewicz *et al.*, 2007) and 4 (Ecosystems, their properties, goods and services; Fischlin *et al.*, 2007), but also Chapter 1 (Assessment of observed changes and responses in natural and managed systems, Sections 1.3.4 and 1.3.5; Rosenzweig *et al.*, 2007). The WGII SPM said "Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases", though they noted that documentation of observed changes in tropical regions and the Southern Hemisphere was sparse (Rosenzweig *et al.*, 2007). Fischlin *et al.* (2007) found that 20-30% of the plant and animal species that had been assessed to that time were considered to be at increased risk of extinction if the global average temperature increase exceeds 2-3°C above the pre-industrial level *with medium confidence*, and that substantial changes in structure and functioning of terrestrial, marine and other aquatic ecosystems are *very likely* under that degree of warming and associated atmospheric CO_2 concentration. No timescale was associated with these findings. The carbon stocks in terrestrial ecosystems were considered to be at high risk from climate change and land use change. The report warned that the capacity of ecosystems to adapt naturally to the combined effect of climate change and other stressors is likely to be exceeded if greenhouse emission continued at or above the then-current rate.

4.2. A Dynamic and Inclusive View of Ecosystems

There are three aspects of the contemporary scientific view of ecosystems that are important to know for policy purposes. Firstly, ecosystems usually have imprecise and variable boundaries. They span a wide range of spatial scales, nested within one another, from the whole biosphere, down through its major ecosystem types (biomes) to local and possibly short-lived associations of organisms. Secondly, the human influence on ecosystems is globally pervasive. Humans are regarded as an integral, rather than separate, part of social-ecological systems (Gunderson and Holling, 2001; Berkes *et al.*, 2003). Ecosystems are connected across boundaries through the movement of energy, materials and organisms, and subsidies between terrestrial and freshwater systems are known to be particularly important (Polis *et al.*, 1997; Loreau *et al.*, 2003). As a consequence, human activities in terrestrial systems can significantly impact freshwater ecosystems and their biota (Allan, 2004). The dynamics of social-ecological systems are governed not only by biophysical processes such as energy flows, material cycles, competition and predation, but also by social processes such as economics, politics, culture and individual preferences (Walker and Salt, 2006). Thirdly, ecologists do not view ecosystems as necessarily inherently static and at equilibrium in the absence of a human disturbance (Hastings, 2004). Ecosystems vary over time and space in the relative magnitude of their components and fluxes, even under a constant environment, due to internal dynamics (Scheffer, 2009). Furthermore, attempts to restrict this intrinsic variation - or that resulting from externally-generated disturbances - are frequently futile, and may damage the capacity of the ecosystem to adapt to a changing environment (Folke *et al.*, 2004). This contrasts with the popular view that ecosystems exhibit a 'balance of Nature' and benefit from being completely protected from disturbance.

4.2.1. Ecosystems, Adaptation, Thresholds, and Tipping Points

The term "adaptation" has different meanings in climate policy, ecology and evolutionary biology. In climate policy (see glossary) it implies human actions intended to reduce negative outcomes. In ecology, ecosystems are said to be adaptive because their composition or function can change in response to a changing environment, without necessarily involving deliberate human actions (see Section 4.4.1). In evolutionary biology, adaptation means a change in the genetic properties of a population of individuals as a result of natural selection (Section 4.4.1.2); a possibility seen since the Fourth Assessment Report as increasingly relevant to climate change.

The notion of thresholds has become a prominent ecological and political concern (Lenton *et al.*, 2008; Knapp *et al.*, 2008a; Leadley *et al.*, 2010). To avoid policy confusion, three types of threshold need to be distinguished. The first reflects a human preference that the ecosystem stays within certain bounds, such as above a certain forest cover. These can be, by definition, negotiated. The second type reflects fundamental biological or physical properties, for instance the temperature at which frozen soils thaw (see Box 4-4) or the physiological tolerance limits of species. The third type is caused by system dynamics: the point at which the net effect of all the positive and negative feedback loops regulating the system is sufficiently large and positive that a small transgression becomes sufficiently amplified to lead to a change in ecosystem state called a regime shift (Lenton *et al.*, 2008). The new state exhibits different dynamics, mean composition, sensitivity to environmental drivers and flows of ecosystem services relative to the prior state. This type of threshold is called a "tipping point" (defined in the glossary as a level of change in system properties beyond which a system reorganizes, often abruptly, and persists in its new state even if the drivers of the change are abated) and is important in the context of climate change because its onset may be abrupt, hard to predict precisely and effectively irreversible (Scheffer *et al.*, 2009; Leadley *et al.*, 2010; Barnosky *et al.*, 2012; Brook *et al.*, 2013; Hughes *et al.*, 2013). Many examples of tipping points have now been identified (Scheffer, 2009). Regional-scale ecosystem tipping points have not occurred in the recent past, but there is good evidence for tipping points in the distant past (Section 4.2.3) and there is concern that they could occur in the near future (see Boxes 4-3 and 4-4).

The early detection and prediction of ecosystem thresholds, particularly tipping points, is an area of active research. There are indications (Scheffer, 2009) that an increase in ecosystem variability signals the impending approach of a threshold. In practice, such signals may not be detectable against background noise and uncertainty until the threshold is crossed (Biggs *et al.*, 2009). The dynamics of ecosystems are complex and our present level of knowledge is inadequate to predict all ecosystem outcomes with confidence, even if the future climate was precisely known.

Field observations over the past century in numerous locations in boreal, temperate and tropical ecosystems have detected biome shifts, the replacement at a location of one suite of species by another (*high confidence*). The effect is usually of biomes moving upwards in elevation and to higher latitudes (Gonzalez *et al.*, 2010). These shifts have often been attributed to anthropogenic climate change, since biome distribution is known to broadly reflect climate zones, and the shifts have been observed in area without major human disturbance (*medium confidence*) (Table 4-1). Projections of future vegetation distribution under climate change indicate that many biomes could shift substantially, including in areas where ecosystems are largely undisturbed by direct human land use (Figure 4-2). The extent of the shift increases with increasing global mean warming, without a sudden threshold (Scholze *et al.*, 2006; Pereira *et al.*, 2010; Rehfeldt *et al.*, 2012).

[INSERT TABLE 4-1 HERE
Table 4-1: Biome shifts of the 20th century from published field research that examined trends over periods > 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.*, 2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). The biome abbreviations match those in Figure 4-1. Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. * rate significant at $P \leq 0.05$.]

[INSERT FIGURE 4-1 HERE
Figure 4-1: Locations of observed biome shifts during the 20th century, listed in Table 4-1, derived from Gonzalez *et al.* (2010). The color of each semi-circle indicates the retracting biome (top for North America, Europe, Asia; bottom for Africa and New Zealand) and the expanding biome (bottom for North America, Europe, Asia; top for Africa and New Zealand), according to published field observations. Biomes, from poles to equator: ice (IC), tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate mixed forest (TM), temperate shrubland (TS), temperate grassland (TG), desert (DE), tropical grassland (RG), tropical woodland (RW), tropical deciduous broadleaf forest (RD), tropical evergreen broadleaf forest (RE). The background is the potential biome according to the MC1 dynamic global vegetation model under the 1961-1990 climate.]

[INSERT FIGURE 4-2 HERE
Figure 4-2: Implications of climate change and land use change for biome shifts. (a) Fraction of land covered by primary vegetation in 2005 (Hurtt *et al.*, 2011); (b) Fraction of simulations showing climate change-driven biome shift for any level of global warming between 1990 and 2100, with no direct anthropogenic land use change, using the MC1 vegetation model under 9 CMIP3 climate projections (3 GCMs each forced by the SRES A2, A1B and B1 scenarios; Gonzalez *et al.*, 2010); (c) Fraction of land covered by primary vegetation in 2100 under the RCP2.6 land use scenario with the IMAGE model, with no effect of climate change (Hurtt *et al.*, 2011); (d) Fraction of land covered by primary vegetation in 2100 under the RCP8.5 land use scenario with the MESSAGE model, with no effect of climate change (Hurtt *et al.*, 2011). Comparison of coloured areas in (b) with those in (a) shows where climate- driven biome shifts would occur in current areas of primary vegetation. Comparison of (b) and (d) shows where climate-driven biome shifts would occur in areas of primary vegetation projected under a land use scenario associated with RCP6.0. Comparison of (c) and (a) illustrates a scenario of land use change associated with RCP2.6, in which global climate change is projected to be smaller than that driving the biome shifts in (b) as a result of mitigation measures, some of which involve land use. Further details of the RCP land use / cover scenarios are given in Box 4-1, Figure 4-3 and Table 4-2.]

4.2.2. Methods and Models Used

Analysis of the current and past impacts of climate change on terrestrial and freshwater ecosystems and their projection into the future relies on three general approaches: inference from analogous situations in the past or elsewhere in the present; manipulative experimentation, deliberately altering one of a few factors at a time; and models with a mechanistic or statistical basis. Studies of the relatively distant past are discussed in depth in 4.2.3. Inferences from present spatial patterns in relation to climate is at the core of climate envelope niche modelling, a well-established but limited statistical technique for making projections of the future distribution under equilibrium conditions (Elith and Leathwick, 2009). Representing the rate of change during the non-equilibrium conditions which will prevail over the next century requires a more mechanistic approach, of which there are some examples (e.g., Keith *et al.*, 2008; Kearney and Porter, 2009). Changes in ecosystem function are usually determined by experimentation (see examples in Section 4.3.3) and are modelled using mechanistic models, in many cases with relatively high uncertainty (Seppelt *et al.*, 2011).

4.2.3. Paleoecological Evidence

Paleoclimatic observations and modelling indicate that the Earth's climate has always changed on a wide range of time-scales. In many cases, particularly over the last million years, it has changed in ways that are well understood in terms of both patterns and causes (Jansen *et al.*, 2007; see WGI AR5 Chapter 5). Paleoecological records demonstrate with *high confidence* that the planet's biota (both terrestrial and aquatic), carbon cycle and associated feedbacks and services have responded to this climatic change, particularly when the climatic change was as large as that projected during the 21st century under mid- to high-end radiative forcing pathways (e.g., MacDonald *et al.*, 2008; Claussen, 2009; Arneth *et al.*, 2010; Willis and MacDonald, 2011; Dawson *et al.*, 2011). Excellent examples of past large climate change events that drove large ecological change, as well as recovery periods in excess of a million years, include the events that led to the Earth's five mass extinctions in the distant past (i.e., during the Ordovician, ca. 443 Ma, the Devonian, ca. 359 Ma, the Permian, ca. 251 Ma, the Triassic, ca. 200 Ma, and the Cretaceous, ca. 65 Ma; Barnosky *et al.*, 2011). Major ecological change was also driven by climate change during the Paleocene-Eocene Thermal Maximum (PETM, 56 Ma; Wing *et al.*, 2005; Jaramillo *et al.*, 2010; Wing and Currano, 2013), the early Eocene Climatic Optimum (EECO, 53-50 Ma; Woodburne *et al.*, 2009), the Pliocene (5.3 to 2.6 Ma; Haywood and Valdes, 2006; Haywood *et al.*, 2011), and the Last Glacial Maximum (LGM) to Holocene transition between 21 and 6 ka (MacDonald *et al.*, 2008; Clark *et al.*, 2009; Gill *et al.*, 2009; Williams *et al.*, 2010a; Prentice *et al.*, 2011; Daniau *et al.*, 2012). The paleoecological record thus provides *high confidence* that large global climate change, comparable in magnitudes to that projected for the 21st century, can result in large ecological changes, including large scale biome shifts, reshuffling of communities and species extinctions.

Rapid, regional warming before and after the Younger Dryas cooling event (11.7-12.9 ka) provides a relatively recent analogy for climate change at a rate approaching, for many regions, that projected for the 21st century for all RCPs (Alley *et al.*, 2003; Steffensen *et al.*, 2008). Ecosystems and species responded rapidly during the Younger Dryas by shifting distributions and abundances, and there were some notable large animal extinctions, probably exacerbated by humans activities (Gill *et al.*, 2009; Dawson *et al.*, 2011). In some regions, species became locally or regionally extinct (extirpated), but there is no evidence for climate-driven global-scale extinctions during this period (Botkin *et al.*, 2007; Willis *et al.*, 2010a). However, the Younger Dryas climate changes differ from those projected for the future because they were regional rather than global; may have only regionally exceeded rates of warming projected for the future; and started from a baseline substantially colder than present (Alley *et al.*, 2003). The mid-Holocene, around ca. 6 ka, provides a very recent example of the effects of modest climate change. Regional mean warming during this period (mean annual temperature ca. 0.5-1.0°C above pre-industrial in some continental-scale regions; see WGI AR5 5.5.1) was the same order of magnitude as the warming the Earth has experienced over the last century. Ecological effects were small compared to periods with larger climate excursions, but even this small warming was characterized by frequent fires in a drier parts of the Amazon (Mayle and Power, 2008), development of lush vegetation and lakes in a wetter Sahara (Watrin *et al.*, 2009), temperate deciduous forests in Europe expanding further north and up to higher elevations (Adamik and Kral, 2008) and large-scale migration of Boreal Forest into a warmer tundra (Jackson and Overpeck, 2000). Past climate change, even more modest than mid-range projected future change, also clearly impacted inland water systems (e.g., Smol and Douglas, 2007a; Battarbee *et al.*, 2009; Beilman *et al.*, 2009). However, there are no exact analogues for future climate change: none of the well-studied past periods of large climate change involved simultaneously the rates, magnitude and spatial scale of climate and atmospheric CO_2 change projected for the next century and beyond (Jansen *et al.*, 2007; Schulte *et al.*, 2010; Wing and Currano, 2013; see WGI AR5 Chapter 5). Direct analogy with the paleoecological record is also unwarranted because future climate change will interact with other global changes such as land-use change, invasive species, pollution and overexploitation of natural resources (Pereira *et al.*, 2010). There is *high confidence* that these interactions will be important: the paleoecological record provides *medium confidence* (*medium evidence, high agreement*) that exploitation by humans helped drive many large mammal species to extinction during periods of climate change in past (Lorenzen *et al.*, 2011).

It has been demonstrated that state-of-the-art vegetation models are able to simulate much of the biome-level equilibrium response of terrestrial vegetation to large paleoclimate change (Prentice *et al.*, 1996; Salzmann *et al.*, 2008; Prentice *et al.*, 2011). The same types of models predict large changes in species ranges, ecosystem function and carbon storage when forced by 21st century climate change, although the future situation is complicated by land-use and other factors absent in the paleoenvironmental case (Sitch *et al.*, 2008; Cheaib *et al.*, 2012; see WGI AR5 6.4). Thus, the paleoecological record and models that have been tested against it provide a coherent message that biomes will alter their functioning and composition in response to changing and often novel future climates: they will move as species mixtures change (Section 4.3.2.5 has more specific information on projected migration rates), novel plant communities will emerge and significant carbon stock changes take place (Williams and Jackson, 2007; MacDonald, 2010; Prentice *et al.*, 2011; Willis and MacDonald, 2011). The paleoecological record and models provide *high confidence* that it will be difficult or impossible to maintain many ecological systems in their current states if global warming exceeds 2 to 3°C, raising questions about the long-term viability of some current protected areas and conservation schemes, particularly where the objective is to maintain present-day species mixtures (Jackson and Hobbs, 2009; Hickler *et al.*, 2012).

Much of the complex, time-dependent change at regional scales has not yet been simulated by models. The paleoecological record indicates that vegetation in many parts of the world has the potential to respond within years to a few decades to climate change (e.g., Watrin *et al.*, 2009; Williams *et al.*, 2009; Mueller *et al.*, 2009a; Harrison and Goni, 2010). This record provides a critical opportunity for model evaluation that should be more thoroughly exploited to gain confidence in time-dependent simulations of future change, particularly given the complex role that interacting climate change and vegetation disturbance has played in the past (e.g., Marlon *et al.*, 2009; Jackson *et al.*, 2009; Williams *et al.*, 2009; Daniau *et al.*, 2010; Dawson *et al.*, 2011). The paleoecological record also highlights the importance of including the direct effects of changing atmospheric CO_2 levels in efforts to simulate future ecosystem functioning and plant species competition (Prentice *et al.*, 2011; Woillez *et al.*, 2011; Bond and Midgley, 2012; Claussen *et al.*, 2013).

The paleoeclimatic record also reveals that past radiative climate forcing change was slower than that anticipated for the 21st century (see WGI AR5 Chapters 5, 8 and 12), but even these slower changes often drove surprisingly abrupt, non-linear, regional-scale change in terrestrial and inland water systems (e.g., Harrison and Goni, 2010; Williams *et al.*, 2011), as did even slower climate change during the most recent Holocene interglacial (e.g., Booth *et al.*, 2005; Kropelin *et al.*, 2008; Williams *et al.*, 2010a; Williams *et al.*, 2011). In all cases, specific periods of abrupt ecological response were regionally distinct in nature and were less synchronous for small, slow changes in forcing (e.g., during the Holocene) than for the global-scale rapid changes listed at the start of this section. State-of-the-art climate and Earth system models are unable to simulate the full range of abrupt change observed in many of these periods (e.g., Valdes, 2011). Thus there is *high confidence* that these models may not capture some aspects of future abrupt climate change and associated ecosystem impacts (Leadley *et al.*, 2010).

4.2.4. Multiple Stressors Interacting with Climate Change

The climatic and non-climatic drivers of ecosystem change need to be distinguished if the joint and separate attribution of changes to their causes is to be performed (see Chapter 18). In this section we elaborate on factors affecting ecosystems, operating simultaneously with climate change. These factors share underlining drivers with one another and with climate change to varying degrees, together they form a syndrome known as “global change”. The individual effects of climate change, habitat loss and fragmentation, chemical pollution, overharvesting and invasive alien species are increasingly well documented (Millennium Ecosystem Assessment, 2005c; Settele *et al.*, 2010a) but much less is known about their combined consequences. Ecosystem changes may occur in cascades, where a change in one factor precipitates increased vulnerability with respect to other factors (Wookey *et al.*, 2009) or propagates through the ecosystem as a result of species interactions (Gilman *et al.*, 2010). Multiple stressors can act in a non-additive way (Settele *et al.*, 2010b; Shaw *et al.*, 2002; Larsen *et al.*, 2011), potentially invalidating findings and interventions based on single-factor analysis. For instance, Larsen *et al.* (2011) demonstrated that non-additive interactions among the climate factors in a multifactor experiment were frequent and most often antagonistic, leading to smaller effects than predicted from the sum of single factor effects. Leuzinger *et al.* (2011) and Dieleman *et al.* (2012) have synthesized multifactor experiments and demonstrated that in general, the effect size is reduced when more factors are involved, but Leuzinger *et al.* (2011) suggest that multifactor models tend to show the opposite tendency.

4.2.4.1. Land-Use and Cover-Change (LUCC)

LUCC is both a cause (WGI AR5 6.1.2) and consequence of climate change. It is the major driver of current ecosystem and biodiversity change (Millennium Ecosystem Assessment, 2005b) and a key cause of changes in freshwater systems (Section 4.3.3.3). In tropical and subtropical areas of Asia, Africa, Oceania and South America, the dominant contemporary changes are conversion of forests and woodlands to annual and perennial agriculture, grazing pastures, industrial logging and commercial plantations; followed by conversion of savannas, grasslands and pastures to annual agriculture (Hosonuma *et al.*, 2012; Macedo *et al*. 2012). In Europe there is net conversion of agricultural lands to forest (Rounsevell and Reay, 2009; Miyake *et al.*, 2012). Conversion of peatlands to agriculture has been an important source of carbon to the atmosphere in Southeast Asia (Limpens *et al.*, 2008; Hooijer *et al.*, 2010; see Section 4.3.3.3).

Contemporary drivers of LUCC include rising demand for food, fibre and bioenergy and changes in lifestyle and technologies (Hosonuma *et al.*, 2012; Macedo *et al*. 2012). By mid-century climate change is projected to become a major driver of land cover change (Leadley *et al.*, 2010). Non-climate environmental changes such as nitrogen deposition, air pollution and altered disturbance regimes are also implicated in LUCC. Some of the underlying drivers of LUCC are also direct or indirect drivers of climate change (Cui and Graf, 2009; McAlpine *et al.*, 2009; Mishra *et al.*, 2010; Schwaiger and Bird, 2010; van der Molen *et al.*, 2011; Groisman *et al.*, 2012); this cause-and-effect entanglement of climate change and LUCC can confound the detection of climate change and make attribution to one or the other difficult. Local-to-regional climate change was at least partly attributed to LUCC in 14 of 26 studies reviewed for this chapter, generally with *limited evidence* and *low confidence*. (Direct climate effects attributed to LUCC: Tseng and Chen, 2008; Cui and Graf, 2009; Li *et al.*, 2009; McAlpine *et al.*, 2009; Zhang *et al.*, 2009; Fall *et al.*, 2010; Graiprab *et al.*, 2010; Jin *et al.*, 2010; Mishra *et al.*, 2010; Schwaiger and Bird, 2010; Wu *et al.*, 2010; Gao and Liu, 2011; Carmo *et al.*, 2012; Groisman *et al.*, 2012. No climate effects attributed: Suarez *et al.*, 1999; Saurral *et al.*, 2008; Wang *et al.*, 2008; Cochrane and Barber, 2009; Jia *et al.*, 2009a; Rounsevell and Reay, 2009; Martin *et al.*, 2010; Wiley *et al.*, 2010; Clavero *et al.*, 2011; Dai *et al.*, 2011; Viglizzo *et al.*, 2011; Yoshikawa and Sanga-Ngoie, 2011).

LUCC (and land use itself) contributes to changes in the climate through altering the greenhouse gas concentrations in the atmosphere, surface and cloud albedos, surface energy balance, wind profiles and evapotranspiration, among other mechanisms. The phrase "biophysical effects" is shorthand for the effect vegetation has on the climate other than through its role as a source or sink of greenhouse gases. These effects are now well documented, significant and are increasingly included in models of global and regional climate change. The greenhouse gas and biophysical effects of vegetation can be opposite in sign (de Noblet-Ducoudre *et al.*, 2012) and operate at different scales. For instance, conversion of forest to non-forest generally releases carbon dioxide from biomass and soils to the atmosphere (causing warming globally); but may result in an increase in seasonally-averaged albedo (local and global cooling, Davin *et al.*, 2007) and a decrease in transpiration (local, but not global warming). Findell *et al.* (2007) concluded on the basis of model studies that the non-GHG climate impacts of LUCC were generally minor, but nevertheless significant in some regions. Brovkin *et al.* (2013), projecting the overall effect of LUCC on climate change for the 21st century, found LUCC to be small driver globally, but locally important. Most global climate models suggest local average cooling effects following forest conversion to croplands and pastures (Pitman *et al.*, 2009; Longobardi *et al.*, 2012). Satellite observations suggest that the effect of conversion of the Brazilian savannas (*cerrado*) to pasture was to induce a local warming which was partly reversed when the pasture was subsequently converted to sugarcane (Loarie *et al.*, 2011). Several modelling studies suggest that the global surface air temperature response to deforestation depends on the latitude at which deforestation occurs. High latitude deforestation results in global cooling, low latitude deforestation causes global warming and that the mid latitude response is mixed (Bathiany *et al.*, 2010; Davin and de Noblet-Ducoudre, 2010; van der Molen *et al.*, 2011; Longobardi *et al.*, 2012), with some exceptions documented for boreal forests (Spracklen *et al.*, 2008). Boreal and tropical forests influence the climate for different reasons: boreal forests have low albedo (i.e., reflect less solar radiation, especially in relation to a snowy background; Levis, 2010; Mishra *et al.*, 2010; Longobardi *et al.*, 2012) and tropical forests pump more water and aerosols into the atmosphere than non-forest systems in similar climates (Davin and de Noblet-Ducoudre, 2010; Delire *et al.*, 2011; Pielke *et al.*, 2011). The implications of these findings for afforestation as a climate mitigation action are discussed in Section 4.3.4.5. Forests may also influence regional precipitation through biophysical effects (Butt *et al.*, 2011; Pielke *et al.*, 2011; see Section 4.3.3). In summary, changes in land cover have biophysical effects on the climate, sometimes opposite in direction to greenhouse gas mediated effects, which can materially alter the net outcome of the land cover change on the global climate (*high certainty*).

In summary, changes in land cover have biophysical effects on the climate, sometimes opposite in direction to greenhouse gas mediated effects, which can materially alter the net outcome of the land cover change on the global climate (*high confidence*).

_____ START BOX 4-1 HERE _____

Box 4-1. Future Land Use Changes

Assessment of climate change effects on terrestrial and inland freshwater ecosystems requires the simultaneous consideration of LUCC. The world is undergoing important shifts in land use, driven by accelerating demand for food, feed, fibre, and fuel. The main underlying driver is the rate at which *per capita* consumption is growing, particularly in emerging economies (Tilman *et al.*, 2011). Policy shifts in developed countries favouring biofuel production have also contributed (Searchinger *et al.*, 2008; Lapola *et al.*, 2010; Miyake *et al.*, 2012). Agricultural commodity prices have risen and may stay high through 2020 (OECD/FAO, 2010), due to: a) demand growth outpacing supply growth, exacerbated by climate-related crop failure (Lobell *et al.*, 2011); b) decline in the rate of improvement in agricultural productivity (Ray *et al.*, 2012); c) shortage of arable land not already under cultivation, especially in the temperate zone; d) growing pressure on as-yet uncultivated ecosystems on soils that are potentially suitable for cultivation and that are concentrated in tropical latitudes, especially South America and Africa (Lambin and Meyfroidt, 2011); and e) declining area under cultivation in temperate zones, mainly in developed countries. The shortage of arable land in temperate systems could put pressure on marginal or sensitive landscapes, mainly in Latin America's *cerrados* and grasslands (Brazil, Argentina) and in African savannahs (Sudan, Democratic Republic of the Congo, Mozambique, Tanzania, Madagascar) (Lambin and Meyfroidt, 2011).

Deforestation in developing countries is correlated with the export of agricultural commodities (DeFries *et al.*, 2010). Future LUCC remains uncertain, since it depends on economic trends and policies themselves dependent upon complex political and social processes, including climate policy. By 2012, the deforestation rate in the Brazilian Amazon had declined by 77% below its 1996-2005 average (INPE, 2013; Nepstad *et al*., 2009) as a result of policy and market signals (Soares-Filho *et al.*, 2010). This single trend represents a 1.5% reduction in global anthropogenic carbon emissions (Nepstad *et al.*, 2013).

[INSERT TABLE 4-2 HERE
Table 4-2: Summary of drivers and outcomes of LUCC scenarios associated with Representative Concentration Pathways (Hurtt *et al.*, 2011). RCPs are identified with the radiative forcing by 2100 (8.5, 6.0, 4.5 and 2.6 Wm^{-2}) and by the name of the model used to generate the associated land use/cover scenarios (MESSAGE, AIM, GCAM and IMAGE; see Hurtt *et al*. (2011) for further details).]

Each of the four main RCPs used for future climate projections has a spatially-explicit future land use scenario consistent with both the emissions scenario and the underlying associated socio-economic scenario simulated by integrated assessment models, as well as conditions in 2005 (Hurtt *et al.*, 2011; Table 4-2; Figure 4-2; Figure 4-3). In scenarios where cropland and pasture are projected to decrease, they are replaced with secondary vegetation. Tropical and boreal forest regions are both projected to undergo declining primary forest cover in most RCPs, but in RCP6.0 total forest area remains approximately constant and in RCP4.5 total forest area expands due to increased secondary forest. The extent to which primary vegetation is replaced by secondary vegetation, crops or pasture varies between the RCPs (Figure 4-3), with no simple linear relationship between the extent of vegetation change and the level of total radiative forcing. Larger reductions in primary vegetation cover are projected in RCP8.5, due to a general absence of pro-active measures to control land cover change in that scenario. Large reductions are also projected in RCP2.6 due to widespread conversion of land to biofuel crops (Figure 4-2). Smaller reductions are foreseen in RCP6.0 and RCP4.5, with the latter involving conservation of primary forest and afforestation as mitigation measures.

[INSERT FIGURE 4-3 HERE
Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005 (Klein Goldewijk *et al.*, 2010; Klein Goldewijk *et al.*, 2011), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt *et al.*, 2011).]

_____ END BOX 4-1 HERE _____

4.2.4.2. Nitrogen Deposition

The global nitrogen (N) cycle has been strongly perturbed by human activity over the past century (Gruber and Galloway, 2008; Canfield *et al.*, 2010). Activities such as fertilizer production and fossil fuel burning currently transform 210 TgN/year of nitrogen gas in the atmosphere into reactive forms of nitrogen (N_r) that can be readily used by plants and microorganisms in land and in the ocean, slightly more than the non-anthropogenic transformation of 203 TgN/year (Fowler *et al.*, 2013). Most of the transformations of anthropogenic N_r are on land (Fowler *et al.*, 2013). The human-caused flow from land to oceans in rivers is 40-70 TgN/year, additional to the estimated natural flux of 30 TgN/year (Galloway *et al.*, 2008; Fowler *et al.*, 2013). Many of the sources of additional reactive nitrogen share root causes with changes in the carbon cycle, such as increased use of fossil fuels and expansion and intensification of global agriculture. N deposition, CO_2 concentrations and temperatures are therefore increasing together at global scales (Steffen *et al.*, 2011). Regional trends in N fluxes differ substantially: N fertilizer use and N deposition are stable or declining in some regions, such as Western Europe; but N deposition and its impacts on biodiversity and ecosystem functioning are projected to increase substantially over the next several decades in other regions, especially in the tropics (Galloway *et al.*, 2008) due to increased needs for food and energy for growing populations in emerging economies (e.g., Zhu *et al.*, 2005).

Experiments and observations, most of which are in temperate and boreal Europe and North America, show a consistent pattern of increase in the dominance of a few nitrogen-loving plant species and loss of overall plant species richness at N deposition loads exceeding between 5 and 20 kgN/ha/year (Power *et al.*, 2006; Clark and Tilman, 2008; Bobbink *et al.*, 2010; but see Stevens *et al.*, 2010a). N deposition is currently above these limits in much of Europe, eastern North America, and Southern Asia (Galloway *et al.*, 2008), including in many protected areas (Bleeker *et al.*, 2011).

The impacts of N deposition are often first manifested in freshwater ecosystems, since they collect and concentrate the excess N (and phosphorus, P) from the land, as well as from sewage and industrial effluents. Primary production in freshwater ecosystems can be either N and P limited or both (Elser *et al.*, 2007), but the biodiversity and capacity of freshwater ecosystems to deliver high quality water, recreational amenity and fisheries services is severely reduced by the addition of nutrients beyond their capacity to process them. Excessive loading of N and P is widespread in the lakes of the Northern Hemisphere (Bergström and Jansson, 2006), although reduced N loading including deposition was observed between 1988 and 2003 in Sweden (Weyhenmeyer *et al.*, 2007). The observed symptoms include a shift from nitrogen limitation of phytoplankton in lakes to phosphorus limitation (Elser *et al.*, 2009).

Since the AR4 report, an increasing number of studies have models, observations and experiments to understand and predict the interactive effects of N deposition, climate change and CO_2 on ecosystem function. Interactions between nitrogen and other global change factors are widespread, strong and complex (Rustad, 2008; Thompson *et al.*, 2008; Langley and Megonigal, 2010; Gaudnik *et al.*, 2011; Eisenhauer *et al.*, 2012; Hoover *et al.*, 2012; but see Zavaleta *et al.*, 2003 for evidence of additive effects). In a study of plant-pollinator relationships, the combination of N deposition, CO_2 enrichment and warming resulted in larger negative impacts on pollinator populations than could be predicted from the individual effects (Hoover *et al.*, 2012). In a perennial grassland species, N limitation constrained the response to rising CO_2 (Reich *et al.*, 2006). Broadly, the overall body of research shows that ecosystem function is mediated by complex interactions between these factors, such that many ecosystem responses remain difficult to understand and predict (Churkina *et al.*, 2010; Norby and Zak, 2011).

In forests in many parts of the world, experiments, observations and models suggest that the observed increase in productivity and carbon storage is due to combinations of N deposition, climate change, fertilization effects of rising CO_2, and forest management (Huang *et al.*, 2007; Magnani *et al.*, 2007; Pan *et al.*, 2009; Churkina *et al.*, 2010; Bellassen *et al.*, 2011; Bontemps *et al.*, 2011; de Vries and Posch, 2011; Eastaugh *et al.*, 2011; Norby and Zak, 2011; Shanin *et al.*, 2011; Lu *et al.*, 2012). N deposition and rising CO_2 appear to have generally dominated in much of the Northern Hemisphere. However, the direct effects of rising temperature and changes in precipitation may exceed N and CO_2 as key drivers of ecosystem primary productivity in a few decades time. In grasslands, however, experiments show that plant productivity is increased more by N addition (within the projected range for this century) than by elevated CO_2, also within its projected range; and that N effects increase with increasing precipitation (Lee *et al.*, 2010).

In contrast to forests and temperate grasslands, N deposition and warming can have negative effects on productivity in other terrestrial ecosystems, such as moss-dominated ecosystems (Limpens *et al.*, 2011). The interactions between N deposition and climate change remain difficult to understand and predict (Menge and Field, 2007; Ma *et al.*, 2011), in part due to shifts in plant species composition (Langley and Megonigal, 2010) and the complex dynamics of coupled C, N and P cycles (Menge and Field, 2007; Niboyet *et al.*, 2011).

Analyses using the multi-factor biodiversity change model GLOBIO3 suggest that N deposition will continue to be a significant contributing factor to terrestrial biodiversity loss in the first third of the century but will be a less important factor than climate change in this period, and a much smaller driver than habitat loss due expansion of agricultural lands (Alkemade *et al.*, 2009). Models that explicitly take into account interactive effects of climate change and N deposition on plant communities project that N deposition impacts will continue to be important, but climate change effects will begin to dominate other factors by the middle of the 21st century (Belyazid *et al.*, 2011).

4.2.4.3. Tropospheric Ozone

The concentration of ozone in the troposphere (the part of the atmosphere adjacent to the Earth's surface) has risen over the past 150 years from a global average of 20-30 ppb to 30-50 ppb, with high spatial and temporal variability (Horowitz, 2006; Oltmans *et al.*, 2006; Cooper *et al.*, 2010; WGI AR5 Figure 2.7). This is due to a) increasing anthropogenic emissions of gases which react in the atmosphere to form ozone (Denman *et al.*, 2007) and b) the increased mixing of stratospheric ozone into the troposphere as a result of climate change (Hegglin and Shepherd, 2009). The key ozone-precursor gases are volatile organic compounds (VOCs) and oxides of nitrogen (NO_x). Intercontinental transport of these precursors contributes to rising global background ozone concentrations, including in regions where local ozone-precursor emissions are decreasing (Dentener *et al.*, 2010). Global sources of VOC are predominantly biogenic (BVOC), and especially forests (Hoyle *et al.*, 2011).

Negative effects of the current levels of ozone have been widely documented (Mills *et al.*, 2011). A meta-analysis of over 300 articles addressing the effect of ozone on tree growth (Wittig *et al.*, 2009) - largely focused on Northern-Hemisphere temperate and boreal species - concluded that current levels of tropospheric ozone suppress growth by 7% relative to pre-industrial levels. Modelling studies which extrapolate experimentally-measured dose-response relationships suggest a 14 to 23% contemporary reduction in Gross Primary Productivity (GPP) worldwide, with higher values in some regions (Sitch *et al.*, 2007) and 1-16% reduction of Net Primary Productivity (NPP) in temperate forests (Ainsworth *et al.*, 2012).

The mechanisms by which ozone affects plant growth are now better known (Hayes *et al.*, 2007; Ainsworth *et al.*, 2012). Chronic exposure to ozone at levels above about 40 ppb generally reduces stomatal conductance and impairs the activity of photosynthetic enzymes (The Royal Society, 2008), although in some cases ozone exposure increases stomatal conductance (Wilkinson and Davies, 2010). For the species studied, carbon assimilation rates and leaf area are generally reduced, while respiration increases and leaf senescence accelerated - all leading to a reduction in NPP.

Conifers are less sensitive than broad-leafed species. In a modelling study, lower stomatal conductance due to ozone exposure increased river runoff by reducing the loss of soil moisture through transpiration, but observational studies that measured runoff in relation to ozone exposure show divergent trends on this issue (McLaughlin *et al.*, 2007; Wittig *et al.*, 2007; Mills *et al.*, 2009; Huntingford *et al.*, 2011).

A modelling study (Sitch *et al.*, 2007) suggests that the negative effects of rising O_3 on plant productivity could offset 17 to 31% of the projected increase in global carbon storage due to increasing CO_2 concentrations over the 21st century, but the possible interactive effects between CO_2 and O_3 are poorly understood (The Royal Society, 2008). Reduced stomatal conductance, widely observed under elevated CO_2, should help protect plants from ozone damage. Some chamber experiments (Bernacchi *et al.*, 2006) and model studies (Klingberg *et al.*, 2011) suggest this to be the case. The one plot-scale study of CO_2 and O_3 interactions in a temperate forest (Karnosky *et al.*, 2005; Hofmockel *et al.*, 2011) suggests that the effects of O_3 and CO_2 are not independent and may partly compensate for one another.

There is genotypic variation in plant sensitivity to O_3 (Ainsworth *et al.*, 2012). Other than changing cultivars or species, few management actions promoting adaptation to higher levels of O_3 are currently available (Wilkinson and Davies, 2010; Teixiera *et al.*, 2011). Research into developing ozone resistant varieties and chemical protectants against damage may provide management options in the future (Wilkinson and Davies, 2010; Ainsworth *et al.*, 2012).

4.2.4.4. Rising CO_2

Rising atmospheric CO_2 concentrations directly affect ecosystems and through biological and chemical processes. The consequences for the global carbon cycle are discussed in WGI AR5 Box 6.3; the discussion here focusses on impacts on terrestrial and inland water systems. Paleo records over the Late Quaternary (past million years) show that changes in the atmospheric CO_2 content between 180 and 280 ppmv had ecosystem-scale effects worldwide (Prentice and Harrison, 2009).

In contrast to the oceans, changes in CO_2 concentrations in inland waters are primarily influenced by biological processes, such as inputs of terrestrial organic matter (particularly DOC) and bacterial respiration (van de Waal *et al.*, 2010; Aufdenkampe *et al.*, 2011). Carbon can, however, become limiting during intense algal blooms, especially in the surface waters of stratified lakes and reservoirs, and rising atmospheric CO_2 concentrations may stimulate higher algal production under these conditions (van de Waal *et al.*, 2010). Higher CO_2 concentrations can lead to increases in the C:N and C:P ratios of phytoplankton, though the trophic consequences of this are difficult to predict because zooplankton may alter their feeding behaviour to select higher quality forms of algae or increase feeding rate (Urabe *et al.*, 2003; van de Waal *et al.*, 2010).

Over the past two decades, and especially since AR4, experimental investigation of elevated CO_2 effects on plants and ecosystems has mainly used Free Air CO_2 Enrichment (FACE) techniques (Leakey *et al.*, 2009). FACE is considered more realistic than earlier approaches using enclosed chambers, because plant community and atmospheric interactions and below-ground conditions are more like those of natural systems. Plants with a C3 photosynthetic system, which includes most species but excludes warm-region grasses, show an increase in photosynthesis under elevated CO_2, the precise magnitude of which varies between species. Acclimation (“down-regulation”) occurs under long-term exposure, leading to cessation of effects in some (Norby and Zak, 2011) but not all studies (Leakey *et al.*, 2009). The C4 photosynthetic system found in most tropical grasses and some important crops is not directly affected by elevated CO_2, but C4 plant productivity generally increases under elevated CO_2 due to increased water use efficiency (WUE). Transpiration is decreased under elevated CO_2 in many species, due to reduced opening of stomatal apertures, leading to greater WUE (Leakey *et al.*, 2009; Leuzinger and Körner, 2010; De Kauwe *et al.*, 2013). Increasing WUE is corroborated by studies of stable carbon isotopes (Barbosa *et al.*, 2010; Koehler *et al.*, 2010; Silva *et al.*, 2010; Maseyk *et al.*, 2011). The WUE increase does not acclimate to higher CO_2 in the medium term, *i.e.* over several years (Leakey *et al.*, 2009). Satellite observations from 1982-2010 show an 11% increase in green foliage cover in warm, arid environments (where WUE is most important) after correcting for the effects of precipitation variability (Donohue *et al.*, 2013); gas exchange theory predicts 5 to 10% greening resulting from rising CO_2 over this period.

The interactive effects of elevated CO_2 and other global changes (such as climate change, nitrogen deposition and biodiversity loss) on ecosystem function are extremely complex. Generally, nitrogen use efficiency is increased under higher CO_2 (Leakey *et al.*, 2009), although in some tree FACE experiments, productivity increases as a result of enhanced CO_2 were sustained by increased nitrogen uptake rather than increased nitrogen use efficiency (Finzi *et al.*, 2007). In one ten-year temperate grassland experiment in Minnesota, elevated CO_2 halved the loss of species richness expected from nitrogen addition (Reich, 2009), whereas no such benefit was reported for an alpine grassland in France (Bloor *et al.*, 2010) or a Danish heathland ecosystem (Kongstad *et al.*, 2012).

Elevated CO_2 can affect plant response to other stresses, such as high temperature (Lloyd and Farquhar, 2008) and drought. Ozone exposure decreases with lower stomatal conductance (Sitch *et al.*, 2007). In savannas, faster growth rates under higher CO_2 can allow woody plants to grow tall enough between successive fires to escape the flames (Bond and Midgley, 2001; Scheiter and Higgins, 2009). Differential species responses to elevated CO_2 appear to be altering competition (Dawes *et al.*, 2011), for example, increasing the likelihood of faster-growing species such as lianas out-competing slower-growing species such as trees (Potvin *et al.*, 2007; Lewis *et al.*, 2009a; Mohan *et al.*, 2006).

Experimental studies have shown that elevated CO_2 leads to increased leaf C:N ratios in woody plants, forbs and C3 grasses (but not C4 grasses), which may decrease their quality as food and increase herbivorous insect feeding rates and changes to their density and community structure (Sardans *et al.*, 2012). Plants may also become more toxic to herbivores under elevated CO_2 levels, through increased concentrations of C-based and N-based defences (Lindroth, 2010; Cavagnaro *et al.*, 2011).

Our understanding of ecosystem responses to elevated CO_2 is incomplete in some respects. The majority of FACE experiments apply upper CO_2 concentrations of approximately 550 ppmv, which is below the concentrations projected by 2100 under higher emissions scenarios. The physiology of photosynthesis suggests that direct CO_2 effects saturate at levels of approximately 700 ppmv (Long *et al.*, 2004). Most elevated CO_2 experiments impose a sudden increase of CO_2 concentration as opposed to the gradual rise experienced in reality. Most large-scale FACE experiments have been carried in temperate locations (e.g., Hickler *et al.*, 2008); there are currently no large-scale tropical or boreal FACE experiments. The magnitude of CO_2 effects decreases as the spatial scale of study increases (Leuzinger *et al.*, 2011).The scale of controlled experiments is limited to approximately 100 m^2. Extrapolation to larger scales ignores large-scale atmospheric feedbacks (Körner *et al.*, 2007) and catchment-scale hydrological effects (see Cross-Chapter Box CC-VW). Overall, there is *medium confidence* (*much evidence, medium agreement*) that increases in CO_2 up to about 600 ppm will continue to enhance photosynthesis and plant water-use efficiency, but at a diminishing rate.

CO_2 effects are a first-order influence on model projections of ecosystem and hydrological responses to anthropogenic climate change (Sitch *et al.*, 2008; Lapola *et al.*, 2009; Friend *et al.*, in press).The direct effect of CO_2 on plant physiology, independent of its role as a greenhouse gas, means that assessing climate change impacts on ecosystems and hydrology solely in terms of global mean temperature rise, (or equivalently, expressing greenhouse gas effects solely in terms of radiative forcing) is an oversimplification (Huntingford *et al.*, 2011; Betts *et al.*, 2012). A 2°C rise in global mean temperature, for example, may have a different net impact on ecosystems depending on the change in CO_2 concentration accompanying the rise (e.g., Good *et al.*, 2011a). A high climate sensitivity and/or a higher proportion of non-CO_2 GHGs would imply a relatively low CO_2 rise at 2°C global warming, so the offsetting effects of CO_2 fertilization and increased water use efficiency would be smaller than for low climate sensitivity and/or a lower proportion of non-CO_2 GHGs.

4.2.4.5. Diffuse and Direct Radiation

The quantity and size-distribution of aerosols in the atmosphere alters both the amount of solar radiation reaching the Earth's surface and the proportions of direct versus diffuse radiation. In some regions, direct radiation has been reduced by up to 30 W m^{-2} over the industrial era, with an accompanying increase in diffuse radiation of up to 20 W m^{-2} (Kvalevåg and Myhre, 2007). The global mean direct and diffuse radiation changes due to aerosols are −3.3 and +0.9 W m^{-2}, respectively (Kvalevåg and Myhre, 2007). For a constant total radiation, an increased fraction received as diffuse radiation theoretically increases net photosynthesis because a smaller fraction of the vegetation canopy is light-saturated, making photosynthesis more light efficient at the canopy scale (Knohl and Baldocchi, 2008; Kanniah *et al.*, 2012). In a global model which included this effect, an increase in diffuse fraction of solar radiation due to volcanic and anthropogenic aerosols and cloud cover was simulated to lead to approximately a 25% increase in the strength of the global land carbon sink between 1960 and 1999; however, under a scenario of climate change and *decreased* anthropogenic aerosol concentration, this enhancement declined to near zero by the end of the 21st century (Mercado *et al.*, 2009), All RCPs project decreased aerosol concentrations due to air quality protection measures, as already seen in some countries. The influence of the form of radiation on plant growth and the land carbon budget is a potentially important unintended consequence of solar radiation management schemes that involve the injection of aerosols into the stratosphere to reduce radiant forcing (see WGI AR5 7.7); but this topic is presently insufficiently researched for adequate assessment.

4.2.4.6. Invasive and Alien Species

Since the IPCC AR4, the number of observations of the spread and establishment of alien species attributed to climate change has increased for several taxa (e.g., Walther *et al.*, 2009) and for particular areas, including mountain tops and polar regions (McDougall *et al.*, 2011; Chown *et al.*, 2012). Species invasions have increased over the last several decades (*very high confidence*), and the aggressive expansion of plant and animal species beyond their historical range is having increasingly negative impacts on ecosystem services and biodiversity (*high confidence*, Brook, 2008; Burton *et al.*, 2010; McGeoch *et al.*, 2010; Simberloff *et al.*, 2013). Climate change will exacerbate some invasion impacts and ameliorate others (Peterson *et al.*, 2008; Bradley *et al.*, 2009; Britton *et al.*, 2010; Bellard *et al.*, 2013). Although there is increasing evidence that some species invasions have been assisted by climate change, there is *low confidence* that species invasions have in general been assisted by recent climatic trends because of the overwhelming importance of human facilitated dispersal in mediating invasions. The spread of alien species has several causes, including habitats made favourable by climate change (Walther *et al.*, 2009), deliberate species transfer and accidental transfer due to increased global movement of goods.

In most cases climate change increases the likelihood of the establishment, growth, spread and survival of invasive species populations (Dukes *et al.*, 2009; Walther *et al.*, 2009; Bradley *et al.*, 2010; Huang *et al.*, 2011; Chown *et al.*, 2012). Some degree of climate/habitat match has been found to be a pre-requisite of establishment success across seven major plant and animal groups (Hayes and Barry, 2008). A range of alien species responses and local consequences are expected (e.g., Rahel and Olden, 2008; Frelich *et al.*, 2012; Haider *et al.*, 2012; West *et al.*, 2012). Invasive species, compared to native species, may have traits that favour their survival, reproduction and adaptation under changing climates; invasive plants in particular tend to have faster growth rates and are particularly favoured when resources are not limited (*medium to high confidence*, van Kleunen *et al.*, 2010; Willis *et al.*, 2010b; Buswell *et al.*, 2011; Davidson *et al.*, 2011; Zerebecki and Sorte, 2011; Haider *et al.*, 2012; Matzek, 2012). Some invasive plants are more drought tolerant (Crous *et al.*, 2012; Matzek, 2012; Perry *et al.*, 2012), and on average they have higher overall metabolic rates, foliar nitrogen concentrations and photosynthetic rates than their native counterparts (Leishman *et al.*, 2007).

Extreme climate events provide opportunities for invasion by generating disturbances and redistributing available resources (Diez *et al.*, 2012) and changing connectivity between different ecosystems. Current warming has already enabled many invasive alien species, including plant, vertebrate, invertebrate and single cell taxa, to extend their distributions into new areas (*high confidence* for plants and insects, Walther *et al.*, 2009; Smith *et al.*, 2012). However, population declines and range contractions are predicted for some invasive species in parts of their ranges (Bradley *et al.*, 2009; Bertelsmeier *et al.*, 2012; Sobek-Swant *et al.*, 2012; Taylor *et al.*, 2012). The expansion of invasive species in some areas and contraction in others will contribute to community re-organisation and the formation of novel ecosystems and interactions in both terrestrial and freshwater habitats (*high confidence*, e.g., Kiesecker, 2011; Britton *et al.*, 2010; Martinez, 2012; see also Section 4.3.2.5). For example, invasive grasses may be favoured over native ones with increasing temperatures (Parker-Allie *et al.*, 2009; Chuine *et al.*, 2012; Sandel and Dangremond, 2012).

In a few cases, benefits to biodiversity and society may result from the interactive effects of climate change and invasive species, such as increases in resources available to some threatened species (Caldow *et al.*, 2007), forest structural recovery (Bolte and Degen, 2010) and available biomass for timber and fuel (van Wilgen and Richardson, 2012). The effect of invasions on net changes in carbon stocks are situation specific and may be either positive or negative (Williams *et al.*, 2007a). Rising CO_2 levels will increase the growth rates of most invasive plant species (Mainka and Howard, 2010; but see Section 4.2.4.4).The effectiveness of invasive alien species management for sequestering carbon is uncertain and context specific (Peltzer *et al.*, 2010). Longer term, indirect effects of invasive alien species will be more important than direct, short-term effects; for instance as a result of changes in soil carbon stocks and tree community composition (*low-medium confidence*, Peltzer *et al.*, 2010).

Synergistic interactions occur between climate change and invasive alien species, along with landscape change, habitat disturbance and human-facilitated breakdown of dispersal barriers (Brook, 2008; Angeler and Goedkoop, 2010; Bradley *et al.*, 2010; Winder *et al.*, 2011a; Cahill *et al.*, 2013). Climate change and invasive alien plant species generally increase the risk and intensity of fire, and the interaction is being reported more frequently as a direct result of higher temperatures and increased invasive plant biomass (*high confidence*, Abatzoglou and Kolden, 2011). In freshwater systems, alien species establishment and survival, species interactions and disease virulence will change as a result of changes in frequency of high-flow events, increasing water temperature, water properties and water demand (*medium confidence*, Schnitzler *et al.*, 2007; Rahel and Olden, 2008; Britton *et al.*, 2010).

A range of climate change-related variables (extreme events, changes in precipitation, temperature and CO_2) will continue to exacerbate the establishment and spread of pests, vectors and pathogens and negatively impact production systems (*medium confidence*, Robinet and Roques, 2010; Clements and Ditommaso, 2011). Warming has contributed to the spread of many invasive insect species, such as the mountain pine bark beetle, and resulted in forest destruction (*high confidence*, Raffa *et al.*, 2008). The interactions between crop growth, climate change and pest dynamics are difficult to predict (West *et al.*, 2012). Management strategies may become less effective as a consequence of the decoupling of biocontrol relationships and less effective mechanical control as biomass and/or population size of invasive species increases (*low to -medium confidence*, Hellmann *et al.*, 2008).

4.3. Vulnerability of Terrestrial and Freshwater Ecosystems to Climate Change

The vulnerability of ecosystems to climate change, i.e. their propensity to be adversely affected, is determined by the sensitivity of ecosystem processes to the particular elements of climate undergoing change and the degree to which the system (including its coupled social elements) can maintain its structure, composition and function in the presence of such change, either by tolerating or adapting to it. Tolerance and adaptability both interact with exposure, which in the case of terrestrial and freshwater ecosystems means the magnitude and rate of climate change relative to ranges of climatic conditions and rates of change under which the ecosystem developed and its organisms evolved. Chapter 19 provides a full discussion on vulnerability concepts.

4.3.1. Changes in the Disturbance Regime

The species composition at a given location is determined by three considerations: the ability of species to reach the location; the physiological tolerance of the species in relation to the range of conditions experienced there; and interactions with other species, including competitors, symbionts, predators, prey and pathogens. Occasional disturbances relieve competition, create opportunities for the establishment and success of less-dominant species; and may facilitate dispersal. Moderate disturbance is thus important in maintaining diversity and ecosystem function (Connell, 1978). Exposure to disturbances keeps tolerance of disturbance in the population high. Fire, floods and strong winds are all examples of biodiversity-sustaining climate disturbances, provided that their frequency and intensity does not deviate greatly above or below the regime to which the species are adapted. Average environmental conditions may be less of a determinant of species range and abundance than the extreme conditions, such as the occurrence of exceptionally cold or hot days or droughts exceeding a certain duration (Zimmermann *et al.*, 2009). The projected changes in probability of extremes are typically disproportionately larger than the projected changes in the mean (see IPCC, 2012; but also Diffenbaugh *et al.*, 2005). Biotic disturbances, such as pest and pathogen outbreaks are also often implicated in with ecosystem change, and may be enabled by climate change.

It is suggested that ecosystem regime shifts resulting from climate change (alone or in interaction with other factors) will often be triggered by changes in the disturbance regime, rather than by physiological tolerance for the mean conditions (Thonicke *et al.*, 2008). A "disturbance regime" refers to the totality of different types of disturbance events in a system, each characterized by their probability of occurrence, intensity and other relevant attributes, such as their seasonal pattern. A corollary is that disturbance-related change is abrupt rather than gradual. Change in the fire disturbance regime is emerging as a key proximal mechanism and early indicator of terrestrial ecosystem change (Girardin *et al.*, 2009; Johnstone *et al.*, 2010). Changes in the fire regime have in some cases been attributed to climate change (Westerling *et al.*, 2006; Littell *et al.*, 2009; Turetsky *et al.*, 2011; Westerling *et al.*, 2011; Moritz *et al.*, 2012). Regional trends in fire occurrence have been observed since 2000 (Giglio *et al.*, 2013), but interpreting their significance requires a longer term perspective (e.g., Bergeron *et al.*, 2010).

4.3.2. Observed and Projected Change in Ecosystems

This section highlights key observed changes in terrestrial and freshwater ecosystems over the recent past, as well as changes projected during the 21st century. For observations, we assess the degree of confidence that change has been detected, and separately the confidence we have in attributing the change to climate change (Figure 4-4). Confidence in detection is considered to be *very high* when there is *high agreement* between many independent studies, species, ecosystems or regions and where there is *robust evidence* that the changes over time are statistically significant (see Chapter 18; Mastrandrea *et al.*, 2010). Note that a slightly different definition of detection is used here than in Chapter 18, because detection here is based solely on the presence of a temporal trend and does not attempt to distinguish natural from climate related variation. Confidence in attribution to climate change is *very high* when three tests are satisfied: changes correspond to a sound mechanistic understanding of responses to climate change; the time series of observations is sufficiently long to detect trends correlated with climate change; and confounding factors can be accounted for or are of limited importance. In the sections that provide the details of the assessment of detection and attribution, estimated levels of confidence are given even in cases where the capacity for detection or attribution capacity is *low* or *very low*, because changes in these ecosystem properties or processes could have large impacts on biodiversity or ecosystem services at regional to global scales. In all cases the estimates of confidence levels are based on global and cross-taxon assessments, so the positioning may be different for specific taxa or regions. Some of the sections include assessments of model-based projections of future change; the confidence assessment of detection and attribution does not extend to these.

A key message arising from the analysis of *detection* and *attribution* is that climate impacts on the functioning of organisms and ecosystems are clearest when temperature is a principal driver, changes are relatively rapid and confounding factors play a small role. At one end of the spectrum, the large warming signal over the last several decades in much of the Arctic tundra combined with minimal human impacts is associated with *high confidence* in detection of an increase in shrubs and permafrost thawing and *high confidence* in the attribution to climate warming (Section 4.3.3.1.1). Likewise, the phenology of most organisms is sensitive to temperature, confounding effects are often small and the response is rapid, leading to *high confidence* in detection and attribution of changes in phenology to warming (Section 4.3.2.1). At the opposite end of the spectrum, species extinctions are very difficult to attribute to climate change (Section 4.3.2.5), in part because other factors dominate recent extinctions. This does not mean that climate has not played an important contributing role; indeed it has been argued that the low level of confidence in attribution is due to the lack of studies looking for climate signals in extinctions (Cahill *et al.* 2013). Similarly there is very good evidence that species composition is changing in cultural landscapes, but the important role of other factors, e.g., land management, nitrogen deposition, makes attribution of a contribution to recent warming difficult. This analysis indicates that responses in most species and ecosystem levels will become more apparent over time because i) observed organism level changes will have long term impacts on ecosystem functioning (*high confidence,* Sections 4.3.2.1, 4.3.2.5, 4.3.3) and ii) warming signals can be detected in ecosystems where the recent warming has been strong and confounding factors are minimal. In addition, the absence of observed changes does not preclude confident projections of future change for three reasons: climate change projected for the 21st century substantially exceeds the changes experienced over the past century in medium to high scenarios (all but RCP 2.6); ecosystem responses to climate change may be non-linear; and change may only be apparent after considerable time lags (Jones *et al.*, 2009).

[INSERT FIGURE 4-4 HERE
Figure 4-4: Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010), attribution criteria outlined in Chapter 18 and detection criteria defined in the text. The symbols in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions. The following sections provide the details of the assessments that were used in positioning each of the points Phenology, Section 4.3.2.1; Primary Productivity, Section 4.3.2.2; Biomass and C stocks, Section 4.3.2.3; Evapotranspiration, Section 4.3.2.4; Species distributions, Section 4.3.2.5**;** Global species extinctions, Section 4.3.2.5**;** Invasive and alien species**,** Section 4.2.4.6**;** Tree mortality, Section 4.3.3.1, Box 4-2; Boreal forest regime shift, Section 4.3.3.1.1, Box 4-4; Amazon forest regime shift, Section 4.3.3.1.3, Box 4-3; Tundra regime shift, Section 4.3.3.4, Box 4-4; Woody encroachment, Section 4.3.3.2.2; Cultural landscapes, Section 4.3.3.5.3; Evolutionary and genetic adaptation, Section 4.4.1.2.]

4.3.2.1. Phenology

Further evidence from ground-based and satellite studies, mainly focused on the Northern Hemisphere, supports the AR4 conclusion that shifts in phenology have occurred over recent decades. “Spring advancement” - earlier occurrence of spring events, such as breeding, bud burst, breaking hibernation, flowering, migration - is seen in hundreds of plant and animal species in many regions (Menzel *et al.*, 2006; Cleland *et al.*, 2007; Parmesan, 2007; Primack *et al.*, 2009; Cook *et al.*, 2012a; Peñuelas *et al.*, 2013) although magnitudes of change vary considerably and some species show no change (Parmesan, 2007). Apparent discrepancies between two estimates of overall Northern-Hemisphere spring advancement noted in AR4 (2.3 days per decade, Parmesan and Yohe, 2003; 5.1 days per decade, Root *et al.*, 2003) are largely resolved when methodological differences are accounted for, particularly the inclusion of species that do not show phenological changes (Parmesan, 2007). A combined analysis of 203 species suggests Northern Hemisphere spring advancement of 2.8±0.35 days per decade (Parmesan, 2007).

Plants – Spring advancement in is seen across the Northern Hemisphere including North America (e.g., Cook *et al.*, 2008; Cook *et al.*, 2012b), Europe (e.g., Menzel *et al.*, 2006; Cook *et al.*, 2012b), Asia (e.g., Primack *et al.*, 2009; Ma and Zhou, 2012) and the High Arctic (Høye *et al.*, 2007). Changes are generally larger at higher latitudes. A meta-analysis indicates mean spring Northern Hemisphere spring advancement of -1.1 ± 0.16 days per decade for herbs and grasses (85 species), -1.1 ± 0.68 days per decade for shrubs (6 species) and -3.3 ± 0.87 days per decade for trees (16 species), over a record period of 35-132 years, depending on the study. The warming trends detected in the well-mixed surface waters (epilimnion) of many lakes in North America, Eurasia and Africa (Adrian *et al.*, 2009) are associated with the earlier onset of spring phytoplankton blooms (Winder and Schindler, 2004; Winder and Sommer, 2012). Satellite data also indicate a general tendency of spring advancement, though there is variation between satellite studies, especially at local scales, due to the use of different instruments and methods (e.g., White *et al.*, 2009). A study using the Advanced Very High Resolution Radiometer (AVHRR) suggests that for vegetation between 30ºN and 80ºN, the start of the growing season advanced by -5.2 days between 1999 and 1982 and advanced a further -0.2 days by 2008; while the growing season end was delayed by 6.6 days between 1982 and 2008 (Jeong *et al.*, 2011). Studies with a more recent satellite instrument, Moderate Resolution Imaging Spectrometer (MODIS) also show spring advancement (e.g., Ahl *et al.*, 2006). The relatively short duration of satellite observations makes trend detection particularly sensitive to the choice of analysis period.

Animals – Many new studies provide further evidence of changes in animal phenology (e.g., amphibians: Kusano and Inoue, 2008; Phillimore *et al.*, 2010; birds: Pulido, 2007; Thorup *et al.*, 2007; mammals: Adamik and Kral, 2008; Lane *et al.*, 2012; insects: Robinet and Roques, 2010; freshwater plankton: Adrian *et al.*, 2009). Changes in breeding phenology are reported from various regions and different taxa (e.g., Parmesan, 2006; Parmesan, 2007; Post *et al.*, 2008; Primack *et al.*, 2009). In the Northern Hemisphere several studies show advancements of egg laying dates in birds (e.g., Parmesan, 2007: -3.7 ± 0.7 days/decade, in 41 species). In contrast, a delay of the mean breeding date by 2.8 to 3.7 days between 1950 and 2004 was seen for two of nine seabirds in the Eastern Antarctic, linked to decreased sea ice extent (Barbraud and Weimerskirch, 2006). Spring arrival dates have advanced for many migratory birds (e.g., Thorup *et al.*, 2007). Patterns of changes in autumn migration in birds are mostly not consistent (delayed, advanced, no change) across analyzed species and regions and appear to be highly related to non-climatic variables (e.g., Sokolov, 2006; Adamik and Pietruszkova, 2008).

A large body of evidence therefore shows that Northern Hemisphere temperate, boreal and Arctic regions, spring advancement has occurred in many plant and animal species over the last several decades (*high confidence* due to *robust evidence* but only *medium agreement* when examined across all species and regions, Figure 4-4).

Understanding of the drivers of phenological change has also improved further since AR4. Many observational studies find a correlation with higher temperatures (Cook et al 2012a). Experimental manipulation generally supports this (e.g., plants, Cleland *et al.*, 2012; bird egg-laying, Visser *et al.*, 2009; insects, Musolin *et al.*, 2010; Kollberg *et al.*, 2013). Some individual studies find good agreement between experimental warming and *in situ* observations (e.g., Gunderson *et al.*, 2012) although a meta-analysis suggests that experiments can substantially under-predict advances in the timing of flowering and leafing of plants in comparison with observational studies (Wolkovich *et al.*, 2012). Observational data can also be affected by methodological issues; for example, flipper-tagging of penguins can alter their migratory behaviour (Saraux *et al.*, 2011). Rates of warming across a season may also be important (Schaper *et al.*, 2012). Models can be used to explain relationships between observed phenological changes and environmental variables. For example, a model based on water temperature captured the observed temporal and spatial variation in *Daphnia* phenology in Northern Hemisphere lakes (Straile *et al.*, 2012). Other environmental factors related to temperature, such as timing of snowmelt, snow cover and snow depth, can play a role. Snowmelt changes led to earlier flowering and appearances of plants and arthropods in Greenland between 1996 and 2005 (Høye *et al.*, 2007) and earlier flowering in an alpine plant in the Rocky Mountains, USA between 1975 and 2008 (Hülber *et al.*, 2010; Lambert *et al.*, 2010). Earlier snowmelts decreased floral resources and hence affected insect population dynamics in mountain ranges in the USA in the years 1980, 1985, 1986 and 1989 (Boggs and Inouye, 2012). In Colorado, USA, the yellow-bellied marmot emerge earlier from hibernation due to snowmelts becoming earlier over 1976-2008 (Ozgul *et al.*, 2010) while in Alberta, Canada, Columbian ground squirrels emerged later over 1992-2012 due to delayed snowmelts associated with increased late-season snowstorms (Lane *et al.*, 2012). Delayed emergence from hibernation was associated with decreased population growth rate (Lane *et al.*, 2012). Food availability can be important; for example, in the Yukon area, Canada, the date of giving birth in North American squirrels (*Tamiascurus hudsonicus*) advanced by an average of -18 days over the period 1989-1998, coinciding with increasing abundance of white spruce cones, their major food source (Réale *et al.*, 2003).

Phenological response can differ with migration strategy in birds, for example short-distance migrants show greater advancements in spring arrivals than long distant migrants (e.g., Saino *et al.*, 2009; but see Parmesan, 2006 for different patterns). In a temperate region (Massachusetts, USA), declining sizes of populations and migrating cohorts of North American Passerine birds account for a large part of the variation in migration times between 1970 and 2002 (Miller-Rushing *et al.*, 2008). The remaining variation was explained by climatic variables, migration distance and date. The variation in bird migration phenology change can also be related to differing patterns of feather changes during moulting times, food availability at stop-over places and differing health conditions of individual species (Gordo, 2007).

Although a number of non-climatic influences on phenology are also identified, an increased number of observational and experimental studies, across many organism types, suggest that warming has contributed to the overall spring advancement observed in the Northern Hemisphere (*high confidence* due to *high agreement* and *medium evidence*).

4.3.2.2. Primary Productivity

Primary production, the process of plant growth, is fundamental to the global carbon cycle (see Section 4.3.2.3. below) and t underpins provisioning ecosystem services such as food, timber and grazing. Trends in the amount, seasonal timing, variability, location and type of primary production are therefore important indicators of ecosystem function. Well-established theory, experimentation and observation all agree that primary production is directly sensitive to most aspects of climate change, is indirectly affected via the effects of climate on pests and diseases, and is responsive to many of the other changes simultaneously taking place in the world, such as the described in Section 4.2.4. The diverse and frequently non-linear form of responses to the factors influencing primary production, combined with the complexity of interactions between them, means that at a given location the net outcome can be an increase, no change or a decrease in productivity.

The concentration of CO_2 in the atmosphere shows clear patterns in space and time largely related to the primary productivity of the land and oceans. The contribution by terrestrial ecosystems to these patterns can be estimated using isotope measurements, emission databases and models (Canadell *et al.*, 2007). It consists of a sink term, due to increased net ecosystem production, plus a source term due to land-use change. During the decade 2000 to 2009, land net primary productivity at the global scale continued to be enhanced about 5% relative to the estimated pre-industrial level, leading to a land sink of 2.6 $\pm$ 1.2 PgC/y (these values are from WGI AR5 6.3.2.6; the uncertainty range is two standard deviations; for the primary literature see also Raupach *et al.*, 2008; Le Quéré *et al.*, 2009). The net uptake of carbon by the land is highly variable year-to-year, mainly in response to climate variation and major volcanic eruptions (Peylin *et al.*, 2005; Sitch *et al.*, 2008; Mercado *et al.*, 2009). Given the uncertainty range, it is not possible to conclude whether the rate of carbon uptake by the residual land sink has increased or decreased over the past two decades (Raupach *et al.*, 2008; WGI AR5 6.3.2.6). CMIP5 model projections, using the RCP scenarios, suggest that the rate of net carbon uptake by terrestrial ecosystem will decrease during the 21st century except under the RCP4.0 scenario, and by the greatest amount under RCP8.5. There is greater uncertainty between models than between scenarios; in some models terrestrial ecosystems become a net source of CO_2 to the atmosphere (WGI AR5 Section 6.4.3.2, especially Figure 6.26).

It is possible to downscale the land sink estimate continentally, using inversion modelling techniques and the growing network of precision atmospheric observations. There is *high agreement and medium evidence* that the net land uptake in natural and semi-natural terrestrial ecosystems is broadly distributed around the world, almost equally between forested and non-forested ecosystems, but is offset in the tropics by a large carbon emission flux resulting from land-use change, principally deforestation (Pan *et al.*, 2011).

The observed trends in NDVI, a satellite proxy for primary productivity, are discussed under various ecosystem-specific discussions above and below. In some cases the trends are sufficiently strong and consistent to support a confident statement about the underlying phenomenon, but in many cases they are not. This may mean that no change has occurred, or simply reflect inadequacies in the indicator, method of analysis and length of the record in relation to the high inter-annual variability. AR4 reported a trend of increasing seasonally-accumulated NDVI ("greening") at high northern latitudes (Fischlin *et al.*, 2007; based on Sitch *et al.*, 2007), but subsequent observations show a lower rate and no geographical uniformity (Goetz *et al.*, 2007). More than 25% of high latitude North American forest areas, excluding areas recently disturbed by fire, showed a decline in greenness and no systematic change in growing season length, particularly after 2000 (Goetz *et al.*, 2007). NDVI trend analyses in rangelands show varying patterns around the world, with substantial disagreement between studies (Millennium Ecosystem Assessment, 2005a; Bai *et al.*, 2008; Beck *et al.*, 2011a; Fensholt *et al.*, 2012). There is agreement that the Sahel showed widespread NDVI increase between the mid-1980s and about 2000, along with an increase in rainfall, but no consensus on whether the detected signal represents increased productivity by grasses, trees or herbs; and to what degree it reveals land management efforts or responses to climate (Anyamba and Tucker, 2005; Prince *et al.*, 2007; Hellden and Tottrup, 2008; Seaquist *et al.*, 2009). In the period 2000 to 2009 no NDVI trend was apparent in the Sahel (Samanta *et al.*, 2011).

Tree rings record changes in tree growth over approximately the past millennium. Many tree ring records show accelerated tree growth during much of the 20th century (Briffa *et al.*, 2008), which often correlates with rising temperature. Variations in tree ring width, density and isotopic composition arise from many factors, including temperature, moisture stress, CO_2 fertilization, N deposition and ozone damage, but also stand structure and management. Direct CO_2 effects, inferred from the ring record once the effects of drought and temperature have been accounted for, have been proposed for approximately 20% of the sites in the International Tree Ring Data Base (Gedalof and Berg, 2010) and studied in detail at some sites (Koutavas, 2008). Since the 1980s, a number of tree ring records show a decline in tree growth (Wilson *et al.*, 2007). Several possible causes have been suggested for this, including increasing water stress and ozone damage; but the most recent rings in most published tree ring chronologies date from before the 1990s (Gedalof and Berg, 2010) so tree ring-based conclusions for the past two decades are based on a relatively small body of evidence and may therefore be biased. Recent tree ring studies were often specifically designed to examine growth in response to environmental changes (Gedalof and Berg, 2010) and may therefore not be representative of global tree growth. Direct repeated measurements of tree girth increment in forest monitoring plots (discussed in Section 4.3.2.3) are an alternate data source for recent decades.

Primary production in freshwater lakes has been observed to increase in some arctic (Michelutti *et al.*, 2005) and boreal lakes, but decrease in Lake Tanganyika in the tropics (O'Reilly *et al.*, 2003). In both cases the changes were attributed by the authors to climate change.

In summary, there is *high confidence* that net terrestrial ecosystem productivity at the global scale has increased relative to the pre-industrial era (Figure 4-4). There is *low confidence* in attribution of these trends to climate change. Most studies speculate that rising CO_2 concentrations are contributing to this trend through stimulation of photosynthesis, but there is no clear, consistent signal of a climate change contribution (Figure 4-4).

4.3.2.3. Biomass and Carbon Stocks

The forest biomass carbon stock can be estimated from the routine forest monitoring that takes place for management and research purposes. Forest inventories were generally designed to track timber volumes; inferring total biomass and ecosystem carbon stocks requires further information and assumptions, which make absolute values less certain, but have a lesser effect on trend detection. Forest inventory systems are well-developed for Northern Hemisphere temperate and boreal forest (Nabuurs *et al.*, 2010; Ryan *et al.*, 2010; Wang *et al.*, 2010a). Data for tropical and Southern Hemisphere forests and woodlands also exist (Maniatis *et al.*, 2011; Tomppo *et al.*, 2010) but are typically less available and comprehensive (Romijn *et al.*, 2012). More and better data may become available due to advances in remote sensing (e.g., Baccini *et al.*, 2012) and increased investment in forest monitoring through initiatives such as the Reduced Emissions from Deforestation and Degradation (REDD) of the UNFCCC.

Forests have increased in biomass and carbon stocks over the past half century in Europe (Ciais *et al.*, 2008; Luyssaert *et al.*, 2010) and the USA (Birdsey *et al.*, 2006). Canadian managed forests increased in biomass only slightly during 1998-2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson *et al.*, 2011). Several dozen sites across the moist tropics have been monitored to estimate forest biomass changes. In the Amazon (Phillips *et al.*, 2009) forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005. Globally, for the period 2000-2007, recently-undisturbed forests are estimated to have withdrawn 2.30 ± 0.49 PgC/y from the atmosphere, while formerly-cleared tropical forests, now regrowing, withdrew an additional 1.72 ± 0.54 PgC/y (Pan *et al.*, 2011). The global terrestrial carbon sink is partly offset by the losses of forest carbon stocks to the atmosphere through land use change, largely in the tropics, of 1.1 ± 0.8 PgC/y (2000-2009, WGI AR5 6.3.2.6).

The carbon stock in global soils, including litter and peatlands is 1500-2400 PgC, with permanently frozen soils adding another 1700 PgC (Davidson and Janssens, 2006). The soil carbon stock is thus more than ten times greater than the carbon stock in forest biomass (Kindermann *et al.*, 2008). Changes in the size of the soil carbon stock result from changes in the net balance of inputs and losses over a period of many years. Inputs derive from primary production, discussed in Section 4.3.2.2, and are mostly modestly increasing under climate change. Losses result principally through the respiration of soil microbes, which increases with increasing temperature. The present and future temperature sensitivity of microbial respiration remains uncertain (Davidson and Janssens, 2006). An analysis of long-term respiration measurements from the soil around the world suggests that it has increased over the past two decades by an amount of 0.1PgC/y, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). If soil respiration were to exceed terrestrial net primary production globally and on a sustained basis, the present net terrestrial sink would become a net source, accelerating the rate of CO_2 build up in the atmosphere (Luo, 2007).

The carbon stock in freshwater systems is also quite high in global terms. Annual rates of storage (0.03 – 0.07 Pg C/yr) may be trivial compared with sequestration by soils and terrestrial vegetation, but lake sediments are preserved over longer time scales (+10,000 years compared with decades to centuries), and Holocene storage of C in lake sediments has been estimated at 820 Pg (Cole *et al.*, 2007). Manmade impoundments represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 – 0.2 Pg C/yr (Cole *et al.*, 2007).

A short-duration study of the temperature sensitivity of decomposition in flooded coastal soils, extrapolated to the 21st century, suggested that increases in respiration would exceed increases in production in future (Kirwan and Blum, 2011). Further detail on wetland soil carbon stocks can be found in Section 4.3.3.3 on peatlands; and on permafrost carbon stocks in Box 4-4 and in Chapter 28.

In summary, biomass and soil carbon stocks in terrestrial ecosystems are currently increasing (*high confidence*) but are vulnerable to loss to the atmosphere as a result of rising temperature, drought and fire projected in the 21st century (Figure 4-4). Measurements of increased tree growth over the last several decades, a large sink for carbon, are consistent with this but confounding factors such as N deposition, afforestation and land management make attribution of these trends to climate change difficult (*low confidence*).

4.3.2.4. Evapotranspiration and Water Use Efficiency

Evapotranspiration (ET) includes evaporation from the ground and vegetation surfaces, and transpiration through plant stomata. Both are affected by multiple factors (Luo *et al.*, 2008) including temperature, solar (shortwave) and thermal (longwave) radiation, humidity, soil moisture and terrestrial water storage; transpiration is additionally affected by CO_2 concentration through its influence on plant stomatal conductance. Studies using lysimeters, evaporation pans, the balance of observed precipitation and runoff, and model reconstructions, indicate both increases and decreases in ET in different regions and between approximately 1950 and the present (Huntington, 2008; Teuling *et al.*, 2009; Douville *et al.*, 2013). Flux tower records have at most 15 years duration (FLUXNET, 2012) so there are insufficient data to calculate large-scale, long-term trends. ET can also be estimated from meteorological observations or simulated with models constrained by observations. Estimates of ET from 1120 globally (but non-uniformly) distributed stations indicate that global land mean ET increased by approximately 2.2% between 1982 and 2002, a rate of increase of 0.75 mm yr^{-2} (Wang *et al.*, 2010b). Other studies, using data-constrained models indicated global ET rises of between 0.25 - 1.1 mm yr^{-2} during the 1980s and 1990s (Jung *et al.*, 2010; Vinukollu *et al.*, 2011; Zeng *et al.*, 2012), possibly linked with increased surface solar radiation and thermal radiation (Wild *et al.*, 2008) or warming (Jung *et al.*, 2010). There has been no significant ET trend since approximately 2000 (Jung *et al.*, 2010; Vinukollu *et al.*, 2011; Zeng *et al.*, 2012), possibly due to soil moisture limitation (Jung *et al.*, 2010). Overall, there is *low confidence* in both detection and attribution of long-term trends in ET (Figure 4-4).

Experiments show that rising CO_2 decreases transpiration and increases intrinsic water use efficiency (iWUE, the ratio of photosynthesis to stomatal conductance, Leakey *et al.*, 2009). Some modelling studies suggest that over the last century, the effects of CO_2 on decreasing transpiration are of comparable size but opposite to the effects of rising temperature (Gerten *et al.*, 2008; Peng *et al.*, 2013). However the observed general increase in ET argues that reduced transpiration cannot be the dominant factor (Huntington, 2008). A meta-analysis of studies at 47 sites across 5 ecosystem types (Peñuelas *et al.*, 2011) suggests that iWUE for mature trees increased by 20.5% between the 1970s and 2000s. Increased iWUE since pre-industrial times (1850 or before) has also been found at several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and also in a temperate semi-natural grassland since 1857 (Koehler *et al.*, 2010), although in one boreal tree species iWUE ceased to increase after 1970 (Gagen *et al.*, 2011).

4.3.2.5. Changes in Species Range, Abundance and Extinction

Species respond to climate change through genotypic adaptation and phenotypic plasticity; by moving out of unfavourable and into favourable climates; or by going locally or globally extinct (Dawson *et al.*, 2011; Bellard *et* *al.*, 2012; Peñuelas *et al.*, 2013; Section 4.2.3). These responses to climate change can potentially have large impacts on biodiversity and ecosystem services. Genotypic adaptation in the face of strong selection pressure from climate change is typically accompanied by large reductions in abundance (see Section 4.4.1.2). Species range shifts are accompanied by changes in abundance, local extinctions and colonization that can alter ecosystem services when they affect dominant species such as trees, keystone species such as pollinators, or species that are vectors for disease (Zarnetske *et al.*, 2012). Global extinctions result in the permanent loss of unique forms of life.

Substantial evidence has accumulated since AR4 reinforcing the conclusion that the geographical ranges of many terrestrial and freshwater plant and animal species have moved over the last several decades in response to warming and that this movement is projected to accelerate over the coming decades under high rates of climate change. Some changes in species abundances appear to be linked to climate change in a predictable manner, with species abundances increasing in areas where climate has become more favourable and vice versa. In contrast, uncertainties concerning attribution to climate change of recent global species extinctions, and in projections of future extinctions, have become more apparent since the AR4 report.

Observed species range shifts - The number of studies looking at observed range shifts and the breadth of species examined has greatly increased since AR4. The most important advances since AR4 concern improvements in understanding the relationship between range shifts and changes in climate over the last several decades. The "uphill and poleward" view of species range shifts in response to recent warming (Parmesan and Yohe, 2003; Parmesan, 2006; Fischlin *et al.*, 2007; Chen *et al.*, 2011) is a useful simplification of species responses; however, responses to warming are conditioned by changes in precipitation, land use, species interactions and many other factors. Investigations of the mechanisms underlying observed range shifts show that climate signals can often be detected, but the impacts of and interactions between changing temperature, precipitation and land use often result in range shifts that are downhill or away from the poles (Rowe *et al.*, 2010; Crimmins *et al.*, 2011; Hockey *et al.*, 2011; McCain and Colwell, 2011; Rubidge *et al.*, 2011; Pauli *et al.*, 2012; Tingley *et al.*, 2012; Zhu *et al.*, 2012). There are large differences in the ability of species groups (i.e., broad taxonomic categories of species) and species within these groups to track changes in climate through range shifts (Angert *et al.*, 2011; Mattila *et al.*, 2011; Chen *et al.*, 2011). For example, butterflies appear to be able track climate better than birds (community shifts: Devictor *et al.*, 2012; but see Chen *et al.*, 2011 for range shifts) while some plants appear to be lagging far behind climate trends except in mountainous areas (Bertrand *et al.*, 2011; Doxford and Freckleton, 2012; Gottfried *et al.*, 2012; Zhu *et al.*, 2012; Telwala *et al.*, 2013). There is growing evidence that responses at the “trailing edge” of species distributions (i.e., local extinction in areas where climate has become unfavourable) are often less pronounced than responses at the “leading edge” (i.e., colonization of areas where climate has become favourable), which may be related to differences in the rates of local extinction vs. colonization processes (Doak and Morris, 2010; Chen *et al.*, 2011; Brommer *et al.*, 2012; Sunday *et al.*, 2012) and difficulties in detecting local extinction with confidence (Thomas *et al.*, 2006).

Rising water temperatures are also implicated in species range shifts in river fish communities (e.g., Comte and Grenouillet, 2013), combined with a decrease in recruitment and survival as well as range-contraction of cold-water species such as salmonids (Bartholow, 2005; Bryant, 2009; Ficke *et al.*, 2007; Jonsson and Jonsson, 2009; Hague *et al.*, 2011). Shifts in freshwater fish species range towards higher elevation and upstream (Hickling et al., 2006; Comte and Grenouillet, 2013) also are not keeping pace with the rate of warming in streams and rivers. While these changes in river temperature regimes may also open up new habitat at higher latitudes (or altitudes) for migratory (Reist *et al.*, 2006) and cool- and warm-water species of fish (Tisseuil *et al.*, 2012), there is *high confidence* that range contraction threatens the long term persistence of some fully aquatic species.

Rates of recent climate change have varied greatly across the globe, ranging from rapid warming to cooling (Burrows *et al.*, 2011; Dobrowski *et al.*, 2013). Taking this spatial variation into account should enhance the ability to detect climate related range shifts. A recent synthesis of range shifts indicates that terrestrial animal species have moved at rates that correspond better with changes in temperature when climate is measured only in the regions where the range shifts were observed (Chen *et al.*, 2011), providing greater confidence in attribution of the range shifts to climate change. Average range shifts across taxa and regions in this study were ca. 17 km poleward and 11 m up in altitude per decade; velocities which are 2 to 3 times greater than previous estimates (compare with Parmesan and Yohe, 2003; Fischlin *et al.*, 2007), but these responses differ greatly among species groups. However, this approach remains a simplification, since the climate drivers of species range changes, e.g., temperature and precipitation, have frequently shifted in different geographical directions (Dobrowski *et al.*, 2013). Disentangling these conflicting climate signals can help explain complex responses of species ranges to changes in climate (Tingley *et al.*, 2012). Overall, studies since AR4 show that species range changes result from interactions among climate drivers and between climate and non-climate factors. It is the greater understanding of these interactions, combined with increased geographical scope that leads to *high confidence* that the ranges of several well-studied species groups, such as insects and birds, have shifted their ranges significant distances (10s of km or more) over the last several decades, and that these range shifts can be attributed to changes in climate. But for many other species groups range shifts are more difficult to attribute to changes in climate because the climate signal is small, there are many confounding factors, differences between expected and observed range shifts are large, or variability within or between studies is high. Thus there is only *medium confidence* in detection and attribution when examined across all species and all regions.

Future range shifts - Projections of climate change impacts on future species range shifts since the AR4 report have been dominated by studies using ecological niche models (ENMs) that project future ranges based on correlative models of current relationships between environmental factors and species distribution (Peterson *et al.*, 2011). A variety of process-based models are starting to be more widely used to make projections of future species distributions (Buckley *et al.*, 2010; Beale and Lennon, 2012; Cheaib *et al.*, 2012; Higgins *et al.*, 2012; Foden *et al.*, 2013). Model comparisons show that correlative models generally predict larger range shifts than process-based models for trees (Morin and Thuiller, 2009; Kearney *et al.*, 2010; Cheaib *et al.*, 2012). For other species groups that have been studied, differences in projections between model types show no clear tendency (Kearney *et al.*, 2009; Buckley *et al.*, 2010; Bateman *et al.*, 2012). There has been some progress in model validation: projected species shifts are broadly coherent with species responses to climate change in the paleontological record and with observed recent species shifts (see Section 4.2.2 and above), but further validation is needed (Green *et al.*, 2008; Pearman *et al.*, 2008; Nogues-Bravo *et al.*, 2010; Dawson *et al.*, 2011). Modelling studies typically do not account for a number of key mechanisms mediating range shifts, such as genetic adaptation and phenotypic plasticity (see Section 4.4.1.2), species interactions or human-mediated effects. An important limitation in most studies is that realistic species displacement rates are not accounted for (i.e., rates at which species are able to shift their ranges through dispersal and establishment); as such, they only indicate changes in the location of favourable and unfavourable climates, from which potential shifts in species distribution can be inferred, but not rates of change (Bateman *et al.*, 2013).

Analyses and models developed since AR4 permit the estimation of the ability of a wide range of species to track climate change. Figure 4-5 provides a synthesis of the projected abilities of several species groups to track climate change. This analysis is based on: i) past and future climate velocity, which is a measure of the rate of climate displacement across a landscape and provides an indication of the speed at which an organism would need to move in order to keep pace with the changing climatic conditions (Loarie *et al.*, 2009; Burrows *et al.*, 2011; Chen *et al.*, 2011; Sandel *et al.*, 2011; Feeley and Rehm, 2012; Dobrowski *et al.*, 2013); and ii) species displacement rates across landscapes for a broad range of species (e.g., Stevens *et al.*, 2010b; Nathan *et al.*, 2011; Barbet-Massin *et al.*, 2012; Kappes and Haase, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012; see additional references in Figure 4-5 legend). Comparisons of these rates indicate whether species are projected to be able to track climate as it changes. When species displacement capacity exceeds climate velocity it is inferred that species will be able to keep pace with climate change; when displacement capacity is lower than projected climate velocities then they will not, within the bounds of uncertainty of both parameters. This simplified analysis is coherent with more sophisticated model analyses of climate induced species displacement across landscapes, some of which have evaluated additional constraints such as demographics, habitat fragmentation or competition (e.g., Meier *et al.*, 2012; Schloss *et al.*, 2012).

Rates of climate change over the 20^{th} century and projected for the 21^{st} century are shown in Figure 4-5A. Rates of climate change for global land surfaces are given for IPCC AR5 climate projections under a wide range of greenhouse gas emissions scenarios (i.e. WGI AR5 Chapter 12; Knutti and Sedláček, 2012). Rates of global warming for land surfaces have averaged ca. 0.03 °C/yr since 1980, but have slowed over the last decade and a half (WGI Chapter 2). At the low end of projected future rates of warming, rates decrease over time, reaching near zero by the end of the century (RCP 2.6). At the high end, projected rates increase over time, exceeding 0.06 °C/yr by the end of the century (RCP 8.5), and perhaps above 0.08 °C/yr at the upper bound for this scenario.

Climate velocity is defined as the rate of change in climate over time (e.g., °C/yr, if only temperature is considered) divided by the rate of change in climate over distance (e.g., °C/km, if only temperature is considered) and therefore depends on regional rates of climate change and the degree of altitudinal relief (Figure 4-5B, Loarie *et al.*, 2009; Dobrowski *et al.*, 2013). For example, climate velocity for temperature is low in mountainous areas because the change in temperature over short distances is large (e.g., Rocky mountains, Andes, Alps, Himalayas, Figure 4-5B, leftmost axis). Climate velocity for temperature is generally high in flat areas because the rate of change in temperature over distance is low (e.g., parts of the US Mid-west, Amazon basin, West Africa, central Australia, Figure 4-5B, rightmost axis). In flat areas, climate velocity can exceed 8 km/yr for the highest rates of projected climate change (RCP 8.5). We have focused on climate velocity for temperature change, but several analyses also account for precipitation change.

Rates of displacement vary greatly within and among species groups (Figure 4-5C). Some species groups, notably herbaceous plants and trees, generally have very low displacement capacity. Other species groups such as butterflies, birds (not shown) and large vertebrates generally have a very high capacity to disperse across landscapes, nonetheless some species in these groups have low dispersal capacity. Current and future rates of climate change correspond to climate velocities that exceed rates of displacement for several species groups for most climate change scenarios. This is particularly true for mid- and late-successional trees that have maximum displacement rates that are on the order of 10s to a few 100s of m/yr. Overall, many plant species are foreseen to be able to track climates only in mountainous areas at medium to high rates of warming, though there is uncertainty concerning the potential role of long-distance dispersal (Pearson, 2006). Primates generally have substantially higher dispersal capacity than trees; however, a large fraction of primates are found in regions with very high climate velocities, in particular the Amazon basin, thereby putting them at high risk of being unable to track climates even at relatively low rates of climate change (Schloss *et al.*, 2012). On a global average, many rodents, as well as some carnivores and freshwater molluscs are projected to be unable to track climate at very high rates of climate change (i.e., >0.06°C/yr). These projected differences in species ability to keep pace with future climate change are broadly coherent with observations of species ability or inability to track recent global warming (see *Observed species range shifts* above).

Humans can increase species displacement rates by intentionally or unintentionally dispersing individuals or propagules. For example, many economically important tree species may be deliberately moved on large scales as part of climate adaptation strategies in forestry in some regions (Lindner *et al.*, 2010). Human activities can also substantially reduce displacement rates. In particular, habitat loss and fragmentation typically reduces displacement rates, sometimes substantially (Eycott *et al.*, 2012; Hodgson *et al.*, 2012; Meier *et al.*, 2012; Schloss *et al.*, 2012). The degree to which habitat fragmentation slows displacement depends on many factors, including the spatial pattern of the fragments and corridors, maximum dispersal distances, population dynamics and the suitability of intervening modified habitats as stepping-stones (Pearson and Dawson, 2003). Species and habitat dependencies may also speed or hinder species displacement. For example, host plants are projected to move much more slowly than most herbivorous insects, substantially slowing displacement of the insects if they are unable to switch host plants (Schweiger *et al.*, 2012). Likewise, many habitats are structured by slow moving plants, so habitat shifts are projected to lag behind climate change (Jones *et al.*, 2012; Hickler *et al.*, 2012) which will in turn mediate the movements of habitat specialists.

There are significant uncertainties in climate velocities, measured estimates of dispersal and establishment rates, and model formulations. Climate velocities are calculated using a variety of methods and spatial resolutions, making direct comparisons difficult and leading to *low confidence* in estimates of climate velocities in Figure 4-5B (*limited evidence* and *medium agreement*). The lowest estimates of global average climate velocity (Figure 4-5B, centre axis), are about half the best estimate values we show on the climate velocity axes (Loarie *et al.*, 2009), while the highest estimates are about four times higher (Burrows *et al.*, 2011), but high estimates may be artefacts of using very large spatial resolutions (Dobrowski *et al.*, 2013). In addition, the climate velocities used in Figure 4-5 are based on temperature alone, and recent analyses indicate that including more climate factors increases climate velocity (Feeley and Rehm, 2012; Dobrowski *et al.*, 2013). Species displacement rates are calculated based on a very wide range of methods including rates of displacement in the paleontological record, rates of current range shifts due to climate warming, models of dispersal and establishment, maximum observed dispersal distances and genetic analyses (e.g., Kinlan and Gaines, 2003; Stevens *et al.*, 2010b). There are often large differences in estimates of dispersal rates across methods due to intrinsic uncertainties in the methods and differences in the mechanisms included (Kinlan and Gaines, 2003; Stevens *et al.*, 2010b). For example, estimates of tree displacement rates are frequently based on models or observations that explicitly or implicitly include both dispersal of seeds and biotic and abiotic factors controlling establishment of adult trees. Displacement rates of trees are often more strongly limited by establishment than dispersal (Higgins *et al.*, 2003; Meier *et al.*, 2012). It is reasonable to expect that limits on establishment could also be important for other species groups, but often only dispersal rates have been calculated, leading to an overestimation of displacement rates. For trees there is *medium confidence* in projections of their displacement rates due to the large number of studies of past, current and future displacement rates (*robust evidence* and *medium agreement*). Less is known for other broad species groups such as mammals, so there is only *low confidence* in estimates of their displacement capacity. Estimates for other groups, such as freshwater molluscs are based on very little data, so estimates of their dispersal capacity are poorly constrained.

Despite large uncertainties in displacement capacity and climate velocity, the rates of displacement required to track the highest rates of climate change (RCP8.5) are so high that many species will be unable to do so (*high confidence*). Moderate rates of projected climate change (RCP4.5 and RCP6.0) would allow more species to track climate, but would still exceed the capacity of many species to track climate (*medium confidence*). The lowest rates of projected climate change (RCP2.6) would allow most species to track climate towards the end of the century (*high confidence*). This analysis highlights the importance of rates of climate change as an important component of climate change impacts on species and ecosystems. For example, differences in the magnitude of climate change between scenarios are small at mid-century (WGI Chapter 12), but the differences in rates of climate change are large. At mid-century, it is projected that species would need to move little at the lowest rates of climate change (RCP 2.6), but will need to move approximately 70 km/decade in flat areas in order to track climate at the highest rates of climate change (RCP 8.5).

Species that cannot move fast enough to keep pace with the rate of climate change will lose favourable climate space and experience large range contractions (Warren *et al.*, 2013), whereas displacement that keeps pace with climate change greatly increases the fraction of species that can maintain or increase their range size (Menéndez *et al.*, 2008; Pateman *et al.*, 2012). Mountains provide an extremely important climate refuge for many species because the rate of displacement required to track climate is low (Figure 4-5B, Colwell *et al.*, 2008; Engler *et al.*, 2011; Gottfried *et al.*, 2012; Pauli *et al.*, 2012; but see Dullinger *et al.*, 2012). However, species that already occur near mountaintops (or other boundaries) are among the most threatened by climate change because they cannot move upwards (Ponniah and Hughes, 2004; Thuiller *et al.*, 2005; Raxworthy *et al.*, 2008; Engler *et al.*, 2011; Sauer *et al.*, 2011). The consequences of losing favourable climate space are not yet well understood. The extent to which adaptive responses might allow persistence in areas of unfavourable climates is discussed in Section 4.4.1.2. In the absence of adaptation, losing favourable climate space is projected to lead to reduced fitness, declining abundance and local extinction, with potentially large effects on biodiversity and ecosystem services (see evidence of early signs of this for trees in Box 4-2).

[INSERT FIGURE 4-5 HERE
Figure 4-5: (A) Rates of climate change, (B) corresponding climate velocities and (C) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. Horizontal and vertical pink bands illustrate the interpretation of this figure. Climate velocities for a given range of rates of climate change are determined by tracing a band from the range of rates in panel A to the points of intersection with the three climate velocity scalars in panel B. Comparisons with species displacement rates are made by tracing vertical bands from the points of intersection on the climate velocity scalars down to the species displacement rates in panel C. Species groups with displacement rates below the band are projected to be unable to track climate in the absence of human intervention. (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis, all other rates are calculated based on the average of CMIP5 climate model ensembles for the historical period (grey shading indicates model uncertainty) and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one member per model. Global average temperatures at the end of the 21st century for the four RCP scenarios are from WGI AR5 Chapter 12. (B) Estimates of climate velocity for temperature were synthesized from historical and

projected future relationships between rates of temperature change and climate velocity (historical: Burrows *et al.*, 2011; Chen *et al.*, 2011; Dobrowski *et al.*, 2013; projected future: Loarie *et al.*, 2009; Sandel *et al.*, 2011; Feeley and Rehm, 2012). The three scalars are climate velocities that are representative of mountainous areas (left), averaged across global land areas (centre), and large flat regions (right). (C) Rates of displacement are given with an estimate of the median (black bars) and range (boxes = ca. 95% of observations or models for herbaceous plants, trees and plant-feeding insects or median ± 1.5 inter-quartile range for mammals). Displacement rates for herbaceous plants were derived from paleobotanical records, modern plant invasion rates and genetic analyses (Kinlan and Gaines, 2003). Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark *et al.*, 2003; Kinlan and Gaines, 2003; McLachlan *et al.*, 2005; Nathan, 2006; Pearson, 2006) and modelled tree dispersal and establishment in response to future climate change (Higgins *et al.*, 2003; Iverson *et al.*, 2004; Epstein *et al.*, 2007; Goetz *et al.*, 2011; Nathan *et al.*, 2011; Meier *et al.*, 2012; Sato and Ise, 2012). Displacement rates for mammals were based on modelled dispersal rates of a wide range of mammal species (mean of Schloss *et al.*, 2012 for Western Hemisphere mammals and rates calculated from global assessments of dispersal distance by Santini *et al.*, 2013 and generation length by Pacifici *et al.*, 2013). Displacement rates for phytophagous insects are based on observed dispersal distances and genetic analyses (Peterson and Denno, 1998; Kinlan and Gaines, 2003; Schneider, 2003; Berg *et al.*, 2010; Chen *et al.*, 2011). The estimate of median displacement rate for this group exceeds the highest rates on the axis. These displacement rates do not take into account limitations imposed by host plants. Displacement estimates for freshwater molluscs correspond to the range of passive plus active dispersal rates for upstream movement (Kappes and Haase, 2012).]

Observed changes in abundance and local extinctions - Observations of range shifts imply changes in abundance; i.e., colonization at the “leading edge” and local extinction at the “trailing edge” of ranges. Evidence that the attribution of these responses to recent changes in climate can be made with *high confidence* for several species groups is reviewed here (Section 4.3.2.5), in AR4 and by Cahill *et al.* (2013). Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have also occurred in response to recent global warming (*high confidence*, Thaxter *et al.*, 2010; Bertrand *et al.*, 2011; Naito and Cairns, 2011; Rubidge *et al.*, 2011; Devictor *et al.*, 2012; Tingley *et al.*, 2012; Vadadi-Fulop *et al.*, 2012; Cahill *et al.*, 2013; Ruiz-Labourdette *et al.*, 2013). Confident attribution to recent global warming is hindered by confounding factors such as disease, land use change and invasive species (Cahill *et al.*, 2013). New tentative conclusions since AR4 is that climate related changes in abundance and local extinctions appear to be more strongly related to species interactions than to physiological tolerance limits (*low confidence*, Cahill *et al.*, 2013) and that precipitation can be a stronger driver of abundance change than temperature in many cases (Tian *et al.*, 2011; Tingley *et al.*, 2012). This gives weight to concerns that biological interactions, which are poorly known and modelled, may play a critical role in mediating the impacts of future climate change on species abundance and local extinctions (Dunn *et al.*, 2009; Bellard *et al.*, 2012; Hannah, 2012; Urban *et al.*, 2012; Vadadi-Fulop *et al.*, 2012).

A few examples illustrate the types of change in abundance that are being observed and the challenges in attributing these to recent global warming. Some of the clearest examples of climate-related changes in species populations come from high latitude ecosystems where non-climate drivers are of lesser importance. For example, both satellite data and a large number of long-term observations indicate that shrub abundance is generally increasing over broad areas of Arctic tundra, which is coherent with predicted shifts in community structure due to warming (Epstein *et al.*, 2007; Goetz *et al.*, 2011; Myers-Smith *et al.*, 2011). In the Antarctic, two native vascular plants, Antarctic pearlwort (*Colobanthus quitensis*) and Antarctic hair grass (*Deschampsia antarctica*) have become more prolific over recent decades, perhaps because they benefit more from warming of soils than do mosses (Hill *et al.*, 2011). Penguin populations have declined in several areas of the Antarctic, including a recent local extinction of an Emperor penguin *(Aptenodytes forsteri)* population that has been attributed to regional changes in climate (Trathan *et al.*, 2011). The attribution of these declines to changes in regional climate is well supported, but the link to global warming is tenuous (Barbraud *et al.*, 2011).

Mountains also provide good examples of changes in abundance that can be linked to climate because very strong climate gradients are found there. AR4 highlighted these responses and the case for changes in abundance, in particular plants, has become stronger since then. For example, Pauli *et al.* (2012) reported an increase in species richness from plant communities of mountaintops in the European boreal and temperate zones due to increasing temperatures and a decrease in species richness on the Mediterranean mountain tops, probably due to a decrease in the water availability in Southern Europe. An increase in the population size of warm adapted species at high altitudes also appears to be attributable to increasing temperatures (Gottfried *et al.*, 2012). However, these attributions are complicated by other anthropogenic influences such as changes in grazing pressure, atmospheric nitrogen deposition, and forest management practices (Gottfried *et al.*, 2012). Altitudinal gradients in local and global extinctions of amphibians also contributed to the attribution of these extinctions to recent global warming, although this attribution remains controversial (see below).

Projected changes in abundance and local extinction - Ecological niche models do not predict population changes, but the shifts in suitable climates can be used to infer areas where species populations might decline or increase. These models project that local extinction risk by the end of the 21st century due to climate change will vary widely, ranging from almost no increase in local extinction risk within the current range for some species or species groups to greatly increased risk of local extinctions in more than 95% of the present-day range for others (Settele *et al.*, 2008; Bellard *et al.*, 2012). Projected local colonization rates are equally variable. There has been progress in coupling species distribution models and species abundance models for a wide range of organisms (Keith *et al.*, 2008; Midgley *et al.*, 2010; Matthews *et al.*, 2011; Schippers *et al.*, 2011; Oliver *et al.*, 2012a; Renwick *et al.*, 2012). These hybrid approaches predict extinction risk directly, rather than by inference from changes in climate suitability (Fordham *et al.*, 2012). The main conclusions from these studies are that changes in species abundance and local extinction risk as a result of climate change can range from highly positive to highly negative, and are determined by a combination of factors, including its environmental niche, demographics and life history traits, as well as interactions among these factors (Aiello-Lammens *et al.*, 2011; Clavero *et al.*, 2011; Conlisk *et al.*, 2012; Fordham *et al.*, 2012; Swab *et al.*, 2012).

Changes in abundances will also be accompanied by changes in genetic diversity (see also Section 4.4.1.2). At the intraspecific level, future climate change is projected to induce losses of genetic diversity when it results in range contraction (Balint *et al.*, 2011; Pauls *et al.*, 2013). In addition, there is theoretical and observational evidence this loss of genetic diversity will depend on rates of migration and range contraction (Arenas *et al.*, 2012). In these cases, reductions in genetic diversity may then decrease the ability of species to adapt to further climate change or other global changes. Climate change may also compound losses of genetic diversity that are already occurring due other global changes such as the introduction of alien species or habitat fragmentation (Winter *et al.*, 2009; Section 4.2.4.6.).

Observed global extinctions - Global species extinctions, many of them caused by human activities, are now at rates that approach or exceed the upper limits of observed natural rates of extinction in the fossil record (Barnosky *et al.*, 2011). However, across all taxa there is only *low confidence* that rates of species extinctions have increased over the last several decades (Szabo *et al.*, 2012 - birds; but see Kiesecker, 2011 - amphibians). Most extinctions over the last several centuries have been attributed to habitat loss, overexploitation, pollution or invasive species, and these are the most important current drivers of extinctions (Millennium Ecosystem Assessment, 2005b; Hofmann and Todgham, 2010; Cahill *et al.*, 2013). Of the more than 800 global extinctions documented by the IUCN, only 20 have been tenuously linked to recent climate change (Cahill *et al.*, 2013; see also Hoffmann *et al.*, 2011; Szabo *et al.*, 2012). Molluscs, especially freshwater molluscs, have by far the highest rate of documented extinctions of all species groups (Barnosky *et al.*, 2011). Mollusc extinctions are primarily attributed to invasive species, habitat modification and pollution — changes in climate are rarely evoked as a driver (Lydeard *et al.*, 2004; Regnier *et al.*, 2009; Chiba and Roy, 2011; but see a few cases in Kappes and Haase, 2012; Cahill *et al.*, 2013). Freshwater fish have the highest documented extinction rates of all vertebrates, and again very few have been attributed to changing climate, even tenuously (Burkhead, 2012; Cahill *et al.*, 2013). In contrast, changes in climate have been identified as one of the key drivers of extinctions of amphibians (Pounds *et al.*, 2006). There have been more than 160 probable extinctions of amphibians documented over the last two decades, many of them in Central America (Pounds *et al.*, 2006; Kiesecker, 2011). The most notable cases have been the golden toad (*Bufo periglenes*) and Monteverde harlequin frog (*Atelopus varius*) of Central America, which belong to a group of amphibians with high rates of extinction previously ascribed to global warming with “very high confidence” (Pounds *et al.*, 2006; Fischlin *et al.*, 2007). This case has raised a number of important issues about attribution since i) the proximate causes of extinction of these and other Central American frogs appear to be an extremely virulent invasive fungal infection and land use change, with regional changes in climate as a potential contributing factor, and ii) changes in regional climate may have been related to natural climate fluctuations rather than anthropogenic climate change (Sodhi *et al.*, 2008; Lips *et al.*, 2008; Anchukaitis and Evans, 2010; Bustamante *et al.*, 2010; Collins, 2010; Vredenburg *et al.*, 2010; Kiesecker, 2011; McKenzie and Peterson, 2012; McMenamin and Hannah, 2012). Due to *low agreement* among studies there is only *medium confidence* in detection of extinctions and attribution of Central American amphibian extinctions to climate change. While this case highlights difficulties in attribution of extinctions to recent global warming, it also points to a growing consensus that it is the interaction of climate change with other global change pressures that poses the greatest threat to species (Brook *et al.*, 2008; Pereira *et al.*, 2010; Hof *et al.*, 2011b). Overall, there is *very low confidence* that observed species extinctions can be attributed to recent climate warming, due to the very low fraction of global extinctions that have been ascribed to climate change and tenuous nature of most attributions.

Projected Future Species Extinctions - Projections of future extinctions due to climate change have received considerable attention since AR4. AR4 stated with *medium confidence* “that approximately 20-30% of the plant and animal species assessed to date are at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above pre-industrial levels” (Fischlin *et al.*, 2007). All model-based analyses since AR4 broadly confirm this concern, leading to *high confidence* that climate change will contribute to increased extinction risk for terrestrial and freshwater species over the coming century (Pereira *et al.*, 2010; Sinervo *et al.*, 2010; Pearson, 2011; Warren *et al.*, 2011; Bellard *et al.*, 2012; Hannah, 2012; Ihlow *et al.*, 2012; Sekercioglu *et al.*, 2012; Wearn *et al.*, 2012; Foden *et al.*, 2013; Warren *et al.*, 2013). Most studies indicate that extinction risk rises rapidly with increasing levels of climate change, but some do not (Pereira *et al.*, 2010). The limited number of studies that have directly compared land use and climate change drivers have concluded that projected land use change will continue to be a more important driver of extinction risk throughout the 21st century (Pereira *et al.*, 2010). There is, however, broad agreement that land use, and habitat fragmentation in particular, will pose serious impediments to species adaptation to climate change as it is projected to reduce the capacity of many species to track climate (see above). These considerations lead to the assessment that future species extinctions are a high risk because the consequences of climate change are potentially severe, widespread and irreversible since extinctions constitute the permanent loss of unique life forms.

There is, however, *low agreement* concerning the overall fraction of species at risk, the taxa and places most at risk, and the time scale for climate-change driven extinctions to occur. Part of this uncertainty arises from differences in extinction risks within and between modelling studies: this uncertainty has been evaluated in AR4 and subsequent syntheses (Pereira *et al.*, 2010; Warren *et al.*, 2011; Bellard *et al.*, 2012; Cameron, 2012). All studies project increased extinction risk by the end of the 21st century due to climate change, but as indicated in AR4 the range of estimates is large. Recent syntheses indicate that model-based estimates of the fraction of species at substantially increased risk of extinction due to 21st century climate change range from below 1% to above 50% of species in the groups that have been studied (Pereira *et al.*, 2010; Bellard *et al.*, 2012; Cameron, 2012; Foden *et al.*, 2013). Differences in modelling methods, species groups, and climate scenarios between studies make comparisons between estimates difficult (Pereira *et al.*, 2010; Warren *et al.*, 2011; Cameron, 2012).

Many papers published since AR4 argue that the uncertainty may be even higher than indicated in syntheses of model projections, due to limitations in the ability of current models to evaluate extinction risk (e.g., Kuussaari *et al.*, 2009; Pereira *et al.*, 2010; Dawson *et al.*, 2011; McMahon *et al.*, 2011; Pearson, 2011; Araujo and Peterson, 2012; Bellard *et al.*, 2012; Fordham *et al.*, 2012; Hannah, 2012; Kramer *et al.*, 2012; Zurell *et al.*, 2012; Halley *et al.*, 2013; Moritz and Agudo, 2013). Models frequently do not account for genetic and phenotypic adaptive capacity, dispersal capacity, population dynamics, the effects of habitat fragmentation and loss, community interactions, micro-refugia and the effects of rising CO_2 concentrations, all of which could play a major role in determining species vulnerability to climate change, causing models to either over- or under-estimate risk. In addition, difficulties in model validation, large variation in the climate sensitivity of species groups and uncertainties about timescales linking extinction risks to range reductions also lead to large uncertainty in model-based estimates of extinction risk.

A variety of studies since AR4 illustrate how accounting for these factors alters estimates of extinction risk. Accounting for biotic interactions such as pollination or predator-prey networks can increase modelled extinction risks, at least for certain areas and species groups (Schweiger *et al.*, 2008; Urban *et al.*, 2008; Hannah, 2012; Nakazawa and Doi, 2012), or can decrease extinction risk (Menéndez *et al.*, 2008; Pateman *et al.*, 2012).

Accounting for climatic variation at fine spatial scales may increase (Randin *et al.*, 2009; Gillingham *et al.*, 2012; Suggitt *et al.*, 2012; Dobrowski *et al.*, 2013; Franklin *et al.*, 2013) or decrease (Trivedi *et al.*, 2008; Engler *et al.*, 2011; Shimazaki *et al.*, 2012) the persistence of small populations under future climate change. Several recent studies indicate that correlative species distribution models (the type of model most frequently used for evaluating species extinction risk) tend to be much more pessimistic concerning plant species range contractions and the inferred extinction risks due to climate change when compared to mechanistic models that explicitly account for the interactions between climate change and protective effects of rising CO_2 concentrations on plants (Morin and Thuiller, 2009; Kearney *et al.*, 2010; Cheaib *et al.*, 2012). Models that account for population dynamics indicate that some species populations, like those of polar bears (Hunter *et al.*, 2010), will decline precipitously over the course of the next century due to climate change, greatly increasing extinction risk, while others may not (Keith *et al.*, 2008). Phenotypic plasticity in one very well-studied temperate bird population has been estimated to be sufficient to keep extinction risk low even with projected warming exceeding 2-3°C (Vedder *et al.*, 2013), but this and other studies suggest that capacity for adaptation is often substantially lower in species with long generation times (see Section 4.4.1.2). There is evidence that interactions between physiological tolerances and regional climate change will lead to large taxonomic and spatial variation in extinction risk (Deutsch *et al.*, 2008; Sinervo *et al.*, 2010). Even species whose populations are not projected to decline rapidly over the next century can face a substantial "extinction debt"; i.e., will be in unfavourable climates that over a period of many decades to many centuries, leading to large projected reductions in population size (Dullinger *et al.*, 2012). Finally, evidence from the paleontological record indicating very low extinction rates over the last several hundred thousand years of substantial natural fluctuations in climate — with a few notable exceptions such as large land animal extinctions during the Holocene — has led to concern that forecasts of very high extinction rates due entirely to climate change may be overestimated (Botkin *et al.*, 2007; Dawson *et al.*, 2011; Hof *et al.*, 2011a; Willis and MacDonald, 2011; Moritz and Agudo, 2013). However, as indicated in Section 4.2.3, no past climate changes are precise analogues of future climate change in terms of speed, magnitude and spatial scale; nor did they occur alongside the habitat modification, over-exploitation, pollution, and invasive species that are characteristic of the twenty-first century. Therefore the paleontological record cannot easily be used to assess future extinction risk due to climate change.

4.3.3. Impacts on and Risks for Major Systems

This section covers impacts of climate change on broad categories of terrestrial and freshwater ecosystems of the world. We have placed a particular emphasis on those ecosystems that have high exposure to climate change or that may be pushed past thresholds or "tipping points" by climate change.

Two geographical regions of particularly high risk have been identified in recent studies: i) tropics, due to the limited capacity of species to adapt to moderate global warming and ii) high northern latitude systems, because temperature increases are projected to be large. There has been a tendency to oppose these two points of view, but there is a high risk in *both* types of systems, albeit for different reasons (Corlett, 2011). Tropical species, which experienced low inter and intra-annual climate variability, have evolved within narrow thermal limits, and are already near their upper thermal limits (ectotherms: Deutsch *et al.*, 2008; Huey *et al.*, 2012; birds: Sekercioglu *et al.*, 2012; trees: Corlett, 2011). On this basis, tropical species and ecosystems are predicted to be more sensitive to climate change than species and ecosystems that have evolutionary histories of climatic variability (e.g., Arctic and boreal ecosystems; Beaumont *et al.*, 2011). However, there are physiological, evolutionary and ecological arguments that tropical species and ecosystem sensitivities to climate change are complex and may not be particularly high compared to other systems (Gonzalez *et al.*, 2010; Corlett, 2011; Laurance *et al.*, 2011; Gunderson and Leal, 2012; Walters *et al.*, 2012). High latitude systems have the greatest projected exposure to rising temperatures (WGI AR5 Chapter 12; Diffenbaugh and Giorgi, 2012), which all else being equal would put them at higher risk. The greatest degree of recent climate warming has occurred at high northern latitudes (Burrows *et al.*, 2011) and the strongest and clearest signals of recent climate warming impacts on ecosystems come from these regions. A comparison of modelled biome level vulnerability indicated that temperate and high northern latitude systems are also the most vulnerable in the future (Gonzalez *et al.*, 2010).

Several potential tipping points (see Section 4.2.1) with regional and global consequences have been identified (Scheffer, 2009); two are elaborated in Boxes 4-3 (Amazon die-back) and 4-4 (Tundra-boreal regime shift).

An assessment by the authors of this chapter of the top risks in relation to climate change and terrestrial and freshwater ecosystems, is presented in Table 4-3.

[INSERT TABLE 4-3 HERE
Table 4-3: Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three timeframes: the present, near-term (here, assessed over 2030-2040), and longer-term (here, assessed over 2080-2100). For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.]

4.3.3.1. Forests and Woodlands

Forests and woodlands are principal providers of timber, pulp, bioenergy, water, food, medicines and recreation opportunities and can play prominent roles in cultural traditions. Forests are the habitat of a large fraction of the earth's terrestrial plant and animal species, with the highest concentrations and levels of endemism found in tropical regions (Gibson *et al.*, 2011). Climate change and forests interact strongly; air temperature, solar radiation, rainfall and atmospheric CO_2 concentrations are major drivers of forest productivity and forest dynamics, and forests help control climate through the large amounts of carbon they can remove from the atmosphere or release, through absorption or reflection of solar radiation (albedo), cooling through evapotranspiration and the production of cloud-forming aerosols (Arneth *et al.*, 2010; Pan *et al.*, 2011; Pielke *et al.*, 2011).

Combinations of ground based observations, atmospheric carbon budgets and satellite measurements indicate with *high confidence* that forests are currently a net sink for carbon at the global scale. It is estimated that intact and regrowing forests currently contain 860±70 PgC and sequestered 4.0 ± 0.7 Pg C $year^{-1}$ globally between 2000 and 2007 (WGI AR5 Chapter 6; Canadell *et al.*, 2007; Pan *et al.*, 2011; Le Quéré *et al.*, 2012). The carbon taken up by intact and regrowing forests was counterbalanced by a release due to land-use change of 2.8±0.4 Pg C $year^{-1}$ over this same period due mostly to tropical deforestation and forest degradation associated with logging and fire, resulting in a net C balance for global forests of 1.1±0.8 Pg C $year^{-1}$.

The future of the interaction between climate and forests is unclear. The carbon taken up by intact and regrowing forests appears to have stabilized compared to the 1990s, after having increased in the 1970s and 1980s (Canadell *et al.*, 2007; Pan *et al.*, 2011). There is *medium confidence* that the terrestrial carbon sink is weakening. The drivers behind the forest carbon sink vary greatly across regions. They include forest regrowth and stimulation of C sequestration by climate change, rising atmospheric CO_2 concentrations and N deposition (Pan *et al.*, 2011; Sections 4.2.4.1; 4.2.4.2; 4.2.4.4). Most models suggest that rising temperatures, drought and fires will lead to forests becoming a weaker sink or a net carbon source before the end of the century (Sitch *et al.*, 2008; Bowman *et al.*, 2009). Fires play a dominant role in driving forest dynamics in many parts of the world; forest susceptibility to fire is projected to change little for the lowest emissions scenario (RCP 2.6), but substantially for the high emissions scenario (RCP 8.5, Figure 4-6). There is *low agreement* on whether climate change will cause fires to become more or less frequent in individual locations (Figure 4-6). Climate change-mediated disease and insect outbreaks could exacerbate climate-driven increases in fire susceptibility (Kurz *et al.*, 2008). The greatest risks for large positive feedbacks from forests to climate through changes in disturbance regimes arise from widespread tree mortality and fire in tropical forests and low latitude areas of boreal forests, as well as northward expansion of boreal forests into arctic tundra (Lenton *et al.*, 2008; Kriegler *et al.*, 2009; Good *et al.*, 2011b).

[INSERT FIGURE 4-6 HERE
Figure 4-6: Projected changes in meteorological fire danger, fire probability and fire frequency with different methods and climate models. (a)-(e) 30-year annual mean MacArthur Forest Fire Danger Index (FFDI) and change simulated with the HadGEM2-ES Earth System Model, with areas of no vegetation excluded (Betts *et al.*, 2013; (a) FFDI 1970-2000; (b) FFDI 2070-2100, RCP2.6; (c) change in FFDI by 2070-2100 relative to 1970-2000, RCP2.6;(d) FFDI 2070-2100; RCP8.5 (e) change in FFDI by 2070-2100 relative to 1970-2000, RCP8.5. (f) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the GISS GCM and IMAGE IAM (Pechony and Shindell, 2010). (g) Change in fire frequency by 2051-2100 relative to 1951-2000, SRES A1B, simulated with the MC1 vegetation model driven by 3 GCMs (CSIRO-Mk3.0, HadCM3, MIROC 3.2medres; mean over 3 simulations; Gonzalez et al., 2010). (h) Agreement on changes in fire probability simulated with a statistical model using climate projections from 16 CMIP3 GCMs, SRES A2 (i) Change in fire frequency by 2100 relative to 2004, SRES A2, simulated using climate and land cover projections from the GISS GCM (AR4 version) and IMAGE IAM (Pechony and Shindell, 2010). Changes in FFDI (a)-(e) and fire probability (h) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (f) (g) (i) depend on both meteorological quantities and vegetation.]

Recent evidence suggests (*low confidence*) that the stimulatory effects of global warming and rising CO_2 concentrations on tree growth may have already peaked in many regions (Charru *et al.*, 2010; Silva *et al.*, 2010; Silva and Anand, 2013) and that warming and changes in precipitation are increasing tree mortality in a wide range of forest systems, acting *via* heat stress, drought stress, pest outbreaks and a wide range of other indirect impact mechanisms (Allen *et al.*, 2010a; Box 4-2). Detection of a coherent global signal is hindered by the lack of long-term observations in many regions, and attribution to climate change is difficult due to the multiplicity of mechanisms mediating mortality (Allen *et al.*, 2010a).

Deforestation has slowed over the last decade (Meyfroidt and Lambin, 2011). This includes substantial reductions in tropical deforestation in some regions, such as the Brazilian Amazon, where deforestation rates declined rapidly after peaking in 2005 (Nepstad *et al.*, 2009; INPE, 2013). Growing pressure for new crop (Section 4.4.4) and grazing land will continue to drive tropical deforestation (*medium confidence*) although recent policy experiments and market-based interventions in land use demonstrate the potential to reduce deforestation (Meyfroidt and Lambin, 2011; Westley *et al.*, 2011; Nepstad *et al.*, 2013).

_____ START BOX 4-2 HERE _____

Box 4-2. Tree Mortality and Climate Change

Extensive tree mortality and widespread forest dieback (high mortality rates at a regional scale) linked to drought and temperature stress have been documented recently on all vegetated continents (Allen *et al.*, 2010a; Figure 4-7). However, appropriate field data sets are currently lacking for many regions (Anderegg *et al.*, 2013a), leading to *low confidence* in our ability to detect a global trend. Nevertheless, long-term increasing tree mortality rates associated with temperature increases and drought have been documented in boreal and temperate forests in western North America (van Mantgem *et al.*, 2009; Peng *et al.*, 2011). Increased levels of tree mortality following drought episodes have also been detected in multiple tropical forests (Kraft *et al.*, 2010; Phillips *et al.*, 2010) and Europe (Carnicer *et al.*, 2011). Episodes of widespread die-back (high mortality rates at a regional scale) have been observed in multiple vegetation types, particularly in western North America, Australia, and southern Europe (Raffa *et al.*, 2008; Carnicer *et al.*, 2011; Anderegg *et al.*, 2013a). Some widespread die-back events have occurred concomitant with infestation outbreaks (Hogg *et al.*, 2008; Michaelian *et al.*, 2011; Raffa *et al.*, 2008), where insect populations are also directly influenced by climate, such as population release by warmer winter temperatures (Bentz *et al.*, 2010). While strong attribution of extensive tree mortality to recent warming has been made in a few studies, the paucity of long-term studies of the mechanisms driving mortality means that there is *low confidence* that this attribution can be made at the global scale.

Forest dieback has influenced the species composition, structure and age demographics, and successional trajectories in affected forests, and in some cases led to decreased plant species diversity and increased risk of invasion (Kane *et* *al.*, 2011; Anderegg *et al.*, 2012). Widespread tree mortality also has multiple effects on biosphere-atmosphere interactions and could play an important role in future carbon-cycle feedbacks through complex effects on forest biophysical properties and biogeochemical cycles (Breshears *et al.*, 2005; Kurz *et al.*, 2008; Anderson *et al.*, 2011).

Projections of tree mortality due to climate stress and potential thresholds of widespread forest loss are currently highly uncertain (McDowell *et al.*, 2011). Most current vegetation models have little-to-no mechanistic representation of tree mortality (Fisher *et al.*, 2010; McDowell *et al.*, 2011). Nonetheless, a global analysis of tree hydraulic safety margins found that 70% of surveyed tree species operate close to their limits of water stress tolerance (Choat *et al.*, 2012), indicating that vulnerability to drought and temperature stress will not be limited to arid and semi-arid forests. Furthermore, timescales of tree and plant community recovery following drought are largely unknown, but preliminary evidence from several forests indicates that full recovery times may be longer than drought return intervals, leading to "compounding" effects of multiple droughts (Mueller *et al.*, 2005; Anderegg *et al.*, 2013b; Saatchi *et al.*, 2013). Projected increases in temperature are also expected to facilitate expansion of insect pest outbreaks poleward and in altitude which may also cause or contribute to tree mortality (Bentz *et al.*, 2010).

[INSERT FIGURE 4-7 HERE
Figure 4-7: Locations of substantial drought- and heat-induced tree mortality around the globe since 1970 (global forest cover and other wooded regions based on FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen *et al.* (2010a). Localities and measurement networks not included in Allen *et al.* (2010a), which are largely from post-2009 publications, have been added to this map (white dots and shapes). New locality references by region: Africa – Mehl *et al.*, 2010, van der Linde *et al.*, 2011; Fauset *et al.*, 2012; Gonzalez *et al.*, 2012; Kherchouche *et al.*, 2012; Asia – Dulamsuren *et al.*, 2009; Kharuk *et al.*, 2013; Liu *et al.*, 2013; Zhou *et al.*, 2013; Australasia – Brouwers *et al.*, 2012; Fensham *et al.*, 2012; Keith *et al.*, 2012; Matusick *et al.*, 2012; Brouwers *et al.*, 2013; Matusick *et al.*, 2013; Europe – Innes, 1992; Peterken and Mountford, 1996; Linares *et al.*, 2009; Galiano *et al.*, 2010; Vennetier and Ripert, 2010; Aakala *et al.*, 2011; Carnicer *et al.*, 2011; Linares *et al.*, 2011; Sarris *et al.*, 2011; Marini *et al.*, 2012; Cailleret *et al.*, 2013; Vilà-Cabrera *et al.*, 2013; North America – Fahey, 1998; Minnich, 2007; Klos *et al.*, 2009; Ganey and Vojta, 2011; Michaelian *et al.*, 2011; Peng *et al.*, 2011; DeRose and Long, 2012; Fellows and Goulden, 2012; Kaiser *et al.*, 2012; Millar *et al.*, 2012; Garrity *et al.*, 2013; Kukowski *et al.*, 2013; Williams *et al.*, 2013; Worrall *et al.*, 2013; South America – Enquist and Enquist, 2011; Lewis *et al.*, 2011; Saatchi *et al.*, 2013.]

_____ END BOX 4-2 HERE _____

4.3.3.1.1. Boreal forests

Most projections suggest a poleward expansion of forests into tundra regions, accompanied by a general shift in composition towards more temperate plant functional types (e.g., evergreen needleleaf being replaced by deciduous broadleaf; or in colder regions, deciduous needleleaf replaced by evergreen needleleaf (Lloyd *et al.*, 2011; Pearson *et al.*, 2013). Projections of climate-driven changes in boreal forests over the next few centuries remain uncertain on some issues, partly as a result of different processes of change being considered in different models. In particular, the inclusion or exclusion of fire and insects makes a big difference, possibly making the boreal forest more susceptible to a rapid, non-linear or abrupt decline in some regions (Bernhardt *et al.*, 2011; Mann *et al.*, 2012; Scheffer *et al.*, 2012; see WGI AR5 Chapter 12). Recent observed change (Box 4-2) and dynamic vegetation modelling (e.g., Sitch *et al.*, 2008) suggest that regions of the boreal forest could experience widespread forest dieback, although there is *low confidence* due to conflicting results (Sitch *et al.*, 2008; Gonzalez *et al*, 2010) and poor understanding of relevant mechanisms (WG1 AR5 Section 12.5.5.6.2). If such shifts were to occur, they would put the boreal carbon sink at risk (Pan *et al.*, 2011; Mann *et al.*, 2012).

Whereas boreal forest productivity has been expected to increase as a result of warming (Hari and Kulmata, 2008; Bronson *et al.*, 2009; Zhao and Running, 2010; Van Herk *et al.*, 2011), and early analyses of satellite observations confirmed this trend in the 1980s (*medium confidence*), more recent and longer-term assessments indicate with *high confidence* that many areas of boreal forest have instead experienced productivity declines (*high confidence*, Goetz *et al.*, 2007; Parent and Verbyla, 2010; Beck *et al.*, 2011b; de Jong *et al.*, 2011). The best evidence to date indicates that these “browning trends” are due to warming-induced drought, specifically the greater drying power of air (vapour pressure deficit, Williams *et al.*, 2013), inducing photosynthetic down-regulation of boreal tree species, particularly conifer species, most of which are not adapted to the warmer conditions (Welp *et al.*, 2007; Bonan, 2008; Van Herk *et al.*, 2011). Satellite evidence for warming-induced productivity declines has been corroborated by tree ring studies (Barber *et al.*, 2000; Hogg *et al.*, 2008; Beck *et al.*, 2011b; Porter and Pisaric, 2011; Griesbauer and Green, 2012) and long-term tree demography plots in more continental and densely forested areas (Peng *et al.*, 2011; Ma *et al.*, 2012). Conversely, productivity has increased at the boreal-tundra ecotone where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (Rupp *et al.*, 2001; McGuire *et al.*, 2007; Goldblum and Rigg, 2010; Beck *et al.*, 2011b). The complexity of boreal forest response also involves tree age and size, with younger trees and stands perhaps being more able to benefit from warming where other factors are not limiting (Girardin *et al.*, 2011; Girardin *et al.*, 2012).

Where they occur, warming and drying, coupled with productivity declines, insect disturbance and associated tree mortality, also favour greater fire disturbance (*high confidence*). The boreal biome fire regime has intensified regionally in recent decades, exemplified by increases in the extent of area burned but also a longer fire season and more episodic fires that burn with greater energy output or intensity (Girardin and Mudelsee, 2008; Macias Fauria and Johnson, 2008; Kasischke *et al.*, 2010; Turetsky *et al.*, 2011; Mann *et al.*, 2012; Girardin *et al.*, 2013a). The latter is particularly important because more severe burning consumes soil organic matter to greater depth, often to mineral soil, providing conditions that favour recruitment of deciduous species that in some regions of the North American boreal forest replace what was previously evergreen conifer forest (Johnstone *et al.*, 2010; Bernhardt *et al.*, 2011). Fire-mediated composition changes in post-fire succession influence a host of ecosystem feedbacks to climate, including changes in net ecosystem carbon balance (Bond-Lamberty *et al.*, 2007; Goetz *et al.*, 2007; Welp *et al.*, 2007; Euskirchen *et al.*, 2009) as well as albedo and energy balance (Randerson *et al.*, 2006; Jin *et al.*, 2012; O'Halloran *et al.*, 2012). The extent to which the net effect of these feedbacks will exacerbate or mitigate additional warming is not well known over the larger geographic domain of the boreal biome, except via modelling studies that are relatively poorly constrained due to sparse *in situ* observations.

The vulnerability of the boreal biome to this cascading series of interacting processes (Wolken *et al.*, 2011), and their ultimate influence on climate feedbacks, differs between North America and northern Eurasia (*high confidence*). The latter is dominated by deciduous conifer (larch) forest, extending from western Russia across central to eastern Siberia – a region more than twice the size of the North American boreal biome, most of it underlain by permafrost. In terms of post-fire succession analogous to the North American boreal biome, larch function more like deciduous species than evergreen conifers, with greater density and biomass gain in more severely burned areas, given adequate seed survival through fire events or post-fire seed dispersal (Zyryanova, 2007; Osawa *et al.*, 2010; Alexander *et al.*, 2012). Although the fire regime has intensified in the last 100 years in Siberia, as well as in parts of North America (Soja *et al.*, 2007; Ali *et al.*, 2012; Mann *et al.*, 2012; Marlon *et al.*, 2013), the likelihood of regime shifts in larch forests is currently unknown, partly because larch are self-replacing (albeit at different densities) and partly because it is largely dependent on the fate of permafrost across the region. In summary, an increase in tree mortality is observed in many boreal forests, with the clearest indicators of this in North America. However, tree health in boreal forests varies greatly among regions, which coupled with insufficient temporal coverage means that there is *low confidence* in the detection and attribution of a clear temporal trend in tree morality at the global scale (Figure 4-4).

The vulnerability of permafrost to thawing and degradation with climate warming is critical not only for determining the rate of a boreal-tundra biome shift and its associated net feedback to climate, but also for predicting the degree to which the mobilization of very large carbon stores frozen for centuries could provide additional warming (*high confidence*; Schuur *et al.*, 2008; 2009; Tarnocai *et al.*, 2009; Romanovsky *et al.*, 2010; Schaefer *et al.*, 2011; see WGI AR5 Chapters 6 and 12; see also Section 4.3.3.4). The extent and rate of permafrost degradation varies with temperature gradients from warmer discontinuous permafrost areas to colder, more continuous areas; but also with the properties of the soil composition and biology (e.g., Mackelprang *et al.*, 2011). The degree of thermokarsting (melting of ice-rich soil) associated with different substrates and associated topographic relief is variable because boreal vegetation in latter successional stages (evergreen conifers in North America) insulate permafrost from air temperature increases; soils with differing silt and gravel content tend to have different ice content that, when melted, produces different degradation and deformation rates; and other factors such as the reduction of insulation provided by vegetation cover and soil organic layers due to increased fire (Jorgenson *et al.*, 2010; Grosse *et al.*, 2011). This variability and vulnerability is poorly represented in earth system models (McGuire *et al.*, 2012) and is thus the emphasis of research initiatives currently underway. Carbon management strategies to keep permafrost intact, for example by removing forest cover to expose the land surface to winter temperatures (Zimov *et al.*, 2009), are impractical, not only because of the vast spatial domain underlain by permafrost, but also because of the broad societal and ecological impacts that would result.

4.3.3.1.2. Temperate forests

The largest areas of temperate forest are found in eastern North America, Europe and eastern Asia. The overall trend for forests in these regions has until recently been an increase in growth rates of trees and in total carbon stocks. This has been attributed to a combination of increasing growing season length, rising atmospheric CO_2 concentrations, nitrogen deposition and forest management – specifically regrowth following formerly more intensive harvesting regimes (Ciais *et al.*, 2008). The relative contribution of these factors has been the subject of substantial and unresolved debate (Boisvenue and Running, 2006). Most temperate forests are managed such that any change is and will be to a large extent anthropogenic.

The world's temperate forests act as an important carbon sink (*high confidence* due to *robust evidence and high agreement)*, absorbing 0.7±0.08 Pg C year^{-1} from 1990 to 1999 and 0.8±0.09 from 2000 to 2007 (Pan *et al.*, 2011).This represents 34% of global carbon accumulation in intact forests and 65% of the global net forest carbon sink (total sink minus total emissions from land use).

Recent indications are that temperate forests and trees are beginning to show signs of climate stress, including a reversal of tree growth enhancement in some regions (North America: Silva *et al.*, 2010; Silva and Anand, 2013; Europe: Charru *et al.*, 2010; Bontemps *et al.*, 2011; Kint *et al.*, 2012), increasing tree mortality (Allen *et al.*, 2010a; Box 4-2), and changes in fire regimes, insect outbreaks and pathogen attacks (Adams *et al.*, 2012; Edburg *et al.*, 2012). In north-eastern France, widespread recent declines in growth rates of European beech (*Fagus sylvatica L.*) have been attributed to decreasing water availability (Charru *et al.*, 2010). These trends threaten the substantial role of temperate forests as net carbon sinks, but it is still unclear to what extent the observations are representative for temperate forests as a whole. Several studies find that tree growth rates in temperate forests passed their peak in the late 20th century and that the decline in tree growth rates can be attributed to climatic factors, especially drought or heatwaves (Charru *et al.*, 2010; Silva *et al.*, 2010). Extreme climate events have had a major impact on temperate forests over the last decade (Ciais *et al.*, 2005; Witte *et al.*, 2011; Kasson and Livingston, 2012). Extensive forest fires occurred in Russia during the exceptionally hot and dry summer of 2010 (Witte *et al.*, 2011). The complex interactions between climate and forest management in determining susceptibility to extreme events make it difficult to unequivocally attribute these events to recent climate warming (Allen *et al.*, 2010a). There is *low confidence (limited evidence; medium agreement)* that climate change is threatening the temperate forest carbon sink directly or indirectly.

At the biome level, there remains considerable uncertainty in the sign and the magnitude of the carbon cycle response of temperate forests to climate change. A comparison of DGVM models showed that for identical end of 21st century climate projections, temperate forests are variously projected to substantially increase in total (biomass plus soil) carbon storage, especially through gains in forest cover; or decrease due to reductions in total carbon storage per hectare and loss of tree cover (Sitch *et al.*, 2008). Projections for eastern Asia are less variable: temperate forests remain carbon sinks over the coming century, with carbon storage generally peaking by mid-century and then declining (He *et al.*, 2007; Sitch *et al.*, 2008; Peng *et al.*, 2009; Ni, 2011). However, regional vegetation models for China predict a substantial northward shift of temperate forest (Weng and Zhou, 2006; Ni, 2011). There is little indication from either models or observations that the responses of temperate forests to climate change are characterized by tipping points (Bonan, 2008). There is *low confidence (medium evidence, low agreement)* on long-term, climate-driven changes in temperate forest biomass and geographical range shifts.

At the species level, models predict that the potential climatic space for most tree species will shift poleward and to higher altitude in response to climate change (Dale *et al.*, 2010; Ogawa-Onishi *et al.*, 2010; Hickler *et al.*, 2012).

Associated long-term projected range shifts generally vary from several km to several tens of km per decade, most probably faster than natural migration (e.g., Chmura *et al.*, 2011; see also Section 4.3.2.5). Therefore, assisted migration has been suggested as an adaptation measure (see Section 4.4.2.4). Such shifts would alter biodiversity and ecosystem services from temperate forests (e.g., Dale *et al.*, 2010). Multi-model comparisons for temperate forests, however, illustrate that there are differences in species response and that models differ greatly in the severity of projected climate change impacts on species ranges (Morin and Thuiller, 2009; Kearney *et al.*, 2010; Kramer *et al.*, 2010; Cheaib *et al.*, 2012). Tree growth models project increased tree growth at the poleward and high altitudinal range limits over most of the 21st century in China (Ni, 2011). New approaches to modelling tree responses, based on the sensitivity of key life-history stages, suggest that climate change impacts on reproduction could be a major limitation on temperate tree distributions (Morin *et al.*, 2007). Comparisons with paleoecological data have helped improve confidence in the ability of models to project future changes in species ranges (Pearman *et al.*, 2008; Allen *et al.*, 2010b; Garreta *et al.*, 2010). Model projections are qualitatively coherent with observations that temperate forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Lenoir *et al.*, 2008). There is *medium confidence (medium evidence, medium agreement)* that temperate tree species are migrating poleward and to higher altitudes.

4.3.3.1.3. Tropical forests

Climate change effects on tropical forests interact with the direct influences of humans and are understood largely through field studies of the responses of forests to extreme weather events and through models that are able to simulate a growing number of ecological and atmospheric processes (Malhi *et al.*, 2008; Davidson *et al.*, 2012).

A key uncertainty in our understanding of future impacts of climate change on tropical forests is the strength of direct CO_2 effects on photosynthesis and transpiration (see Section 4.3.2.4). These responses will play an important role in determining tropical forest trends as temperatures and atmospheric CO_2 concentrations rise. There is a physiological basis for arguing that photosynthesis will increase sufficiently to offset the inhibitory effects of higher temperatures on forest productivity (Lloyd and Farquhar, 2008) although heightened photosynthesis does not necessarily translate into an increase in overall forest biomass (Körner and Basler, 2010). DGVMs and the current generation of Earth System Models, including those used within CMIP5 (e.g., Jones *et al.*, 2011; Powell *et al.*, 2013) generally use formulations for CO_2 effects on photosynthesis and transpiration based on laboratory-scale work (Jarvis, 1976; Farquhar *et al.*, 1980; Ball *et al.*, 1987; Stewart, 1988; Collatz *et al.*, 1992; Leuning, 1995; Haxeltine and Prentice, 1996; Cox *et al.*, 1998) that pre-dates larger ecosystem-scale studies, although some models have been calibrated on the basis of more recent data (Jones *et al.*, 2011).

A second important source of uncertainty is the rate of future CO_2 rise and climate change (Betts *et al.*, 2012). Modelled simulations of future climate in tropical forest regions indicate with *high confidence (robust evidence, high agreement*) that temperature will increase. Future precipitation change, in contrast, is highly uncertain and varies considerably between climate models (WGI AR5 Annex 1: Atlas of Global and Regional Climate Projections), although there is *medium confidence* (*medium evidence, medium agreement*) that some tropical regions, such as the eastern Amazon Basin, will experience lower precipitation and more severe drought (Malhi *et al.*, 2009a; Shiogama *et al*. 2011). The range of possible shifts in the moist tropical forest envelope is large, sensitive to the responsiveness of water use efficiency (WUE) to rising concentrations of atmospheric CO_2, and varies depending on the climate and vegetation model that is used (Scholze *et al.*, 2006; Zelazowski *et al.*, 2011) (Sitch *et al.*, 2008). Recent model studies (Malhi *et al.*, 2009a; Cox *et al.*, 2013; Huntingford *et al.*, 2013) indicate that the future geographical range of moist tropical forests as determined by its shifting climatological envelope is less likely to undergo major retractions or expansions by 2100 than was suggested in AR4. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with sea surface temperature increases in the tropical North Atlantic (*medium confidence*, Marengo et al. 2010). There is *low confidence*, however, that these droughts or the observed sea surface temperatures can be attributed to climate change.

Networks of long-term forest plots reveal that lianas and fast-growing tree species are increasing, as is forest biomass (Phillips *et al.*, 2002; Phillips *et al.*, 2005; Lewis *et al.*, 2009a; Lewis *et al.*, 2009b; Lewis *et al.*, 2011). Faster tree growth is consistent with increasing WUE associated with the rising concentration of CO_2, but also with changes in solar radiation and the ratio of diffuse to direct radiation (Lewis *et al.*, 2009a; Mercado *et al.*, 2009; Brando *et al.*, 2010; Section 4.2.4.5). There is *low confidence* (*limited evidence, medium agreement*) that the composition and biomass of Amazon and African forests are changing through the rise in atmospheric CO_2. The potential suppression of photosynthesis and tree growth in tropical forests through rising air temperatures is supported by physiological and eddy covariance studies (Doughty and Goulden, 2008; Lloyd and Farquhar, 2008; Wood *et al.*, 2012), but is not yet observed as changes in forest biomass (except Clark *et al.*, 2003).

Since AR4, there is new experimental and observational evidence of ecological thresholds of drought and fire in moist tropical forests that points to an important indirect role of climate change in driving large-scale changes in these ecosystems, and to the importance of extreme drought events (see Box 4-3). Forest tree mortality increased abruptly above a critical level of soil moisture depletion in two rainfall exclusion experiments (Nepstad *et al.*, 2007; Fisher *et al.*, 2008) and above a critical level of weather-related fire intensity in a prescribed burn experiment (Brando *et al.*, 2012). These experimental results were corroborated by observations of increased tree mortality during the severe 2005 drought in the Amazon (Phillips *et al.*, 2009) and extensive forest fire (Alencar *et al.*, 2006; Aragão *et al.*, 2008; Alencar *et al.*, 2011; Box 4-3). There is *high confidence* (*medium evidence, high agreement*) that moist tropical forests have many tree species that are vulnerable to drought- and fire-induced mortality during extreme dry periods.

There is also a growing body of evidence that severe weather events interact with land use to influence moist tropical forest fire regimes. Many moist tropical forests are not susceptible to fire during typical rainfall years because of high moisture content of fine fuels (Cochrane, 2003). Selective logging, drought, and fire itself, can reduce this fire resistance by killing trees, thinning the canopy and allowing greater heating of the forest interior (Uhl and Kauffman, 1990; Curran *et al.*, 2004; Ray *et al.*, 2005; Box 4-3). Land use also often increases the ignition sources in tropical landscapes (Silvestrini *et al.*, 2011). These relationships are not yet represented fully in coupled climate-vegetation models. There is *high confidence* (*robust evidence, high agreement*) that forest fire frequency and severity is increasing through the interaction between severe droughts and land use. There is *medium confidence* (*medium evidence, high agreement*) that tree mortality in the Amazon region is increasing through severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (Figure 4-4).

Dry tropical forests are defined by strong seasonality in rainfall distribution (Mooney *et al.*, 1995) and have been reduced to an estimated one million km^2 globally through human activities (Miles *et al.*, 2006). Half of the world's remaining dry tropical forests are located in South America. Using five climate model simulations for the 2040-2069 period under the IS92a "business as usual scenario", Miles et al. (2006) found that approximately one third of the remaining area of tropical dry forests in the Americas will be exposed to higher temperatures and lower rainfall through climate change. Climate change, deforestation, fragmentation, fire, or human pressure place virtually all (97%) of the remaining tropical dry forests at risk of replacement or degradation (Miles *et al.*, 2006). In a regional study a dynamic vegetation model (IBIS) under A2 and B2 scenarios projected by a global climate model (HADRM3) found that most of the dry forests of India would be outside of their climate envelopes later this century (Chaturvedi *et al.*, 2011). There is *low confidence* in our understanding of climate change effects on dry forests globally.

_____ START BOX 4-3 HERE _____

Box 4-3. A Possible Amazon Basin Tipping Point

Since AR4, our understanding of the potential of a large-scale, climate-driven, self-reinforcing transition of Amazon forests to a dry stable state (known as the Amazon "forest dieback") has improved. Modelling studies indicate that the likelihood of a climate-driven forest dieback by 2100 is lower than previously thought (Malhi *et al.*, 2009b; Cox *et al.*, 2013; Good *et al.*, 2013; Huntingford *et al.*, 2013), although lower rainfall and more severe drought is expected in the eastern Amazon (Malhi *et al.*, 2009a). There is now *medium confidence* (*medium evidence, medium agreement*) that climate change alone (that is, through changes in the climate envelope, without invoking fire and land use) will not drive large-scale forest loss by 2100 although shifts to drier forest types are predicted in the eastern Amazon (Mahli et al. 2009a). Meteorological fire danger is projected to increase (Golding and Betts, 2008; Betts *et al.*, 2013; Figure 4-6). Field studies and regional observations have provided new evidence of critical ecological thresholds and positive feedbacks between climate change and land-use activities that could drive a fire-mediated, self-reinforcing dieback during the next few decades (Figure 4-8). There is now *medium confidence* (*medium evidence, high agreement*) that severe drought episodes, land use, and fire interact synergistically to drive the transition of mature Amazon forests to low-biomass, low-statured fire-adapted woody vegetation.

Most primary forests of the Amazon Basin have damp fine fuel layers and low susceptibility to fire, even during annual dry seasons (Uhl and Kauffman, 1990; Ray *et al.*, 2005). Forest susceptibility to fire increases through canopy thinning and greater sunlight penetration caused by tree mortality associated with selective logging (Uhl and Kauffman, 1990; Ray *et al.*, 2005; Barlow and Peres, 2008), previous forest fire (Balch *et al.*, 2008; Brando *et al.*, 2012), severe drought (Alencar *et al.*, 2006), or drought-induced tree mortality (Nepstad *et al.*, 2007; da Costa *et al.*, 2010). The impact of fire on tree mortality is also weather-dependent. Under very dry, hot conditions, fire-related tree mortality can increase sharply (Brando *et al.*, 2012). Under some circumstances, tree damage is sufficient to allow light-demanding, flammable grasses to establish in the forest understory, increasing forest susceptibility to further burning (Veldman and Putz, 2011). There is *high confidence* (*robust evidence, high agreement*) that logging, severe drought, and previous fire increase Amazon forest susceptibility to burning.

Landscape level processes further increase the likelihood of forest fire. Fire ignition sources are more common in agricultural and grazing lands than in forested landscapes (Silvestrini *et al.*, 2011) (*high confidence: robust evidence, high agreement*), and forest conversion to grazing and crop lands can inhibit regional rainfall through changes in albedo and evapotranspiration (Costa *et al.*, 2007; Butt *et al.*, 2011; Knox *et al.*, 2011) (*low confidence: medium evidence, low agreement*) or through smoke, that can inhibit rainfall under some circumstances (Andreae *et al.*, 2004) (*medium confidence*: *medium evidence, medium agreement*). Apart from these landscape processes, climate change could increase the incidence of severe drought episodes (Mahli et al. 2009b; Shiogama *et al.*, 2011).

If recent patterns of deforestation (through 2005), logging, severe drought, and forest fire continue into the future, more than half of the region's forests will be cleared, logged, burned or exposed to drought by 2030, even without invoking positive feedbacks with regional climate, releasing 20±10 Pg of carbon to the atmosphere (Nepstad *et al.*, 2008) (*low confidence: low evidence, medium agreement*) (Figure 4-8). The likelihood of a tipping point being reached may decline if extreme droughts (such as 1998, 2005, and 2010) (Marengo *et al.*, 2011) become less frequent, if land management fires are suppressed, if forest fires are extinguished on a large scale (Soares-Filho *et al.*, 2012), if deforestation declines, or if cleared lands are reforested (Nepstad *et al.*, 2008). The 77% decline in deforestation in the Brazilian Amazon with 80% of the region's forest still standing (INPE, 2013) demonstrates that policy-led avoidance of a fire-mediated tipping point is plausible.

[INSERT FIGURE 4-8 HERE
Figure 4-8: The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (*medium confidence; medium evidence, medium agreement).*]

_____ END BOX 4-3 HERE _____

4.3.3.2. Dryland Ecosystems: Savannas, Shrublands, Grasslands, and Deserts

The following sections treat a wide range of terrestrial ecosystems covering a large part of the land surface, whose common features are that they typically exhibit strong water stress for several months each year and grass-like plants and herbs are a major part of their vegetation cover. Thus the principle land use often involves grazing by domestic livestock or wild herbivores.

4.3.3.2.1. Savannas

Savannas are mixtures of coexisting trees and grasses, covering about a quarter of the global land surface, including tropical and temperate forms. Savannas are characterized by annual to decadal fires (Archibald *et al.*, 2009) of relatively low intensity, which are an important factor in maintaining the tree-grass proportions (Beerling and Osborne, 2006), but also constitute a major and climate-sensitive global source of fire-related emissions from land to atmosphere (Schultz *et al.*, 2008; van der Werf *et al.*, 2010). The geographical distribution of savannas is determined by temperature, the seasonal availability of water, fire and soil conditions (Ellery *et al.*, 1991; Walker and Langridge, 1997; Staver *et al.*, 2011) and is therefore inferred to be susceptible to climate change. In parts of Central Africa, forests have been observed to be moving into adjacent savannas and grasslands (Mitchard *et al.*, 2009), possibly due to depopulation and changes in the fire regime. In northern Australia, forest is expanding into former savanna areas (Brook and Bowman, 2006; Bowman *et al.*, 2011; Tng *et al.*, 2012). It has been projected that drying and greater seasonality, acting in conjunction with increased fire, could lead to former forested areas becoming savannas in parts of the Amazon basin (Malhi *et al.*, 2009b; Box 4-3) In many places around the world the savanna boundary is moving into former grasslands on elevation gradients, in other words into areas inferred to be formerly too cool for trees (Breshears, 2006).

The proportion of trees and grasses in savannas is considered unstable under some conditions (DeMichele *et al.*, 2011; Staver *et al.*, 2011; Wake, 2012). The differential effects of climate change, rising CO_2, fire and herbivory on trees and grasses have the potential to alter the cover of trees savannas, possibly abruptly. There is evidence from many parts of the world that the tree cover and biomass in savannas has increased over the past century and in some places, on all continents, continues to do so (*high agreement, robust evidence*, Moleele *et al.*, 2002; Angassa and Oba, 2008; Cabral *et al.*, 2009; Wigley *et al.*, 2009; Witt *et al.*, 2009; Lunt *et al.*, 2010; Rohde and Hoffman, 2012). The general consequences are more carbon stored per unit land area in form of tree biomass and soil organic matter (Hughes *et al.*, 2006; Liao *et al.*, 2006; Knapp *et al.*, 2007; Throop and Archer, 2008; Boutton *et al.*, 2009), changes in hydrology (Muñoz-Robles *et al.*, 2011) and reduced grazing potential (Scholes and Archer, 1997). Increasing tree cover in savannas has been attributed to changes in land management (Joubert *et al.*, 2008; Van Auken, 2009), rising CO_2 (Bond and Midgley, 2012; Buitenwerf *et al.*, 2012), climate variability and change (Eamus and Palmer, 2007; Fensham *et al.*, 2009) or two or more of these factors acting in combination (Ward, 2005; Bond *et al.*, 2008). As yet, there are no studies that definitively attribute the relative importance of the climate- and non-climate-related causes of woody plant biomass increase in savannas (and the invasion of trees into former grasslands), but there is *medium agreement* and *robust evidence* that climate change and rising CO_2 are contributing factors in many cases. The increased growth rate of C3 photosynthetic system trees relative to C4 grasses under by rising CO_2 could relieve the demographic bottleneck that keeps trees trapped within the flame zone of the grasses, a hypothesis supported by elevated CO_2 experiments with savanna saplings (Kgope *et al.*, 2010).

A model of grasslands, savannas and forests suggests that rising CO_2 does increase the likelihood of abrupt shifts to woodier states, but the transition will take place at different CO_2 concentrations in different environments (Higgins and Scheiter, 2012). On the other hand, observation of contrasts in the degree of savanna thickening between land parcels with the same CO_2 exposure but different land use histories, topographic position or soil depth (Wiegand *et al.*, 2005; Wu and Archer, 2005) imply that land management, water balance and microclimate are also important. Tree cover in savannas is rainfall-constrained (Sankaran *et al.*, 2005), suggesting that future increases in rainfall projected for most but not all savanna areas (WGI AR5 Annex I: Atlas of Global and Regional Climate Projections) – could lead to increased tree biomass.

4.3.3.2.2. Grasslands and shrublands

Rangelands (partly overlapping with savannas, above) cover approximately 30% of the earth's ice-free land surface and hold an equivalent amount of the world's terrestrial carbon (Booker *et al.*, 2013). Much evidence from around the world shows that dry grasslands and shrublands are highly responsive in terms of primary production, species composition and carbon balance to changes in water balance (precipitation and evaporative demand) within the range of projected climate changes (*robust evidence and confidence*) (e.g., Sala *et al.*, 1988; Snyman and Fouché, 1993; Fay *et al.*, 2003; Peñuelas *et al.*, 2004, 2007; Prieto *et al.*, 2009; Peters *et al.*, 2010; Martí-Roura *et al.*, 2011; Booker *et al.*, 2013; Wu and Chen, 2013). Rainfall amount and timing have large effects on a wide range of biological processes in grasslands and shrublands, including seed germination, seedling establishment, plant growth, flowering time, root mass, community composition, population and community dynamics production, decomposition and respiration, microbial processes and carbon, plant and soil nutrient contents (e.g., Fay *et al.*, 2003; Peñuelas *et al.*, 2004; Peñuelas *et al.*, 2007; Beier *et al.*, 2008; Sardans *et al.*, 2008a; Sardans *et al.*, 2008b; Sowerby *et al.*, 2008; Liu *et al.*, 2009; Miranda *et al.*, 2009; Albert *et al.*, 2011; Albert *et al.*, 2012; Selsted *et al.*, 2012; Walter *et al.*, 2012).

Precipitation changes were as important for mountain flora in Europe as temperature changes, and the greatest composition changes will probably occur when decreased precipitation accompany warming (Engler *et al.*, 2011). Responses of shrublands to drought may partly be driven by changes in the soil microbial community (Jensen *et al.*, 2003) or changes in soil fauna (Maraldo *et al.*, 2008). An increase in drought frequency, without an increase in drought severity, leads to loss of soil carbon in moist, carbon-rich moorlands, due to changes in soil structure or soil microbial community leading to increased hydrophobicity and soil respiration (Sowerby *et al.*, 2008; Sowerby *et al.*, 2010). Simulated increased spring temperature and decreased summer precipitation had a general negative effect on plant survival and plant growth, irrespective of the macroclimatic niche characteristics of the species. Against expectation, species with ranges extending into drier regions did not generally perform better under drier conditions (Bütof *et al.*, 2012).

Changing climate and land use have resulted in increased aridity and a higher frequency of droughts in drylands around the world, with increasing dominance of abiotic controls of land degradation (in contrast to direct human- or herbivore-driven degradation) and changes in hydrology and the erosion of soil by wind (Ravi *et al.*, 2010). In mixed shrub grasslands, the influence of drought periods could produce transient pulses of C that are much larger than the pulses produced by fire (Martí-Roura *et al.*, 2011). Most studies of changes in arid systems between grasslands and shrublands have focused on plant-soil feedbacks that favour shrubs growth. Summers drier than three-quarters of current rainfall decreased grass seedling recruitment to negligible values (Peters *et al.*, 2010). Management cannot reliably increase carbon uptake in arid and semiarid rangelands, which is most often controlled by abiotic factors not easily changed by management of grazing or vegetation (Booker *et al.*, 2013).

Other factors being equal, grasslands and shrublands in cool areas are expected to respond to warming with increased primary production, while those in hot areas are expected to show decreased production (*limited evidence, low confidence*). A shift to more woody vegetation states expected to occur (locally but not globally) in tropical grasslands of the African continent (Higgins and Scheiter, 2012). The response to warming and drought depends on site, year and plant species, as shown by manipulation experiments (Peñuelas *et al.*, 2004, 2007; Gao and Giorgi, 2008; Grime *et al.*, 2008; Shinoda *et al.*, 2010; Wu and Chen, 2013). In most temperate and arctic regions, the capacity to support richer (i.e. more diverse) communities is projected to increase with rising temperature, while decreases in water availability suggest a decline in capacity to support species-rich communities in most tropical and subtropical regions (Sommer *et al.*, 2010). Warming may cause an asymmetrical response of soil C and N cycles, causing N limitation that reduces acclimation in plant production (Beier *et al.*, 2008).

Some grasslands are exposed to elevated levels of nitrogen deposition, which alters species composition, increases primary production up to a point and decreases it thereafter (see Section 4.2.4.2; Bobbink *et al.*, 2010; Cleland and Harpole, 2010; Gaudnik *et al.*, 2011). In a study of 162 plots over 25 years, N deposition drove grassland composition at the local scale, in interaction with climate, whereas climate changes were the predominant driver at the regional scale (Gaudnik *et al.*, 2011). N mineralization in shrublands under either arid or wet conditions is more sensitive to periodic droughts than systems under more mesic conditions (Emmett *et al.*, 2004). Decreased tissue concentrations of phosphorus were also associated with warming and drought (Peñuelas *et al.*, 2004; Beier *et al.*, 2008; Peñuelas *et al.*, 2012). Strong interactions between warming and disturbances have been observed, leading to increased N leaching from shrubland ecosystems (Beier *et al.*, 2004).

Most grasslands and shrublands are characterized by relatively frequent but low-intensity fires, which affect their plant species composition and demographics (e.g., Gibson and Hulbert, 1987; Uys *et al.*, 2004; Gill *et al.*, 1999; de Torres Curth *et al.*, 2012). Species composition changes may be as important in determining ecosystem impacts as the direct effects of climate on plant (Suttle *et al.*, 2007). Fire frequency, duration and intensity are primarily influenced by climate and secondarily by management (Pitman *et al.*, 2007; Lenihan *et al.*, 2008; Archibald *et al.*, 2009; Giannakopoulos *et al.*, 2009; Armenteras-Pascual *et al.*, 2011), and are therefore sensitive to climate change; the duration of the fire season is also projected to broaden (Clarke *et al.*, 2013). Changes in fire frequency may interact with changes in rainfall seasonality: for instance, if fires are followed by rainy spring periods in in northwestern Patagonia, as occurs with more frequent ENSO phenomena, there are more recruitment windows for shrubs (Ghermandi *et al.*, 2010). Relatively little is known regarding the combined effect of climate change and increased grazing by large mammals, nor on the consequences for pastoral livelihoods that depend on rangelands (Thornton *et al.*, 2009).

4.3.3.2.3. Deserts

The deserts of the world, defined as land areas with an arid or hyperarid climate regime, occupy 35 % of the global land surface. Species composition in desert areas is expected to shift in response to climate warming (Ooi *et al.*, 2009; Kimball *et al.*, 2010), including night-time warming (Collins *et al.*, 2010). Deserts are sparsely populated, but the people who do live there are amongst the poorest in the world (Millennium Ecosystem Assessment, 2005a). There is *medium agreement* but *limited evidence* that the present extent of deserts will increase in the coming decades, despite the projected increase in rainfall at a global scale, as a result of the strengthening of the Hadley circulation which determines the location of the broad band of hot deserts approximately 15-30° N and S of the equator (Mitas and Clement, 2005; Seidel *et al.*, 2008; Johanson and Fu, 2009; Lu *et al.*, 2009; Zhou *et al.*, 2011). There may be a feedback to the global climate from an increase in desert extent, which differs in sign between deserts closer to the equator than 20° and those closer to the pole: in model simulations, extension of the near-equator 'hot deserts' causes warming, while extension of the near-boreal "cold deserts" causes cooling, in both cases largely through albedo-mediated effects (Alkama *et al.*, 2012). Deserts are expected to become warmer and drier at faster rates than other terrestrial regions (Lapola *et al.*, 2009; Stahlschmidt *et al.*, 2011). Most deserts are already extremely hot, and therefore further warming is likely to be physiologically injurious rather than beneficial. The ecological dynamics in deserts are rainfall event-driven (Holmgren *et al.*, 2006), often involving the concatenation of a number of quasi-independent events. Some desert tolerance mechanisms (e.g., biological adaptations by long-lived taxa) may be outpaced by global climate change (Lapola *et al.*, 2009; Stahlschmidt *et al.*, 2011).

4.3.3.2.4 Mediterranean-type ecosystems

Mediterranean-type ecosystems occur on most continents, and are characterised by cool, wet winters and hot, dry summers. They were identified as being among the most likely to be impacted by climate change in AR4 and received extensive coverage (Fischlin *et al.*, 2007). Since then, further evidence has accumulated of climate risks to these systems from rising temperature (Giorgi and Lionello, 2008), rainfall change (declining in most but not all cases), increased drought (Section 23.2.3, 25.2) and increased fire frequency (Section 23.4.4). There have been observed shifts in phenology (Gordo and Sanz, 2010), range contraction of Mediterranean species (Pauli *et al.*, 2012), declines in the health and growth rate of dominant tree species (Allen *et al.*, 2010a; Sarris *et al.*, 2011; Brouwers *et al.*, 2012; Section 23.4.4) and increased risk of erosion and desertification, especially in very dry areas (Lindner *et al.*, 2010; Shakesby, 2011). Model projections show further species range contractions in the 21st century under all climate change scenarios. This will result in losses of biodiversity (*medium confidence*) (Maiorano *et al.*, 2011; Kuhlmann *et al.*, 2012; 23.6.4, 25.1).

4.3.3.3. Rivers, Lakes, Wetlands, and Peatlands

Freshwater ecosystems are considered to be among the most threatened on the planet (Dudgeon *et al.*, 2006; Vörösmarty *et al.*, 2010). Fragmentation of rivers by dams and the alteration of natural flow regimes have led to major impacts on freshwater biota (Pringle, 2001; Bunn and Arthington, 2002; Nilsson *et al.*, 2005; Reidy Liermann *et al.*, 2012). Floodplains and wetland areas have become occupied for intensive urban and agricultural land use to the extent that many are functionally disconnected from their rivers (Tockner *et al.*, 2008). Pollution from cities and agriculture, especially nutrient loading, has resulted in declines in water quality and the loss of essential ecosystem services (Allan, 2004). As a direct consequence of these and other impacts, fresh waters have some of the highest rates of extinction of any ecosystem for those species groups assessed for the IUCN Red List (estimated as much as 4% per decade for some groups, such as crayfish, mussels, fishes and amphibians in North America) (Dudgeon *et al.*, 2006), with estimates that at least 10,000-20,000 freshwater species are extinct or imperilled as a consequence of human activity (Strayer and Dudgeon, 2010). This is a particular concern given that freshwater habitats support 6% of all described species (Dudgeon *et al.*, 2006), including approximately 40% of the world's fish diversity and a third of the vertebrate diversity (Balian *et al.*, 2008).

It is *very likely* that these stressors to freshwater ecosystems will continue to dominate as human demand for water resources grows, accompanied by increased urbanization and expansion of irrigated agriculture (Vörösmarty *et al.*, 2000; Malmqvist *et al.*, 2008; Dise, 2009). However, climate change will have significant additional impacts (*high confidence*), from altered thermal regimes, altered precipitation and flow regimes and, in the case of coastal wetlands, sea level rise. Specific aquatic habitats that are most vulnerable to these direct climate effects, especially rising temperatures, are those at high altitude and high latitude, including Arctic and subarctic bog communities on permafrost, and alpine and Arctic streams and lakes (see Section 4.3.3.4; Klanderud and Totland, 2005; Smith *et al.*, 2005; Smol and Douglas, 2007b). It is noteworthy that these high latitude systems currently experience a relatively low level of threat from other human activities (Vörösmarty *et al.*, 2010). It is *likely* that the shrinkage and disappearance of glaciers will lead to the reduction of local and regional freshwater biodiversity, with 11-38% of the regional macroinvertebrate species pool expected to be lost following complete disappearance of glaciers (Jacobsen *et al.*, 2012; CC-RF2). Shrinkage of glaciers and the loss of small glaciers will most likely reduce beta diversity at the species and the genetic level, as predicted for the Pyrenees (Finn *et al.*, 2013). Dryland rivers and wetlands, many already experiencing severe water stress from human consumptive use, are also *likely* to be further impacted by decreased and more variable precipitation and higher temperatures. Headwater stream systems in general are also vulnerable to the effects of warming because their temperature regimes closely track air temperatures (Caissie, 2006).

There is widespread evidence of rising stream and river temperatures over the past few decades (Langan *et al.*, 2001; Morrison *et al.*, 2002; Webb and Nobilis, 2007; Chessman, 2009; Ormerod, 2009; Kaushal *et al.*, 2010; van Vliet *et al.*, 2011; Markovic *et al.*, 2013– though see Arismendi *et al.*, 2012). Rising water temperature has been linked by observational and experimental studies to shifts in invertebrate community composition, including declines in cold stenothermic species (Brown *et al.*, 2007; Chessman, 2009; Durance and Ormerod, 2007; Ormerod, 2009). Rising temperature is also implicated in species range shifts (e.g., Comte and Grenouillet, 2013), implying changes in the composition of river fish communities (Daufresne and Boet, 2007; Buisson *et al.*, 2008; Comte *et al.*, 2013), especially in headwater streams where species are more sensitive to warming (e.g., Buisson and Grenouillet, 2009).

Rising temperatures in the well-mixed surface waters in many temperate lakes, resulting in reduced periods of ice formation (Livingstone and Adrian, 2009; Weyhenmeyer *et al.*, 2011) and earlier onset and increased duration and stability of the thermocline during summer (Winder and Schindler, 2004), are projected to favour a shift in dominance to smaller phytoplankton (Parker *et al.*, 2008; Winder *et al.*, 2009; Yvon-Durocher *et al.*, 2011) and cyanobacteria (Wiedner *et al.*, 2007; Jöhnk *et al.*, 2008; Paerl *et al.*, 2011), especially in those ecosystems experiencing high anthropogenic loading of nutrients (Wagner and Adrian, 2009); with impacts to water quality, food webs and productivity (O'Reilly *et al.*, 2003; Verburg *et al.*, 2003; Gyllström *et al.*, 2005; Parker *et al.*, 2008; Shimoda *et al.*, 2011). Prolonged stratification and associated anaerobic conditions near the sediment-water interface can increase the internal loading of phosphorus, particularly in eutrophic lakes (Søndergaard *et al.*, 2003; Wilhelm and Adrian, 2008; Wagner and Adrian, 2009).

In many freshwater ecosystems, the input of dissolved organic carbon through run-off from the catchment has increased, inducing changes in water colour (Hongve *et al.*, 2004; Evans *et al.*, 2005; Erlandsson *et al.*, 2008). Soil recovery from acidification and changed hydrological conditions (partly linked to increased precipitation) appear to be the main factors driving this development (Evans *et al.*, 2005; Monteith *et al.*, 2007). The resulting increased light attenuation can lead to lower algal concentrations and loss of submersed vegetation (Ask *et al.*, 2009; Karlsson *et al.*, 2009).

Emergent aquatic macrophytes *are likely* to expand their northward distribution and percentage cover in boreal lakes and wetlands, posing an increasing overgrowth risk for sensitive macrophyte species (Alahuhta *et al.*, 2011). Long-term shifts in macroinvertebrate communities have also been observed in European lakes where temperatures have increased (Burgmer *et al.*, 2007), noting that warming may increase species richness in smaller temperate water bodies, especially those at high altitude (Rosset *et al.*, 2010). While less studied, it has been proposed that tropical ectothermic ("cold blooded") organisms will be particularly vulnerable because they will approach critical maximum temperatures proportionately faster than species in high latitude environments, despite lower rates of warming (Deutsch *et al.*, 2008; Hamilton, 2010; Laurance *et al.*, 2011).

There is growing evidence that climate induced changes in precipitation will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*high confidence* in detection, *medium confidence* in attribution, see Cross-Chapter Box CC-RF; Xenopoulos *et al.*, 2005; Aldous *et al.*, 2011). Freshwater ecosystems in Mediterranean-montane ecoregions (e.g., Australia, California and South Africa) are projected to experience a shortened wet season and prolonged, warmer summer season (Klausmeyer and Shaw, 2009), increasing the vulnerability of fish communities to drought (Magalhães *et al.*, 2007; Hermoso and Clavero, 2011) and floods (Meyers *et al.*, 2010). Shifts in hydrologic regimes in snow-melt systems, including earlier runoff and declining base flows in summer (Stewart *et al.*, 2005; Stewart, 2009), are projected to alter freshwater ecosystems, through changes in physical habitat and water quality (Bryant, 2009). Declining rainfall and increased inter-annual variability will most likely increase low-flow and dry-spell duration in dryland regions, leading to reduced water quality in remnant pools (Dahm *et al.*, 2003), reduction in floodplain egg- and seed-banks (Capon, 2007; Jenkins and Boulton, 2007), the loss of permanent aquatic refugia for fully aquatic species and water birds (Johnson *et al.*, 2005; Bond *et al.*, 2008; Sheldon *et al.*, 2010, altered freshwater food webs (Ledger *et al.*, 2013), and drying out of wetlands (Davis and Thompson, 2010).

Climate induced changes in precipitation will probably be an important factor altering peatland vegetation in temperate and boreal regions, with decreasing wetness during the growing season generally associated with a shift from a *Sphagnum* dominated to vascular plant dominated vegetation type and a general decline of C sequestration in the long term (Limpens *et al.*, 2008). Mire ecosystems (i.e. bogs, transition bogs and fens) in Central Europe face severe climate-induced risk, with increased summer temperatures being particularly important (Essl *et al.*, 2012). Decreased dry season precipitation and longer dry seasons in major tropical peatland areas in southeast Asia, are projected to result in lower water tables more often and for longer periods, with an increased risk of fire (Li *et al.*, 2007; Rieley *et al.*, 2008; Frolking *et al.*, 2011).

Peatlands contain large stocks of carbon that are vulnerable to change through land use and climate change. Although peatlands cover only about 3% of the land surface, they hold the equivalent of half of the atmosphere's carbon (as CO_2), or one third of the world's soil carbon stock (400-600 Pg) (Limpens *et al.*, 2008; Frolking *et al.*, 2011; Page *et al.*, 2011). About 14-20% of the world's peatlands are currently used for agriculture (Oleszczuk *et al.*, 2008) and many, particularly peat swamp forests in Southeast Asia, are undergoing rapid major transformations through drainage and burning in preparation for oil palm and other crops or through unintentional burning (Limpens *et al.*, 2008; Hooijer *et al.*, 2010). Deforestation, drainage and burning in Indonesian peat swamp forests can release 59.4 ± 10.2 Mg CO_2 $ha^{-1}.yr^{-1}$ over 25 years (Murdiyarso *et al.*, 2010), contributing significantly to global GHG emissions, especially during periods of intense drought associated with ENSO when burning is more common (Page *et al.*, 2002). Anthropogenic disturbance has changed peatlands from being a weak global carbon sink to a source (Frolking *et al.*, 2011), though inter-annual variability is large. Fluvial export can also be a significant contributor to carbon losses that has been largely overlooked to date, with recent estimates of DOC export from degraded tropical peatlands 50% higher than in intact systems (Moore *et al.*, 2013). Conserving peatland areas not yet developed for biofuels or other crops, or re-wetting and restoring degraded peatlands to preserve their carbon store are potential mitigation strategies.

Sea level rise will lead to direct losses of coastal wetlands with associated impacts on water birds and other wildlife species dependent on fresh water (BMT WBM, 2010; Pearlstine *et al.*, 2010; Traill *et al.*, 2010), but the impact will probably be relatively small compared with the degree of direct and indirect human-induced destruction (Nicholls, 2004). River deltas and associated wetlands are particularly vulnerable to rising sea level, and this threat is further compounded by trapping of sediment in reservoirs upstream and subsidence from removal of oil, gas and water

(Syvitski *et al.*, 2009; see Section 5.4.2.7). Lower river flows might exacerbate the impact of sea level rise and thus salinization on freshwater ecosystems close to the ocean (Ficke *et al.*, 2007).

4.3.3.4. Tundra, Alpine, and Permafrost Systems

The High Arctic region, with tundra-dominated landscapes, has warmed more than the global average over the last century (Kaufman *et al.*, 2009; see WGI AR5 Chapter 2). Changes consistent with warming are evident in the freshwater and terrestrial ecosystems and permafrost of the region (Hinzman *et al.*, 2005; Axford *et al.*, 2009; Jia *et al.*, 2009b; Post *et al.*, 2009; Prowse and Brown, 2010; Romanovsky *et al.*, 2010; Walker *et al.*, 2012). Most of the Arctic has experienced recent change in vegetation photosynthetic capacity, particularly adjacent to rapidly retreating sea ice (Bhatt *et al.*, 2010). Changes in terrestrial environments in Antarctica have also been reported. Vieira *et al.* (2010) show that in in the Maritime Antarctic permafrost temperatures are close to thaw. Permafrost warming in has been observed in continental Antarctica (Guglielmin and Cannone, 2012) and for the Palmer archipelago (Bockheim *et al.*, 2013).

Continued warming is projected to cause the terrestrial vegetation and lake systems of the Arctic to change substantially (*high confidence).* Continued expansion in woody vegetation cover in tundra regions over the 21st century is projected by the CMIP5 Earth System Models (Bosio *et al.*, 2012; see WGI AR5 Chapter 6); by dynamic global vegetation models driven by other climate model projections; and by observationally-based statistical models (Pearson *et al.*, 2013). Changes may be complex (see Box 4-4) and in some cases involve non-linear and threshold responses to warming and other climatic change (Hinzman *et al.*, 2005; Mueller *et al.*, 2009b; Bonfils *et al.*, 2012). Arctic vegetation change is expected to continue long after any stabilization of global mean temperature (see WGI AR5 Chapter 6; Falloon *et al.*, 2012). In some regions, reduced surface albedo due to increased vegetation cover is projected to cause further local warming even in scenarios of stabilized greenhouse gas concentrations (Falloon *et al.*, 2012).

In the Arctic tundra biome (in contrast to the boreal forests discussed in Section 4.3.3.1.1) vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz *et al.*, 2007; Stow *et al.*, 2007; Jia *et al.*, 2009b; de Jong *et al.*, 2011; Myers-Smith *et al.*, 2011; Elmendorf *et al.*, 2012). This phenomenon is amplified by retreat of coastal sea ice (Bhatt *et al.*, 2010) and has been widely discussed in the context of increased shrub growth and expansion over the last half century (Forbes *et al.*, 2010; Myers-Smith *et al.*, 2011). Deciduous shrubs and graminoids respond to warming with increased growth (Walker, 2006; Epstein, 2008; Euskirchen *et al.*, 2009; Lantz *et al.*, 2010). Analyses of satellite time series data show the increased productivity trend is not unique to shrub-dominated tundra areas (Jia *et al.*, 2009b; Beck and Goetz, 2011), thus greening is a response shared by multiple vegetation communities and continued changes in the tundra biome can be expected irrespective of shrub presence. The very large spatial scale over which these changes are occurring, the strong warming signal over much of the Arctic for the last five decades (Burrows et al. 2011) and the absence of strong confounding factors means that detection these changes in Arctic systems and their attribution to global warming can be made with *high confidence*, despite the relatively short time frame of most observations (Figure 4-4).

Shrub expansion and height changes are particularly important because they trap snow, mediate winter soil temperature and summer moisture regimes, increase nutrient mineralization, and produce a positive feedback for additional shrub growth (Sturm *et al.*, 2005; Lawrence *et al.*, 2007; Bonfils *et al.*, 2012). Although increased shrub cover and height produce shadowing that reduce ground heat flux and active layer depth, they also reduce surface albedo, increase energy absorption and evapotranspiration (Chapin III *et al.*, 2005; Blok *et al.*, 2010), and produce feedbacks that reinforce shrub densification and regional warming (Lawrence and Swenson, 2011; Bonfils *et al.*, 2012). On balance, these feedbacks can act to partially offset one another, but when coupled with warmer and wetter conditions they act to increase active layer depth and permafrost thaw (Yi *et al.*, 2007; Bonfils *et al.*, 2012).

The Arctic tundra biome is experiencing increasing fire disturbance and permafrost degradation. Both of these processes facilitate conditions for woody species establishment in tundra areas, either through incremental migration or via more rapid long-distance dispersal to areas reinitialized by burning (Epstein *et al.*, 2007; Goetz *et al.*, 2011). When already present at the boreal-tundra ecotone, shrub and tree species show increased productivity with warmer conditions (Devi *et al.*, 2008; Andreu-Hayles *et al.*, 2011; Elmendorf *et al.*, 2012). Tundra fires not only emit large quantities of combusted carbon formerly stored in vegetation and organic soils (Mack *et al.*, 2011; Rocha and Shaver, 2011), but also increase active layer depth during summer months (Racine *et al.*, 2004; Liljedahl *et al.*, 2007; Jorgenson *et al.*, 2010), produce landforms associated with thawing of ice-rich permafrost, and can create conditions that alter vegetation succession (Racine *et al.*, 2004; Lantz *et al.*, 2009; Higuera *et al.*, 2011).

It is *virtually certain* that the area of Northern Hemisphere permafrost will continue to decline over the first half of the 21st century (see WGI Chapter 12) in all RCP scenarios (Figure 4-9; Caesar *et al.*, 2013; Koven *et al.*, 2013). In the RCP2.6 scenario of an early stabilization of CO_2 concentrations, the permafrost area is projected to stabilize at a level approximately 20% below the 20th century area, and then begin a slight recovering trend. In RCP4.5, in which CO_2 concentration is stabilized at approximately 550ppmv by the mid-21st century, the simulations that extend beyond 2100 show permafrost continuing to decline for at least another 250 years. In the RCP8.5 scenario of ongoing CO_2 rise, the permafrost area is simulated to approach zero by the middle of the 22nd century in simulations that extend beyond 2100. RCP8.5 simulations that ended at 2100 showed continued permafrost decline in the late 21st century, although at slower rates in some cases as the remaining permafrost area decreases (Figure 4-9.).

[INSERT FIGURE 4-9 HERE
Figure 4-9: CMIP5 multi-model simulated area of Northern Hemisphere permafrost in the upper 3m of soil, from 1850 to 2100 or 2300 depending on extent of individual simulations. Each panel shows historical (1850-2005) and projected (2005 to 2100 or 2300) simulations for (a) RCP2.6, (b) RCP4.5, and (c) RCP8.5. The observed current permafrost extent is 15×10^6 km^2. (Based on Koven *et al.*, 2013, with analysis extended to 2300 following Caesar *et al.*, 2013).]

Frozen soils and permafrost currently hold about 1700 PgC, more than twice the carbon than the atmosphere, and thus represent a particularly large vulnerability to climate change (i.e., warming) (see WGI AR5 Chapter 6). Although the Arctic is currently a net carbon sink, continued warming will act to turn the Arctic to a net carbon source, that will in turn create a potentially strong positive feedback to accelerate Arctic (and global) warming with additional releases of CO_2, CH_4, and perhaps N_2O, from the terrestrial biosphere into the atmosphere (*high confidence*, Schuur *et al.*, 2008; Schuur *et al.*, 2009; Maslin *et al.*, 2010; McGuire *et al.*, 2010; O'Connor *et al.*, 2010; Schaefer *et al.*, 2011; see WGI AR5 Chapter 6 for detailed treatment of biogeochemistry, including feedbacks). Moreover, this feedback is already accelerating due to climate-induced increases in fire (McGuire *et al.*, 2010; O'Donnell *et al.*, 2011). The rapid retreat of snow cover and resulting spread of shrubs and trees into areas currently dominated by tundra has begun, and will continue to serve as a positive feedback accelerating high latitude warming (Chapin III *et al.*, 2005; Bonfils *et al.*, 2012).

There is *medium confidence* that rapid change in the Arctic is affecting its animals. For example, seven of 19 sub-populations of the polar bear are declining in number, while four are stable, one is increasing and the remaining seven have insufficient data to identify a trend (Vongraven and Richardson, 2011). Declines of two of the sub-populations are linked to reductions in sea ice (Vongraven and Richardson, 2011). Polar bear populations are projected to decline greatly in response to continued Arctic warming (Hunter *et al.*, 2010; Stirling and Derocher, 2012), and it is expected that the populations of other Arctic animals will be affected dramatically by climate change, often in complex, but potentially dramatic ways (e.g., Post *et al.*, 2009; Sharma *et al.*, 2009; Gallant *et al.*, 2012; Gilg *et al.*, 2012; Post and Brodie, 2012; Gauthier *et al.*, 2013; Nielsen and Wall, 2013; Prost *et al.*, 2013; White *et al.*, 2013). Simple niche-based, or climatic envelope models have difficulty in capturing the full complexity of these future changes (MacDonald, 2010).

There is *high confidence* that alpine systems are already showing a high sensitivity to on-going climate change and will be highly vulnerable to change in the future. In western North America, warming, glacier retreat, snowpack decline and drying of soils is already causing a large increase in mountain forest mortality and wildfire, plus other ecosystem impacts (e.g., Westerling *et al.*, 2006; Crimmins *et al.*, 2009; van Mantgem *et al.*, 2009; Pederson *et al.*, 2010; Muhlfeld *et al.*, 2011; Brusca *et al.*, 2013; Williams *et al.*, 2013), and disturbance will continue to be an important agent of climate-induced change in this region (Littell *et al.*, 2010). Globally, tree line altitude appears to be changing, although not always in simple ways (Harsch *et al.*, 2009; Tingley *et al.*, 2012) and may sometimes be due to factors not related to climate change (Schwilk and Keeley, 2012). Responses to climate change in high-altitude ecosystems are taking place in Africa, Asia, Europe and elsewhere (Yasuda *et al.*, 2007; Cannone *et al.*, 2007, Cannone *et al.*, 2008; Lenoir *et al.*, 2008; Britton *et al.*, 2009; Chen *et al.*, 2009; Cui and Graf, 2009; Normand *et al.*, 2009; Allen *et al.*, 2010a; Eggermont *et al.*, 2010; Lenoir *et al.*, 2010; Chen *et al.*, 2011; Engler *et al.*, 2011; Kudo *et al.*, 2011; Laurance *et al.*, 2011; Dullinger *et al.*, 2012). For example, in a study of permanent plots from 1994 to 2004 in the Austrian high Alps, a range contraction of subnival to nival plant species was indicated at the downslope edge, and an expansion of alpine pioneer species at the upslope edge (Pauli *et al.*, 2007). Thermophilous vascular plant species were observed to colonize in alpine mountain-top vegetation across Europe during the past decade (Gottfried *et al.*, 2012). As with the Arctic, permafrost thawing in alpine systems could provide a strong positive feedback (e.g., Tibet; Cui and Graf, 2009).

_____ START BOX 4-4 HERE _____

Box 4-4. Boreal – Tundra Biome Shift

Changes in a suite of ecological processes currently underway across the broader arctic region are consistent with Earth system model predictions of climate-induced geographic shifts in the range extent and functioning of the tundra and boreal forest biomes (Figure 4-10). Until now, these changes have been gradual shifts across temperature and moisture gradients, rather than abrupt. Responses are expressed through gross and net primary production, microbial respiration, fire and insect disturbance, vegetation composition, species range expansion and contraction, surface energy balance and hydrology, active layer depth and permafrost thaw, and a range of other inter-related variables. Because the high northern latitudes are warming more rapidly than other parts of the Earth, due at least in part to arctic amplification (Serreze and Francis, 2006), the rate of change in these ecological processes are sufficiently rapid that they can be documented *in situ* (Hinzman *et al.*, 2005; Post *et al.*, 2009; Peng *et al.*, 2011; Elmendorf *et al.*, 2012) as well as from satellite observations (Goetz *et al.*, 2007; Beck *et al.*, 2011b; Xu *et al.*, 2013) and captured in Earth system models (McGuire *et al.*, 2010).

Gradual changes in composition resulting from decreased evergreen conifer productivity and increased mortality, as well as increased deciduous species productivity, can be facilitated by more rapid shifts associated with fire disturbance where it can occur (Mack *et al.*, 2008; Johnstone *et al.*, 2010; Roland *et al.*, 2013). Each of these interacting processes, as well as insect disturbance and associated tree mortality, are tightly coupled with warming-induced drought (Choat *et al.*, 2012; Ma *et al.*, 2012; Anderegg *et al.*, 2013a). Similarly, gradual productivity increases at the boreal-tundra ecotone are facilitated by long distance dispersal into areas disturbed by tundra fire and thermokarsting (Tchebakova *et al.*, 2009; Brown, 2010; Hampe, 2011). In North America these coupled interactions set the stage for changes in ecological processes, already documented, consistent with a biome shift characterized by increased deciduous composition in the interior boreal forest and evergreen conifer migration into tundra areas that are, at the same time, experiencing increased shrub densification. The net feedback of these ecological changes to climate is multi-faceted, complex, and not yet well known across large regions except via modelling studies, which are often poorly constrained by observations.

[INSERT FIGURE 4-10 HERE
Figure 4-10: Tundra-Boreal Biome Shift. Earth system models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra-forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing and methane emissions, with net feedbacks to additional climate change.]

_____ END BOX 4-4 HERE _____

4.3.3.5. Highly Human-Modified Systems

About a quarter of the land surface is now occupied by ecosystems highly modified by human activities. In this section we assess the vulnerability to climate change only of those modified systems not dealt with elsewhere, i.e. excluding agriculture (Chapter 7), freshwater fisheries (Chapter 3) and urban areas (Chapter 8).

4.3.3.5.1. Plantation forestry

Plantation forests are established through afforestation or reforestation, often with tree crop replacement (Dohrenbusch and Bolte, 2007; FAO, 2010). They differ from natural or semi-natural forests (Section 4.3.3.1) by generally being even-aged, having a reduced species diversity (sometimes of non-native species) and being dedicated to the production of timber, pulp and/or bioenergy. Plantation forests contribute 7% to the global forest area (FAO, 2010), an increase of five million ha between 2000 and 2010 (FAO, 2010). Most recent plantations have been established by afforestation of non-forest areas in the tropics and subtropics and some temperate regions, particularly China (Kirilenko and Sedjo, 2007; FAO, 2010) Afforestation usually results in net CO_2 uptake from the atmosphere (Canadell and Raupach, 2008; Van Minnen *et al.*, 2008) but does not necessarily result in a reduction in global warming (Bala *et al*., 2007; see Section 4.3.4.5).

Growth rates in plantation forests have generally increased during the last decades but the variability is large. In forests that are not highly water-limited, increased growth is consistent with higher temperatures and extended growing seasons. As in the case of forests in general, clear attribution is difficult because of the interaction of multiple environmental drivers as well as changes in forest management (e.g., Boisvenue and Running, 2006; Ciais *et al.*, 2008; Dale *et al.*, 2010; see also Section 4.3.3.1). In Europe much of the increase has been attributed to recovery following previously more intense harvesting (Ciais *et al.*, 2008; Lindner *et al.*, 2010).

Several studies using forest yield models suggest future increases in forest production (Kirilenko and Sedjo, 2007). These results may over-estimate the positive effects of elevated CO_2 (Kirilenko and Sedjo, 2007; see Section 4.2.4.4). The effects of disturbances such as wildfires, forest pests, pathogens and windstorms, which are major drivers of forest dynamics, are poorly represented in the models (Loustau, 2010; see also Section 4.3.3.1 and Box 4-2). The results from different models often differ substantially both regarding forest productivity (e.g., Sitch *et al.*, 2008; Keenan *et al.*, 2011) and potential species ranges (see Section 4.3.3.1.2). Decreased forest production is expected in already-dry forest regions for which further drying is projected, such as the south-western U.S. (Williams *et al.*, 2010b). Extreme drying may also decrease yields in forests currently not water-limited (e.g., Sitch *et al.*, 2008; see Section 4.3.3.1). Plantations in cold-limited areas could benefit from global warming, provided that increased fires, storms, pests and pathogens do not outweigh the potential direct climate effects on tree growth rates.

Low species diversity (and low genetic diversity within species where clones or selected provenances are used) renders plantation forests less resilient to climate change than natural forests (e.g., Hemery, 2008). Choosing provenances that are well adapted to current climates but pre-adapted to future climates is difficult because of uncertainties in climate projections at the timescale of a plantation forest rotation (Broadmeadow *et al.*, 2005). How forest pests and pathogens will spread as a result of climate change and other factors is highly uncertain. New pathogen-tree interactions may arise (e.g., Brasier and Webber, 2010). Adaptive management can decrease the vulnerability of plantation forests to climate change (Hemery, 2008; Bolte *et al.*, 2009; Seppälä, 2009; Dale *et al.*, 2010). For example, risk spreading by promoting mixed stands, containing multiple species or provenances, combined with natural regeneration (Kramer *et al.*, 2010), has been advocated as an adaptation strategy for temperate forests (Hemery, 2008; Bolte *et al.*, 2010) and tropical forests (Erskine *et al.*, 2006; Petit and Montagnini, 2006). Incomplete knowledge of the ecology of tropical tree species and little experience in managing mixed tropical tree plantations remains a problem (Hall *et al.*, 2011). Especially at the equator-ward limits of cold-adapted species, such as Norway spruce (*Picea abies*) in Europe, climate change will *very likely* lead to a shift in the main tree species used for forest plantations (Iverson *et al.*, 2008; Bolte *et al.*, 2010).

4.3.3.5.2. Bioenergy systems

The production of modern bioenergy is growing rapidly throughout the world in response to climate mitigation and energy security policies (Cochrane and Barber, 2009). WGIII AR5 Chapter 7 addresses the potential of bioenergy as a climate mitigation strategy. The vulnerability of bioenergy systems to climate change is similar to that of plantation forestry (Section 4.3.3.5.1) or food crops (Section 7.3): in summary, they remain viable in the future in most but not all locations, but their viability is increasingly uncertain for high levels of climate change (Ma and Zhou, 2012). Oliver *et al.* (2009a) suggested that rising CO_2 might contribute to increased drought tolerance in bioenergy crops (since it leads to improved plant water use efficiency).

The unintended consequences of large-scale land-use changes driven by increasing bioenergy demand are addressed in Section 4.4.4.

4.3.3.5.3. Cultural landscapes

Cultural landscapes are characterized by a long history of human-nature interactions, which results in a particular configuration of species and landscape pattern attaining high cultural significance (Rössler, 2006). Examples are grassland or mixed agriculture landscapes in Europe, rice landscapes in Asia (Kuldna *et al.*, 2009) and many others across the globe (e.g., Rössler, 2006; Heckenberger *et al.*, 2007). Such landscapes are often agricultural, but we deal with them here because their perceived value is only partly in terms of their agricultural products.

It has been suggested that protected area networks (such as Natura 2000 in Europe, which includes many cultural landscape elements) be adjusted to take into account climate change (Jin *et al.*, 2010; Heubes *et al.*, 2011). Conserving species in cultural landscapes (e.g., EU Council, 1992) generally depends on maintaining certain types of land use. Doing so under climate change requires profound knowledge of the systems and species involved, and conservation success so far has been limited (see Kirdyanov *et al.*, 2012 for a notable exception). Understanding the relative importance of climate change and land management change is critical (Settele and Kühn, 2009). To date land use changes have been the most obvious driver of change (Nowicki *et al.*, 2007); impacts have been attributed climate change (with *low* to *medium confidence*) in only a few examples (Devictor *et al.*, 2012). Even in these, combined land use-climate effects explain the pattern of observed threats better than either alone (Schweiger *et al.*, 2008; Clavero *et al.*, 2011; Schweiger *et al.*, 2012).

There is *very high confidence* that species composition and landscape structure are changing in cultural landscapes such as Satoyama landscapes in Japan or mixed forest, agricultural landscapes in Europe. Models and experiments suggest that climate change should be contributing to these observed changes. The land use and land management signal is so strong in these landscapes, that there is *very low confidence* that we can attribute these observations to climate change (Figure 4-4).

4.3.3.5.4. Urban ecosystems

Although urban areas (for definition see Section 8.1.2) cover only 0.5 % of Earth's land surface (Schneider *et al.*, 2009), over half of humanity lives there (increasing annually by 74 million people; United Nations *et al.*, 2012) and they harbour a large variety of species (McKinney, 2008). The frequency and magnitude of warm days and nights (heat waves) is *virtually certain* to increase globally the future it (IPCC, 2012); this trend is higher in urban than rural areas (Leonelli *et al.*, 2011). Heavy rainfall events are also projected to increase (IPCC, 2012), and although the hydrological conditions in urban areas make them prone to flooding *(medium confidence)*, there is *limited evidence* that they will be over-proportionally affected. It is *very likely* that sea level rise in future will contribute to flooding, erosion and salinisation of coastal urban ecosystems (IPCC, 2012). Climate change is projected to increase the frequency of landslides (UN Habitat, 2011). Climate change impacts on urban ecosystems and biodiversity have received comparatively little attention, with water availability being an exception (Hunt and Watkiss, 2011). Changes in water availability and quality either due to changes in precipitation, evaporation or in salinity regimes will especially affect urban freshwater ecosystems (Hunt and Watkiss, 2011). As in other ecosystems, climate change will leaded to a change in species composition, the frequency of traits and ecosystem services from urban ecosystems. Knapp *et al.* (2008b) found that trait composition of plant communities changes during urbanization towards adaptive characteristics of dry and warm environments (see also Sections 4.2.4.6 and 4.3.2.5). Urban areas are one of the main points of introduction of alien species (e.g., for plants through urban gardening; Li *et al.*, 2009). Increased damage by phytophagous insects to plants in urban environments is anticipated (Kollár *et al.*, 2009; Lopez-Vaamonde *et al.*, 2010; Tubby and Webber, 2010; see also Section 8.2.4.5).

4.3.4. Impacts on Key Ecosystem Services

Ecosystem services are the benefits which people derive from ecosystems (see glossary). Many ecosystem services are plausibly vulnerable to climate change. The Millennium Ecosystem Assessment classification (Millennium Ecosystem Assessment, 2003) recognises *provisioning services* such as food (Chapter 7), fibre (Section 4.3.4.2), bioenergy (Section 4.3.4.3) and water (Chapter 3); *regulating services* such as climate regulation (Section 4.3.4.5), pollination, pest and disease control (Section 4.3.4.4) and flood control (Chapter 3); *supporting services* such as primary production (Section 4.3.2.2) and nutrient cycling (Section 4.2.4.2, and indirectly Section 4.3.2.3); and *cultural services*, including recreation, aesthetic and spiritual benefits (Section 10.6). The following section focusses on ecosystem services not already covered in the sections referenced above.

4.3.4.1. Habitat for Biodiversity

Climate change can alter habitat for species by inducing: i) shifts in habitat distribution that are not followed by species, ii) shifts in species distributions that move them outside of their preferred habitats, and, iii) changes in habitat quality (Dullinger *et al.*, 2012; Urban *et al.*, 2012). Climate change impacts on habitats for biodiversity are already occurring (see the polar bear example in Section 28.2.2.1.3) but are not yet a widespread phenomenon. Models of future climate change-induced shifts in the distribution of ecosystems suggest that many species could be outside of their preferred habitats with the next few decades (Urban *et al.*, 2012; see Sections 4.3.2.5, 4.3.3, and Figure 4-1).

Hole *et al.* (2009) report that the majority of African birds would have to move large distances (up to several hundred kilometres) over the next 60 years (under SRES B2a), resulting in substantial turnover of species within protected areas (>50% turnover in more than 40% of Important Bird Areas of Africa). In order to reach suitable climates they will have to migrate across unfavourable habitats. Many may continue to find suitable climate within the protected area network, but will be forced to cope with new habitat constraints (Hole *et al.*, 2009). Araujo *et al.* (2011) estimate that by 2080 approximately 60% (58 ± 2.6%) of plants and vertebrate species will no longer have favourable climates within European protected areas, often pushing them into unsuitable or less preferred habitats (based on SRES A1, A2, B1 and A1FI scenarios). Wiens *et al.* (2011) project similar effects in the western US (until the year 2069, based on SRES A2 scenarios), but also find that climate change may open up new opportunities for protecting species in areas where climate is currently unsuitable. In some cases climate change may allow species to move into areas of lower current or future land use pressure including protected areas (Bomhard *et al.*, 2005). These studies strongly argue for a rethinking of protected areas networks and of the importance of the habitat matrix outside of protected areas as a key to migration and long-term survival of species (see Sections 4.4.2.2 and 4.4.2.3).

In the long term, some habitat types may disappear entirely due to climate change (see Section 4.3.3 and Figure 4-1). Climates are projected to occur in the future which at least in some features do not represent climates that existed in the past (Williams *et al.*, 2007b; Wiens *et al.*, 2011), and in the past climate shifts have resulted in vegetation types that have no current analogue (Section 4.2.3). The impacts of habitat change on species abundance and extinction risk is difficult to evaluate because at least some species are able to adapt to novel habitats (Prugh *et al.*, 2008; Oliver *et al.*, 2009b). The uncertainty in habitat specificity is one reason why quantitative projection of changes in extinction rates is difficult (Malcolm *et al.*, 2006).

The effects of climate change on habitat quality are less well studied than shifts in species or habitat distributions. Several recent studies indicate that climate change may have altered habitat quality already and will continue to do so (Iverson *et al.*, 2011; Matthews *et al.*, 2011). For example, decreasing snowfall in the southwestern US has negatively affected the habitat for songbirds (Martin and Maron, 2012).

4.3.4.2. Timber and Pulp Production

In most areas with forest plantations, forest growth rates have increased during the last decades, but the variability is large, and in some areas production has decreased (see Section 4.3.3.1). In forests that are not highly water-limited, these trends are consistent with higher temperatures and extended growing seasons, but, as in the case of forests in general, clear attribution is difficult because many environmental drivers and changes in forest management interact (e.g., Boisvenue and Running, 2006; Ciais *et al.*, 2008; Dale *et al.*, 2010; see also Section 4.3.3.1). In Europe a reduction in harvesting intensity has contributed (Ciais *et al.*, 2008; Lindner *et al.*, 2010).

Forest yield models project future increases in forest production under climate change, perhaps over-optimistically (Kirilenko and Sedjo, 2007; see Section 4.2.4.4. Using a model that accounts for fire effects and insect damage, Kurz *et al.* (2008) showed that the Canadian forest sector may have transitioned from a sink to a source of carbon.

4.3.4.3. Biomass-derived Energy

Bioenergy sources include traditional forms such as wood and charcoal from forests (see Section 4.3.3.1) and more modern forms such as the industrial burning of biomass wastes, the production of ethanol and biodiesel and plantations of bioenergy crops. While traditional biofuels have been in general decline as users switch to fossil fuels or electricity, they remain dominant energy sources in many less-developed parts of the world, such as Africa, and retain a niche in developed countries. Generally, potentials of bioenergy production under climate change may be high, but are very uncertain (Ma and Zhou, 2012).

4.3.4.4. Pollination, Pest, and Disease Regulation

It can be inferred that global change will result in new communities (Gilman *et al.*, 2010; Schweiger *et al.*, 2010). As these will have had little opportunity for coevolution, changes in ecological interactions, such as shifts herbivore diets, the range of prey of predators or in pollination networks are to be expected (Tylianakis *et al.*, 2008; Schweiger *et al.*, 2012). This may result in temporarily reduced effectiveness of the "regulating services", which generally depend on species interactions (Montoya and Raffaelli, 2010). Burkle *et al.* (2013) show that the loss of species reduces co-occurrence of interacting species and thus reduces ecosystem functions based on them.

Climate change tends to increase the abundance of pest species, particularly in previously cooler climates, but assessments of changes in impacts are hard to make (Payette, 2007). Insect pests are directly influenced by climate change, e.g. through a longer warm season during which to breed, and indirectly e.g. through the quality of food plants (Jamieson *et al.*, 2012) or *via* changes in their natural enemies (predators and parasitoids). Insects have well-defined temperature optima; warming towards the optimum leads to increased vitality and reproduction (Allen *et al.*, 2010a). Mild winters in temperate areas promote pests formerly controlled by frost sensitivity. For the vast majority of indirect effects, information is scarce. Further assessments of climate change effects on pest and disease dynamics are found in Sections 7.3.2.3 for agricultural pests and 11.5.1 for human diseases.

Climate change has severe negative impacts on pollinators (including honeybees) and pollination (Kjøhl *et al.*, 2011) (*medium confidence*). After land-use changes, climate change is regarded as the second most relevant factor responsible for the decline of pollinators (Potts *et al.*, 2010; for other factors see Biesmeijer *et al.*, 2006; Brittain *et al.*, 2010a; Brittain *et al.*, 2010b). The potential influence of climate change on pollination can be manifold (compare Hegland *et al.*, 2009; Schweiger *et al.*, 2010; Roberts *et al.*, 2011). There are a few observational studies, which mostly relate to the phenological de-coupling of plants and their pollinators (Gordo and Sanz, 2005; Bartomeus *et al.*, 2011). While Willmer (2012) states, based on experimental studies, that phenological effects may be less important than has been suggested, an analysis of phenological observations in plants by Wolkovich *et al.* (2012) shows that experimental data on phenology may grossly underestimate the actual phenological shifts.

Le Conte and Navajas (2008) state that the generally observed decline in honeybees is a clear indication of an increasing susceptibility to global change phenomena, with pesticide application, new diseases and stress (and a combination of these) as the most relevant causes. Climate change may contribute by modifying the balance between honeybees and their environment (including exposure or susceptibility to diseases). Honeybees show a high capacity to adjust to a variety of environments; their high genetic diversity should allow them to also cope with climatic change (Bartomeus *et al.*, 2011). The preservation of genetic variability within honeybees is regarded as a key adaptation strategy for pollination services (Le Conte and Navajas, 2008).

4.3.4.5. Moderation of Climate Change, Variability, and Extremes

The focus of this section is on processes operating at regional to global scales, rather than the well-known microclimatic benefits of ecosystems in smoothing day-night temperature variations and providing local evaporative cooling. In the decade 2000-2009, the global net uptake of CO_2 by terrestrial ecosystems was a large fraction of the anthropogenic CO_2 emissions to the atmosphere from all sources, reducing the rate of climate change proportionately (Section 4.3.2.3; WGI AR5 Section 6.3.2).

Afforestation or reforestation are a potential climate mitigation options (Van Minnen *et al.*, 2008; Vaughan and Lenton, 2011; Fiorese and Guariso, 2013; Singh *et al.*, 2013), but as discussed in Section 4.2.4.1, the net effect of afforestation on the global climate is mixed and context-dependent. Wickham *et al.* (2012) found significant positive correlations between the average annual surface temperature and the proportion of forest in the landscape and conclude that the climate benefit of temperate afforestation is unclear. Where low-albedo forest canopies replace higher-albedo surfaces such as soil, grassland or snow, the resultant increase in net radiative forcing counteracts the benefits of carbon sequestration to some degree (Arora and Montenegro, 2011). Where the cloud cover fraction is low and the albedo difference is large, i.e. outside the humid tropics, the long-term net result of afforestation can be global warming (Bala *et al.*, 2007; Bathiany *et al.*, 2010; Schwaiger and Bird, 2010). Accounting for changes in albedo and indirect greenhouse effects are not currently required in the formal rules for quantifying for the climate effects of land use activities (Schwaiger and Bird, 2010; Kirschbaum *et al.*, 2012). There are potential negative tradeoffs between afforestation for climate mitigation purposes and other ecosystem services, such as water supply (Jackson *et al.*, 2005) and biodiversity maintenance (CBD, 2012; Russell *et al.*, 2012).

It has been suggested (Ridgwell *et al.*, 2009) that planting large areas of crop varieties with highly reflective leaves could help mitigate global change. Model analyses indicate this “geo-engineering” strategy would be marginally effective at high latitudes, but have undesirable climate consequences at low latitudes. Measurements of leaf albedo in major crops show that the current range of variability is insufficient to make a meaningful difference to the global climate (Doughty *et al.*, 2011).

4.4. Adaptation and its Limits

4.4.1. Autonomous Adaptation by Ecosystems and Wild Organisms

Autonomous adaptation (see glossary under adaptation) refers to the adjustments made by ecosystems, including their human components, without external intervention, in response to a changing environment (Smit *et al.*, 2000); also called “spontaneous adaptation” (Smit *et al.*, 2007). In the context of human systems it is sometimes called “coping capacity”. The capacity for autonomous adaptation is part of resilience but is not exactly synonymous (Walker *et al.*, 2004).

All social and ecological systems have some capacity for autonomous adaptation. Ecosystems which have persisted for a long time can reasonably be inferred to have a high capacity for autonomous adaptation, at least with respect to the variability which they have experienced in the past. An environmental change that is more rapid than in the past or is accompanied by other stresses may exceed the previously-demonstrated adaptive capacity of the system. Adaptation at one level, for instance by organisms in a community, can confer greater resilience at higher organization levels, such as the ecosystem (Morecroft *et al.*, 2012). The mechanisms of autonomous adaptation of organisms and ecosystems consist of changes in the physiology, behaviour, phenology or physical form of organisms, within the range permitted by their genes and the variety of genes in the population; changes in the genetic composition of the populations; and change in the composition of the community, through in- or out-migration, or local extinction.

The ability to project impacts of climate change on ecosystems is complicated by the potential for species to adapt. Adaptation by individual species increases their ability to survive and flourish under different climatic conditions, possibly leading to lower risks of extinction than predicted from statistical correlations between current distribution and climate (Botkin *et al.*, 2007). It may also affect their interactions with other species leading to disruption of the biotic community (Visser and Both, 2005).

4.4.1.1. Phenological

Changes in phenology are occurring in many species and locations (Section 4.3.2.1). Further evidence since AR4 shows how this can be an adaptation to climate change, but also the limits to phenological adaptation. An organism's phenology is typically highly adapted to the climate seasonality of the environment in which it evolved. Species unable to adjust their phenological behaviour will be negatively affected, particularly in highly seasonal habitats (Both *et al.*, 2010).

Moreover, the phenology of any species also needs to be keyed to the phenology of other species with which it interacts, such as competitors, food species and pollinators. Systematic cross-taxa studies indicate different rates of phenological change for different species and trophic levels (Parmesan, 2007; Cook *et al.*, 2008; Thackeray *et al.*, 2010). If adaptation is insufficiently rapid or coordinated between interdependent species, disruption of ecological features such as trophic cascades, competitive hierarchies, and species coexistence is inferred to result (Nakazawa and Doi, 2012). Lack of coordination can occur if one of the species is cued to environmental signals that are not affected by climate change, such as day length (Parmesan, 2006). Increasing temperatures may either bring species more into or out of synchrony, depending on their respective starting positions (Singer and Parmesan, 2010), although evidence is more towards a loss of synchrony (Thackeray *et al.*, 2010).

Changes in interspecific interactions, such as predator-prey or interspecific competition for food, stemming from changes in phenological characteristics and breakdown in synchrony between species have been observed. For example, bird breeding is most effective when synchronized with the availability of food, so changes in the phenology of food supplies can exert a selective pressure on birds. In a study of 100 European migratory bird species, those that advanced their arrival date showed stable or increasing populations between 1990 and 2000, while those that did not adjust their arrival date on average showed declining populations (Møller *et al.*, 2008). In a comparison of nine Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) between 1987 and 2003, populations declined by 90% in areas where food peaked early in the season and the arrival of the birds was mis-timed, but not in areas with a later food peak which could still be exploited by early-breeding birds (Both *et al.*, 2006). However, compensating processes can exist: for example, in a 4-decade study of great tits (*Parus major*), breeding populations were buffered against phenological mismatch due to relaxed competition between individual fledglings (Reed *et al.*, 2013). Between 1970 and 1990, changes in migration date did not predict changes in population (Møller *et al.*, 2008).

Bird breeding can also be affected by phenological shifts in competing species and predators. Between 1953 and 2005 in south-western Finland, the onset of breeding of the resident great tit *Parus major* and the migratory pied flycatcher (*Ficedula hypoleuca*) became closer to each other, increasing competition between them (Ahola *et al.*, 2007). The edible dormouse (*Glis glis*), a nest predator, advanced its hibernation termination by -8 days per decade in the Czech Republic between 1980 and 2005 due to increasing annual spring air temperatures, leading to increased nest predation in three out of four bird surveyed species (Adamik and Kral, 2008).

Plant-insect interactions have also been observed to change. In Illinois, USA, the pattern of which plants were pollinated by which bees were altered by differing rates of phenological shifts and landscape changes over 120 years, with 50% of bee species becoming locally extinct (Burkle *et al.*, 2013). Increasing asynchrony of the winter moth (*Operophtera brumata*) and its feeding host oak tree (*Quercus robur*) in the Netherlands was linked to increasing spring temperatures but unchanging winter temperatures (van Asch and Visser, 2007). Warmer temperatures shorten the development period of European pine sawfly larvae (*Neodiprion sertifer* Geoffr.), reducing the risk of predation and potentially increasing the risk of insect outbreaks, but interactions with other factors including day length and food quality may complicate this prediction (Kollberg *et al.*, 2013). In North America, the spruce budworm (*Choristaneura fumiferana*) lays eggs with a wide range of emergence timings, so the population as a whole is less sensitive to changing phenology of host trees (Volney and Fleming, 2007).

The environmental cues for phenological events are complex and multi-layered (Körner and Basler, 2010; Singer and Parmesan, 2010). For instance, many late-succession temperate trees require a chilling period in winter, followed by a threshold in day length, and only then are sensitive to temperature. As a result, simple projections of current phenological trends may be misleading, since the relative importance of cues can change (Cook *et al.*, 2012b). The effects are complex and sometimes apparently counterintuitive, such as the increased sensitivity of flowering in high-altitude perennial herbs in the Rocky Mountains to frost, since plants begin flowering earlier as a result of earlier snowmelt (Inouye, 2008).

It has been suggested that shorter generation times give greater opportunity for autonomous adaptation through natural selection (Rosenheim and Tabashnik, 1991; Bertaux *et al.*, 2004), but a standardized assessment of 25,532 rates of phenological change for 726 UK taxa indicated that generation time only had limited influence on adaptation rates (Thackeray *et al.*, 2010).

There is *high confidence* [*much evidence, medium agreement*] that climate change-induced phenological shifts will continue to alter the interactions between species in regions with a marked seasonal cycle.

4.4.1.2. Evolutionary and Genetic

Since AR4 there has been substantial progress in defining the concepts and tools necessary for documenting and predicting evolutionary and genetic responses to recent and future climate change, often referred to as "rapid evolution". Evolution can occur through many mechanisms, including selection of existing genes or genotypes within populations, hybridization, mutation and selection of new adaptive genes and perhaps even through epigenetics (Chevin *et al.*, 2010; Chown *et al.*, 2010; Lavergne *et al.*, 2010; Paun *et al.*, 2010; Hoffmann and Sgro, 2011; Anderson *et al.*, 2012a; Donnelly *et al.*, 2012; Franks and Hoffmann, 2012; Hegarty, 2012; Merilä, 2012; Bell, 2013; Zhang *et al.*, 2013). Mechanisms such as selection of existing genes and genotypes, hybridization and epigenetics can lead to adaptation in very few generations, while others, notably mutation and selection of new genes, typically take many tens of generations. This means that species with very fast life cycles, e.g., bacteria, should in general have greater capacity to respond to climate change than species with long life cycles, such as large mammals and trees. There is a paucity of observational or experimental data that can be used for detection and attribution of recent climate effects on evolution.

Observed evolutionary and genetic responses to rapid changes in climate - There is a small but growing body of observations supporting the AR4 assessment that some species may have adapted to recent climate warming or to climatic extremes through genetic responses (e.g., plants: Franks and Weis, 2008; Hill *et al.*, 2011; Anderson *et al.*, 2012b; vertebrates: Ozgul *et al.*, 2010; Phillimore *et al.*, 2010; Husby *et al.*, 2011; Karell *et al.*, 2011; insects: Buckley *et al.*, 2012; van Asch *et al.*, 2012). Karell *et al.* (2011) found increasing numbers of brown genotypes of the tawny owl (*Strix aluco*) in Finland over the course of the last 28 years and attributed it to fewer snow-rich winters, which creates strong selection pressure against the white genotype. Earlier spawning by the common frog (*Rana temporaria*) in Britain could be attributed largely to local genetic adaptation to increasing spring temperatures (Phillimore *et al.*, 2010). Using a combination of models and observations, Husby *et al.* (2011) have built a case for detection and attribution of genetic adaptation in an insectivorous bird, and in an herbivorous insect that has tracked warming-related changes in the budburst timing of its host tree (van Asch *et al.*, 2012). In contrast, many species appear to be maladapted to changing climates, in part because factors such as limited existing genetic variation, weak heritability of adaptive traits or conflicting constraints on adaptation create low potential for rapid evolution (Knudsen *et al.*, 2011; Ketola *et al.*, 2012; Mihoub *et al.*, 2012; Merilä, 2012). Most studies of rapid evolution suffer from methodological weaknesses, making it difficult to clearly demonstrate a genetic basis underlying observed phenotypic responses to environmental change (Gienapp *et al.*, 2008; Franks and Hoffmann, 2012; Hansen *et al.*, 2012; Merilä, 2012). Rapid advances in quantitative genetics, genomics and phylogenetics, combined with recent progress on conceptual frameworks, will substantially improve the detection and attribution of genetic responses to changing climate over the next few years (Davis *et al.*, 2010; Salamin *et al.*, 2010; Hoffmann and Sgro, 2011). In sum, there are few observational studies of rapid evolution and difficulties in detection and attribution, so there is only *medium confidence* that some species have responded to recent changes in climate through genetic adaptations, and insufficient evidence to determine if this is a widespread phenomenon (thus *low confidence* for detection and attribution across all species; Figure 4-4).

The ability of species to adapt to new environmental conditions through rapid evolutionary processes can also be inferred from the degree to which environmental niches are conserved when environment is changed. There is evidence that environmental niches are conserved for some species under some conditions (plants: Petitpierre *et al.*, 2012; birds: Monahan and Tingley, 2012; review: Peterson *et al.*, 2011), but also evidence suggesting that environmental niches can evolve over time scales of several decades following changes in climate (Broennimann *et al.*, 2007; Angetter *et al.*, 2011; Konarzewski *et al.*, 2012; Leal and Gunderson, 2012; Lavergne *et al.*, 2013). The paleontological record provides insight into evolutionary responses in the face of natural climate variation. In general, environmental niches appear to be broadly conserved through time although there is insufficient data to determine the extent to which genetic adaptation has attenuated range shifts and changes in population size (Peterson *et al.*, 2011; Willis and MacDonald, 2011). Phylogeographic reconstructions of past species distributions suggest that hybridization may have helped avoid extinctions during cycles of glaciation and could also play a key role in future adaptation (Soliani *et al.*, 2012; Hegarty, 2012). There is new evidence that epigenetic mechanisms, such as DNA methylation, could allow very rapid adaptation to climate (Paun *et al.*, 2010; Zhang *et al.*, 2013).

Mechanisms mediating rapid evolutionary response to future climate change - Studies of genetic variability across species ranges, and models that couple gene flow with spatially-explicit population dynamics, suggest counterintuitive responses to climate change. Too much or too little gene flow to populations at range margins can create fragile, maladapted populations, which is in contrast to the current wisdom that populations at the range margins may be best adapted to global warming (Bridle *et al.*, 2010; Hill *et al.*, 2011). Conversely, there is evidence from experiments, models and observations that populations in the centre of species ranges may in some cases be more sensitive to environmental change than those at range boundaries (Bell and Gonzalez, 2009). Generalization is complicated by the interactions between local adaptation, gene flow, population dynamics and species interactions (Bridle *et al.*, 2010; Norberg *et al.*, 2012).

Substantial progress has been made since AR4 in developing models for exploring whether genetic adaptation is fast enough to track climate change. Models of long-lived tree species suggest that existing genetic variation may be sufficient to slightly attenuate negative impacts of future climate change (Kuparinen *et al.*, 2010; Kremer *et al.*, 2012), which is coherent with observations and experiments (Jump *et al.*, 2006, Jump *et al.*, 2008). However, these studies also indicate that adaptive responses will lag far behind even modest rates of projected climate change, due to the very long generation time of trees. In a species with much shorter generation times, the great tit (*Parus major*), Gienapp *et al.* (2013) found that modelled avian breeding times tracked climate change, only at low to moderate rates of change. For a herbivorous insect with an even faster life cycle, van Asch *et al.*, (2007; 2012) predicted that rapid evolution of the phenological response should have allowed it to track recent warming, which it has. More broadly, models suggest that species with short generation times, (one year or less), potentially have the capacity to genetically adapt to even the most rapid rates of projected climate change given large enough present-day populations, but species with longer generation times or small populations could be at risk of extinction at moderate to high rates of climate change (Walters *et al.*, 2012; Vedder *et al.*, 2013). Recent experimental and theoretical work on “evolutionary rescue” shows that long-term avoidance of extinction through genetic adaptation to hostile environments is possible, but requires large initial genetic variation and population sizes and is accompanied by substantial loss of genetic diversity, reductions in population size and range contractions over many generations before population recovery (Bell, 2013; Schiffers *et al.*, 2013). Model-based projections must be viewed with considerable caution because there are many evolutionary and ecological mechanisms not accounted for in most models that can either speed up or inhibit heritable adaptation to climate change (Cobben *et al.*, 2012; Norberg *et al.*, 2012; Kovach-Orr and Fussmann, 2013). In some cases, accounting for evolutionary processes in models even leads to predictions of greater maladaptation to climate change, resulting in rapid population declines (Hendry and Gonzalez, 2008; Ferriere and Legendre, 2013). Phenotypic plasticity is thought to generally improve the odds of adaptation to climate change. High plasticity in the face of climate change that has low fitness costs can greatly improve the odds of adaptation; however, plasticity with high costs leads to only modest amounts of adaptation (Chevin *et al.*, 2010).

AR4 concluded that "projected rates of climate change are *very likely* to exceed rates of evolutionary adaptation in many species (*high confidence*)" (Fischlin *et al.*, 2007). Work since then provides a similar, but more nuanced view of rapid evolution in the face of future climate change. The lack of adaptation in some species to recent changes in climate, broad support for niche conservatism, and models showing limited adaptive capacity in species with long generation times, all indicate that high rates of climate change (RCP8.5) will exceed the adaptive capacities of many species (*high confidence*). On the other hand, evidence from observations and models also indicates that there is substantial capacity for genetic adaptation to attenuate phenological shifts, population declines and local extinctions in many species, especially for low rates of climate change (RCP2.6) (*high confidence*). Projected adaptation to climate change is frequently characterized by population declines and loss of genetic diversity for many generations (*medium confidence*), thereby increasing species vulnerability to other pressures.

4.4.1.3. Migration of Species

This mode of adaptation has been extensively dealt with in Section 4.3.2.5. It is anticipated that the observed movement of species – individually and collectively – will continue in response to shifting climate patterns. Its effectiveness as an adaptation mechanism is constrained by three factors. First, the rate of migration for many species, in many regions of the world, is slower than the rate of movement of the climate envelope (see Figure 4-5). Second, the ecosystem interactions can only remain intact if all parts of the ecosystem migrate simultaneously and at the same rate. Thirdly, the contemporary landscape and inland water systems contain many barriers to migration, in the form of habitat fragmentation, roads, human settlements and dams. Mountain ecosystems are less constrained by these factors than flat-land ecosystems, but have additional impediments for species already close to the top of the mountain.

4.4.2. Human-Assisted Adaptation

Human-assisted adaptation means a deliberate, intervention with the intent of increasing the capacity of the target organism, ecosystem or social-ecological system to survive and function at an acceptable level in the presence of climate change. It is also known as "planned adaptation" (Smit *et al.*, 2007). This chapter focuses less on the adaptation of people, human communities and infrastructure, since they are the topics of Chapters 8 to 17, and more on non-human organisms and ecosystems, while acknowledging the importance of the human elements within the ecosystem. Intervention in this context means a range of actions, including ensuring the presence of suitable habitat and dispersal pathways; reducing non-climate stressors; physically moving organisms, storing and establishing them in new places. In addition to the other approaches assessed in this section, "Ecosystem-based Adaptation" (see Cross-Chapter Box CC-EA) provides an option that integrates the use of biodiversity and ecosystem services into climate change adaptation strategies in ways that can optimize co-benefits for local communities and carbon management, as well as reduce the risks associated with possible maladaptation. Note that there are risks associated with all forms of human-assisted adaptation (see Section 4.4.4), particularly in the presence of far-from-perfect predictive capabilities (Willis and Bhagwat, 2009).

4.4.2.1. Reduction of Non-Climate Stresses and Restoration of Degraded Ecosystems

The alleviation of other stresses acting on ecosystems is suggested to increase the capacity of ecosystems to survive, and adapt to, climate change, since the effects are generally either additive or compounding. Ecosystem restoration is one way of alleviating such stresses while increasing the area available for adaptation (Harris *et al.*, 2006). Building the resilience of at-risk ecosystems by identifying the full set of drivers of change and most important areas and resources for protection is the core of the adaptation strategy for the Arctic (Christie and Sommerkorn, 2012). Protective and restorative actions aimed at increasing resilience can also be cost-effective means as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change and may have other social, economic and cultural benefits. This is part of “ecosystem-based adaptation” (Colls *et al.*, 2009; Box CC-EA).

4.4.2.2. The Size, Location, and Layout of Protected Areas

Additions to, or reconfigurations of, the protected area estate are commonly suggested as pre-adaptations to projected climate changes (Heller and Zavaleta, 2009). This is because for most protected areas, under plausible scenarios of climate change, a significant fraction of the biota will no longer have a viable population within the present protected area footprint. It is noted that the extant geography of protected areas is far from optimal for biodiversity protection even under the current climate; that most biodiversity exists outside rather in protected areas and this between-protected area matrix is as important; that it is usually cheaper to acquire land proactively in the areas of projected future bioclimatic suitability than to correct the current non-optimality and then later add on areas to deal with climate change as it unfolds (Hannah *et al.*, 2007); and that the existing protected area network will still have utility in future climates, even though it may contain different species (Thomas *et al.*, 2012). Hickler *et al.* (2012) analysed the layout of protected areas in Europe and concluded that under projected 21st century climate change a third to a half of them would potentially be occupied by different vegetation than they currently represent. The new areas that need to be added to the existing protected area network to ensure future representativeness is situation-specific, but some general design rules apply: orientation along climate gradients (e.g., altitudinal gradients) is more effective than orientation across them (Roux *et al.*, 2008); regional scale planning is more effective than treating each local case independently since it is the network of habitats and protected areas that confers resilience rather than any single element (Heller and Zavaleta, 2009); and better integration of protected areas with a biodiversity-hospitable landscape outside is more effective than treating the protected areas as islands (Willis and Bhagwat, 2009). Dunlop *et al.* (2012) assessed the implications of climate change for biodiversity conservation in Australia and found many opportunities to facilitate the natural adaptation of biodiversity, including expanding the network of protected areas and restoring habitat at a large scale.

4.4.2.3. Landscape and Watershed Management

The need to include climate change into the management of vulnerable ecosystems is explicitly included in the strategic goals of the Convention on Biological Diversity. Oliver *et al.* (2012b) developed decision trees based on three scenarios: a) *adversely sensitive*, where areas within the species current geographical range will become climatically unsuitable with a changing climate; b) *climate overlap*, where there are areas that should remain climatically suitable within the species’ range; and c) *new climatic space*, which refers to areas outside of the current range that are projected to become suitable. Heller and Zavaleta (2009) reviewed recommendations in the published literature and argue that the majority of them, such as increase habitat heterogeneity of sites and connectivity of habitats across landscapes, lack sufficient specificity to ensure the persistence of many species and related ecosystem services to ongoing climate change. To date, recommendations are overwhelmingly focused on ecological data, neglecting social science insights. Few resources or capacity exist to guide adaptation planning processes at any scale.

Climate-induced impacts to hydrological and thermal regimes in freshwater systems can be offset through improved management of environmental flow releases from reservoirs (Arthington *et al.*, 2006; Poff *et al.*, 2010; Arthington *et al.*, 2010 and references therein). Protection and restoration of riparian vegetation in small stream systems provide an effective strategy to moderate temperature regimes and offset warming, and protect water quality for downstream ecosystems and water supply areas (Davies, 2010; Capon *et al.*, 2013).

General principles for management adaptations were summarized from a major literature review by West *et al.* (2009). They suggest that in the context of climate change, successful management of natural resources will require cycling between "managing for resilience" and "managing for change". This requires the anticipation of changes that can alter the impacts of grazing, fire, logging, harvesting, recreation, and so on. At the national level, principles to facilitate adaptation include: (1) management at appropriate scales, and not necessarily the scales of convenience or tradition; (2) increased collaboration among agencies; (3) rational approaches for establishing priorities and applying triage; and (4) management with the expectation of ecosystem change, rather than keeping them as they have been. Barriers and opportunities were divided into four categories: (1) legislation and regulations, (2) management policies and procedures, (3) human and financial capital, and (4) information and science.

Steenberg *et al.* (2011) simulated the effect on adaptive capacity of three variables related to timber harvesting: the canopy-opening size of harvests, the age of harvested trees within a stand, and the species composition of harvested trees within a stand. The combination of all three adaptation treatments allowed target species and old forest to remain reasonably well represented without diminishing the timber supply. This minimized the trade-offs between management values and climate adaptation objectives. Manipulation of vegetation composition and stand structure has been proposed as a strategy for offsetting climatic change impacts on wildfires in Canada. Large areas of boreal forests are currently being harvested and there may be opportunities for using planned manipulation of vegetation for management of future wildfire risks. This management option could also provide an additional benefit to the use of assisted species migration since the latter would require introducing non-flammable broadleaves species into forests which are otherwise highly flammable (Girardin *et al.*, 2013b; Terrier *et al.*, 2013). Harvesting practices, like partial cuts that limit the opening of the forest cover created by harvest, will be a key element to maintain diverse forest compositions and age class distributions in boreal forests. Other sound option for decreasing the exposure of silvicultural investments to an increasing fire danger is to use tree species necessitating a shorter rotation (Girardin *et al.*, 2013a).

4.4.2.4. Assisted Migration

Assisted migration has been proposed when fragmentation of habitats limits migration potential or when natural migration rates are outstripped by the pace of climate change (Hoegh-Guldberg *et al.*, 2008; Vitt *et al.*, 2010; Chmura *et al.*, 2011; Loss *et al.*, 2011; Ste-Marie *et al.*, 2011). The options for management can be summarized as: i) try to maintain or improve existing habitat or environment so that species don't have to move (e.g., Yan *et al.*, 2013), ii) maintain or improve migration corridors, including active management to improve survival along the moving margin of the distribution (Lawson *et al.*, 2012), and iii) directly translocate species or genetically distinct populations within a species (Aitken *et al.*, 2008; Hoegh-Guldberg *et al.*, 2008; Rehfeldt and Jaquish, 2010; Loss *et al.*, 2011; Pedlar *et al.*, 2012). There is *low agreement* whether it is better to increase the resilience to climate change of ecosystems as they currently occur, or to enhance the capacity of ecosystems to transform in the face of climate change (Richardson *et al.*, 2009).

There is *high agreement* that maintaining or improving migration corridors or ecological networks is a low-regret strategy, partly because it is also seen as useful in combatting the negative effects of habitat fragmentation on population dynamics (Hole *et al.*, 2011; Jongman *et al.*, 2011). This approach has the benefit of improving the migration potential for large numbers of species and is therefore a more ecosystem-wide approach than assisted migration for individual species. However, observational and modelling studies show that increases in habitat connectivity do not always improve the population dynamics of target species, may decrease species diversity, and may also facilitate the spread of invasive species (Cadotte, 2006; Brisson *et al.*, 2010; Matthiessen *et al.*, 2010).

There is *medium agreement* that the practice of assisted migration of targeted species is a useful adaptation option (Hoegh-Guldberg *et al.*, 2008; Vitt *et al.*, 2009; Willis and Bhagwat, 2009; Loss *et al.*, 2011; Hewitt *et al.*, 2011). The velocity of 21st century climate change and substantial habitat fragmentation in large parts of the world means that many species will be unable to migrate or adapt fast enough to keep pace with climate change (Figure 4-5), posing problems for long-term survival of the species. Some ecologists believe that careful selection of species to be moved would minimize the risk of undesirable impacts on existing communities or ecosystem function (Minteer and Collins, 2010), but others argue that the history of intentional species introductions shows that the outcomes are unpredictable and in many cases have had disastrous impacts (Ricciardi and Simberloff, 2009). The number of species that require assisted migration could easily overwhelm funding capacity (Minteer and Collins, 2010). Decisions regarding which species should be translocated are complex and debatable, given variability among and within species and the ethical issues involved (Aubin *et al.*, 2011; Winder *et al.*, 2011b).

4.4.2.5. Ex Situ Conservation

Conservation of plant and animal genetic resources outside of their natural environment, in gardens, zoos, breeding programmes, seed-banks or gene-banks has been widely advocated as an “insurance” against both climate change and other sources of biodiversity loss and impoverishment (Khoury *et al.*, 2010). There are many examples of existing efforts of this type, some with global scope (e.g., Millennium Seed Bank, Svalbard vault, Frozen Ark, Global Genome Initiative and others; Leishman *et al.*, 2007; Lermen *et al.*, 2009; Rawson *et al.*, 2011). Knowledge of which genetic variants within a species have more potential for adaptation to climate change could help prioritise the material stored (Colautti *et al.*, 2010).

Several issues remain largely unresolved (Li and Pritchard, 2009). The physiological, institutional and economic sustainability of such efforts into the indefinite future is unclear. The fraction of the intra-specific variation that needs to be preserved for future viability and how much genetic bias is introduced by collecting relatively small samples from restricted locations, and then later by the selection pressures inadvertently applied during ex-situ maintenance are unknown. Despite some documented successes, it remains uncertain whether it is always possible to reintroduce species successfully into the wild after generations of *ex-situ* conservation.

4.4.3. Consequences and Costs of Inaction and Benefits of Action

Failure to reduce the magnitude or rate of climate change will plausibly lead to changes (often decreases) in the value of ecosystem services provided, or incur costs in order to maintain or restore the services or adapt to their decline. There are several sources of such costs: administration and assessment, implementation, and opportunity costs, including financial cost. Owing to the number of assumptions made, knowledge gaps and recognized uncertainties, such result should be employed with caution. A systematic review of costs related to ecosystems and climate change by Rodriguez-Labajos (2013), shows that the monetary and non-monetary costs are distributed across all ecosystem service categories. Rodriguez-Labajos (2013) also discusses the potential and limits of monetary cost calculations, and issues of timing, trade-offs and the unequal distribution of costs.

A comprehensive monetary estimate of the effects of climate change on ecosystem service provision is not available. The Millennium Ecosystem Assessment (2005c; 2005d; 2005e) included climate change among the direct drivers of ecosystems change and devoted a chapter to the necessary responses. Building on results of the IPCC, the MA offered some estimated costs of action: complying with the Kyoto protocol for industrial countries would range between 0.2 and 2% of GDP; a modest stabilization target of 450 ppm CO_2 in the atmosphere over the 21st century would range from 0.02 to 0.1% of global-average GDP per year. TEEB (2009) underlined priorities in the ecosystem service-climate change coupling (reduction targets in relation to coral reefs, forest carbon markets and accounting, and ecosystem investment for mitigation), without going in depth into analysis of the cost types involved. The Cost of Policy Inaction (COPI) Project (ten Brink *et al.*, 2008) estimated the monetary costs of not meeting the 2010 biodiversity goals. Their model incorporates climate change, among other pressures, through an impaired quality of land, in terms of species abundance in diverse land-use categories. They conclude that the cumulative losses of welfare due to land-use changes, in terms of loss of ecosystem services, could reach an annual amount of EUR 14 trillion (based on values of 2007) in 2050, which may be equivalent to 7% of projected global GDP for that year. Eliasch (2008) estimates the damage costs to forests as reaching USD 1 trillion a year by 2100. The study used the probabilistic model employed by Stern (2006), which did not value effects on biodiversity or water-related ES.

The studies to date agree on the following points. First, climate change has already caused a reduction in ecosystem services which will become more severe as climate change continues. Second, ecosystem-based strategies to mitigate climate change are cost-effective, although more difficult to implement (i.e., more costly) in intensively managed ecosystems such as farming lands. Third, accurately estimating the monetary costs of reduction in ecosystem services that are not marketed is difficult. The provision of monetized costs tends to sideline the non-monetized political, social, and environmental costs relevant for decision making. Finally, there is a large funding gap between the cost of actions necessary to protect ecosystem services against climate change and the actual resources available.

In addition to direct costs, further costs may result from trade-offs between services: e.g. afforestation for climate mitigation and urban greening for climate adaptation may be costly in terms of water provision (Chisholm, 2010; Jenerette *et al.*, 2011; Pataki *et al.*, 2011). Traditional agriculture preserves soil carbon sinks, supports on-site biodiversity and uses less fossil fuel than high-input agriculture (Martinez-Alier, 2011), but due to the typically lower per hectare yields, may require a larger area to be dedicated to cropland. Leaving aside the contested (Searchinger *et al.*, 2008; Plevin *et al.*, 2010) effectiveness of biofuels as a mitigation strategy, there is evidence of their disruptive effect on food security, land tenure, labour rights and biodiversity in several parts of the world (Obersteiner *et al.*, 2010; Tirado *et al.*, 2010).

4.4.4. Unintended Consequences of Adaptation and Mitigation

Actions taken within the terrestrial and freshwater system domain or in other sectors to mitigate or adapt to climate change can have unintended consequences. Some issues relevant to this section are also found in Section 14.7 and the Working Group III report.

Several of the alternatives to fossil fuel require extensive use of the land surface and thus have a direct impact on terrestrial ecosystems and an indirect impact on inland water systems (Paterson *et al.*, 2008; Turner *et al.*, 2010). As an illustration, the RPC2.6 scenario involves both bioenergy and renewables as major components of the energy mix (Box 4-1; van Vuuren *et al.*, 2011).

Policy shifts in developed countries favour the expansion of large-scale bioenergy production, which places new pressures on terrestrial and freshwater ecosystems (Searchinger *et al.*, 2008; Lapola *et al.*, 2010), either through direct use of land or water or indirectly by displacing food crops, which must then be grown elsewhere. Over the past decade there has been a global trend to reduced rates of forest loss; it is unclear if this will continue in the face of simultaneously rising food and biofuel demand (Wise *et al.*, 2009; Meyfroidt and Lambin, 2011). The EU Renewable Energy Sources Directive is estimated to have only a moderate influence on European forests provided that the price paid by the bioenergy producers remained below 50-60 US$ per m^3 wood (Moiseyev *et al.*, 2011). However, a doubled growth rate for bioenergy until 2030 would have major consequences for the global forest sector, including a reduction of forest stocks in Asia of 2 % to 4% (Martin *et al.*, 2010). By 2100 in RCP2.6, bioenergy crops are projected to occupy approximately 4 million km^2, approximately 7% of global cultivated land projected at the time. Modification of the landscape and the fragmentation of habitats are major influences on extinction risks (Fischer and Lindenmayer, 2007), especially if native vegetation cover is reduced or degraded, human land use is intensive and “natural” areas become disconnected. Hence, additional extensification of cultivated areas for energy crops may contribute to extinction risks. Some bioenergy crops may be invasive species (Raghu *et al.*, 2006).

Abandoned former agricultural land could be used for biomass production (McAlpine *et al.*, 2009). However, such habitats may be core elements in cultural landscapes of high conservation value, with European species-rich grasslands often developed from abandoned croplands (Hejcman *et al.*, 2013).

Damming of river systems for hydropower can cause fragmentation of the inland water habitat with implications for fish species, and monitoring studies indicate that flooding of ecosystems behind the dams can lead to declining populations, e.g., of amphibians (Brandão and Araújo, 2007). Reservoirs can be a sink of CO_2 but also a source of biogenic CO_2 and CH_4 – this issue is discussed in WG III AR5 Section 7.8.1.

Wind turbines can kill birds and bats (e.g., Barclay *et al.*, 2007), and inappropriately-sited wind farms can negatively impact on bird populations (Drewitt and Langston, 2006). Effects can be reduced by careful siting of turbines, for example by avoiding migration routes (Drewitt and Langston, 2006). Estimating mortality rates is complex and difficult (Smallwood, 2007) but techniques are being developed in order to inform siting decisions and impact assessments (Péron *et al.*, 2013). Wind farms in Europe and the USA are estimated to cause between 0.3 and 0.4 wildlife fatalities *per* gigawatt-hour (GWh) of electricity, compared to approximately 5.2 fatalities *per* GWh nuclear and fossil-fuel power stations (Sovacool, 2009; but see Willis *et al.*, 2010c). One study found on-site bird populations to be generally affected more by windfarm construction than subsequent operation, with some populations recovering after construction (Pearce-Higgins *et al.*, 2012).

Large-scale solar farms could impact local biodiversity if poorly sited, but the impact can be reduced with appropriate planning (Tsoutsos *et al.*, 2005). Solar PV installations can decrease local surface albedo, giving a small positive radiative forcing. There are some plausible local circumstances in which this may be a consideration, but in general the climate effect is estimated to be 30times smaller than the avoided radiative forcing arising from substituting fossil fuels with PV (Nemet, 2009).

Relocation or expansion of agricultural areas and settlements as climate change adaptation measures could pose risks of habitat fragmentation and loss similar to those discussed above in the context of mitigation through bio-energy. Assisted migration (see Section 4.4.2.4) may directly conflict with other conservation priorities, for example by facilitating the introduction of invasive species (Maclachlan *et al.*, 2007).

4.5. Emerging Issues and Key Uncertainties

Detecting the presence and location of thresholds in ecosystem response to climate change, and specifically the type of thresholds characterized as tipping points, remains a major source of uncertainty with high potential consequences. In general (Field *et al.*, 2007), negative feedbacks currently dominate the climate-ecosystem interaction. For most ecological processes, increasing magnitude of warming shifts the balance towards positive rather than negative feedbacks (Field *et al.*, 2007). In several regions, such as the boreal ecosystems, positive feedbacks may become dominant, under moderate warming). For positive feedbacks to propagate into ‘runaway’ processes leading to a new ecosystem state, the strength of the feedback has to exceed that of the initial perturbation. This has not as yet been demonstrated for any large-scale, plausible and immanent ecological process; but the risk is non-negligible and the consequences if it did occur would be severe: thus further research is needed.

The issue of biophysical interactions between ecosystem state and the climate, over and above the effects mediated through greenhouse gases, is emerging as significant in many areas. Such effects include those caused by changes in surface reflectivity (albedo) or the partitioning of energy between latent energy and sensible heat.

Uncertainty in predicting the response of terrestrial and freshwater ecosystems to climate and other perturbations, particularly at the local scale, remains a major impediment to determining prudent levels of permissible change. A significant source of this uncertainty stems from the inherent complexity of ecosystems, especially where they are coupled to equally-complex social systems. The high number of interactions can lead to cascading effects (Biggs *et al.*, 2011). Some of this uncertainty can be reduced by better systems understanding, but some will remain irreducible because of the failure of predictive models when faced with certain types of complexity (such as those which lead to mathematical bifurcations – a problem that is well-known in climate science). Probabilistic statements about the range of outcomes are possible in this context, but ecosystem science is as yet mostly unable to conduct such analyses routinely and rigorously. One consequence is the ongoing difficulty in attributing observed changes unequivocally to climate change. More comprehensive monitoring is a key element of the solution.

The consequences for species interactions of differing phenological or movement-based responses to climate change are insufficiently known and may make projections based on individual species models unreliable.

Studies of the combined effects of multiple simultaneous elements of global change, such as the effects of elevated carbon dioxide and rising tropospheric ozone on plant productivity - which has critical consequences for the future sink strength of the biosphere, since they are of similar magnitude but opposite sign – are needed as a supplement to the single-factor experiments. For example, uncertainty on the magnitude of CO_2 fertilization is key for forest responses to climate change, particularly in tropical forests, woodlands and savannas (Cox *et al.*, 2013; Huntingford *et al.*, 2013).

The effects of changes in the frequency or intensity of climate-related extreme events, such as floods, cyclones , heat waves, exceptionally large fires on ecosystem change are probably equal to or greater than shifts in the mean values of climate variables. These effects are insufficiently studied, and in particular, are seldom adequately represented in Earth system models.

Understanding of the *rate* of climate change that can be tracked or adapted to by organisms is as important as understanding the *magnitude* of change they can tolerate. Despite being explicitly required under Article 2 of the UNFCCC, rate studies are currently less developed and more uncertain than magnitude (equilibrium) studies. This includes evidence for the achievable migration rates of a range of species as well as the rate of micro-evolutionary change.

The capacity for, and limits to, ecological and evolutionary adaptive processes are only known in a few cases. The development and testing of human-assisted adaptation strategies for their cost-effectiveness in reducing risk is a prerequisite for their widespread adoption.

The costs of the loss of biodiversity and ecosystem services as a result of climate change is known for only a few cases, or is associated with large uncertainties; as are the costs and benefits of assisting ecosystems and species to adapt to climate change.

Frequently Asked Questions

FAQ 4.1: How do land-use and land-cover changes cause changes in climate? *[to be placed in Section 4.2.4.1]*
Land use change affects the local as well as the global climate. Different forms of land cover and land use can cause warming or cooling and changes in rainfall, depending on where they occur in the world, what the preceding land cover was, and how the land is now managed. Vegetation cover, species composition and land management practices (such as harvesting, burning, fertilizing, grazing or cultivation) influence the emission or absorption of greenhouse gases. The brightness of the land cover affects the fraction of solar radiation that is reflected back into the sky, instead of being absorbed, thus warming the air immediately above the surface. Vegetation and land use patterns also influence water use and evapotranspiration, which alter local climate conditions. Effective land-use strategies can also help to mitigate climate change.

FAQ 4.2: What are the non-greenhouse gas effects of rising carbon dioxide on ecosystems?
[to be placed in Section 4.2.4.4]
Carbon dioxide (CO_2) is an essential building block of the process of photosynthesis. Simply put, plants use sunlight and water to convert CO_2 into energy. Higher CO_2 concentrations enhance photosynthesis and growth (up to a point), and reduce the water used by the plant. This means that water remains longer in the soil or recharges rivers and aquifers. These effects are mostly beneficial; however, high CO_2 also has negative effects, in addition to causing global warming. High CO_2 levels cause the nitrogen content of forest vegetation to decline and can increase their chemical defences, reducing their quality as a source of food for plant-eating animals. Furthermore, rising CO_2 causes ocean waters to become acidic (see FAQ 6.3), and can stimulate more intense algal blooms in lakes and reservoirs.

FAQ 4.3: Will the number of invasive alien species increase due to climate change?
[to be placed in Section 4.2.4.6]
Some invasive plants and insects have already been shown to benefit from climate change and will establish and spread into new regions (where they are ‘aliens’), once they are introduced. The number of newly-arrived species

and the abundance of some already-established alien species will increase because climate change will improve conditions for them. At the same time, increasing movement of people and goods in the modern world, combined with land use changes worldwide, increases the likelihood that alien species are accidentally transported to new locations and become established there. There are many actions which can be taken to reduce, but not eliminate, the risk of alien species invasions, such as the treatment of ballast water in cargo ships and wood products, strict quarantine applied to crop and horticultural products, and embargos on the trade and deliberate introduction of known invader species. Some invasive species will suffer from climate change and are expected to decrease in range and population size in some regions. Generally, increased establishment success and spread will be most visible for those alien species that have characteristics favoured by the changing climate, such as those that are drought tolerant or able to take advantage of higher temperatures.

FAQ 4.4: How does climate change contribute to species extinction? *[to be placed in Section 4.3.2.5]*
There is a consensus that climate change over the coming century will increase the risk of extinction for many species. When a species becomes extinct, a unique and irreplaceable life form is lost. Even local extinctions can impair the healthy functioning of ecosystems.

Under the fastest rates and largest amounts of projected climate change, many species will be unable to move fast enough to track suitable environments, which will greatly reduce their chances of survival. Under the lowest projected rates and amounts of climate change, and with the assistance of effective conservation actions, the large majority of species *will* be able to adapt to new climates, or move to places that improve their chances of survival. Loss of habitat and the presence of barriers to species movement increase the risk of extinctions as a result of climate change.

Climate change may have already contributed to the extinction of a small number of species, such as frogs and toads in Central America, but the role of climate change in these recent extinctions is the subject of considerable debate.

FAQ 4.5: Why does it matter if ecosystems are altered by climate change? *[to be placed in Section 4.3.4]*
Ecosystems provide essential services for all life; food, life-supporting atmospheric conditions, drinkable water, as well as raw materials for basic human needs like clothing and housing. Ecosystems play a critical role in limiting the spread of human and non-human diseases. They have a strong impact on the weather and climate itself, which in turn impacts agriculture, food supplies, socio-economic conditions, floods and physical infrastructure. When ecosystems change, their capacity to supply these services changes as well; for better or worse. Human wellbeing is put at risk, along with the welfare of millions of other species. People have a strong emotional, spiritual and ethical attachment to the ecosystems they know, and the species they contain.

By “ecosystem change”, we mean changes in some or all of the following: the number and types of organisms present; the ecosystem's physical appearance (e.g., tall or short, open or dense vegetation); the functioning of the system and all its interactive parts, including the cycling of nutrients and productivity. Though in the long-term not all ecosystem changes are detrimental to all people or to all species, the faster and further ecosystems change in response to new climatic conditions, the more challenging it is for humans and other species to adapt to the new conditions.

FAQ 4.6: Can ecosystems be managed to help them and people to adapt to climate change?
[to be placed in Section 4.4.2.3]
The ability of human societies adapt to climate change will depend, in large measure, upon the management of terrestrial and inland freshwater ecosystems. A fifth of global human-caused carbon emissions today are absorbed by terrestrial ecosystems; this important carbon *sink* operates largely without human intervention, but could be increased through a concerted effort to reduce forest loss and to restore damaged ecosystems, which also co-benefits the conservation of biodiversity.

The clearing and degradation of forests and peatlands represents a *source* of carbon emissions to the atmosphere which can be reduced though management; for instance, there has been a three-quarters decline in the rate of deforestation in the Brazilian Amazon in the last two decades. Adaptation is also helped through more proactive detection and management of wildfire and pest outbreaks, reduced drainage of peatlands, the creation of species migration corridors and assisted migration.

FAQ 4.7: What are the economic costs of changes in ecosystems due to climate change?
[to be placed in Section 4.4.3]
Climate change will certainly alter the services provided by most ecosystems, and for high degrees of change, the overall impacts are most likely to be negative. In standard economics, the value of services provided by ecosystems are known as externalities, which are usually outside the market price system, difficult to evaluate and often ignored.

A good example is the pollination of plants by bees and birds and other species, a service which may be negatively affected by climate change. Pollination is critical for the food supply as well as for overall environmental health. Its value has been estimated globally at $350 billion for the year 2010 (The range of estimates is 200 – 500 $ billion).

Cross-Chapter Boxes

Box CC-EA. Ecosystem Based Approaches to Adaptation - Emerging Opportunities
[Rebecca Shaw (USA), Jonathan Overpeck (USA), Guy Midgley (South Africa)]

Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 24, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012; Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Day et al., 2007; Midgley et al., 2012; Opperman et al., 2009)
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision; traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques

- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach. The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but is should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.]

Box CC-EA References

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Box CC-RF. Impact of Climate Change on Freshwater Ecosystems due to Altered River Flow Regimes

[Petra Döll (Germany), Stuart E. Bunn (Australia)]

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

There is growing evidence that climate change will significantly alter ecologically important attributes of hydrologic regimes in rivers and wetlands, and exacerbate impacts from human water use in developed river basins (*medium confidence*) (Aldous *et al.*, 2011; Xenopoulos *et al.*, 2005). By the 2050s, climate change is projected to impact river flow characteristics like long-term average discharge, seasonality and statistical high flows (but not statistical low flows) more strongly than dam construction and water withdrawals have done up to around the year 2000 (Figure RF-1; Döll and Zhang, 2010). For one climate scenario (SRES A2 emissions, HadCM3 climate model), 15% of the global land area may be negatively affected, by the 2050s, by a decrease of fish species in the upstream basin of more than 10%, as compared to only 10% of the land area that has already suffered from such decreases due to water withdrawals and dams (Döll and Zhang, 2010). Climate change may exacerbate the negative impacts of dams for freshwater ecosystems but may also provide opportunities for operating dams and power stations to the benefit of riverine ecosystems. This is the case if total runoff increases and, as occurs in Sweden, the annual hydrograph becomes more similar to variation in electricity demand, i.e. with a lower spring flood and increased runoff during winter months (Renofalt *et al.*, 2010).

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

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

Due to increased winter temperatures, freshwater ecosystems in basins with significant snow storage are affected by higher river flows in winter, earlier spring peak flows and possibly reduced summer low flows (Section 3.2.3 in Chapter 3). Strongly increased winter peak flows may lead to a decline in salmonid populations in the Pacific Northwest of the USA of 20-40% by the 2050s (depending on the climate model) due to scouring of the streambed during egg incubation, the relatively pristine high-elevation areas being affected most (Battin *et al.*, 2007). Reductions in summer low flows will increase the competition for water between ecosystems and irrigation water users (Stewart *et al.*, 2005). Ensuring environmental flows through purchasing or leasing water rights and altering reservoir release patterns will be an important adaptation strategy (Palmer *et al.*, 2009).

[INSERT FIGURE RF-1 HERE
Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out 10 months. Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and

reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.]

Observations and models suggest that global warming impacts on glacier and snow-fed streams and rivers will pass through two contrasting phases (Burkett *et al.*, 2005; Vuille *et al.*, 2008; Jacobsen *et al.*, 2012). In the first phase, when river discharge is increased due to intensified melting, the overall diversity and abundance of species may increase. However, changes in water temperature and stream-flow may have negative impacts on narrow range endemics (Jacobsen *et al.*, 2012). In the second phase, when snowfields melt early and glaciers have shrunken to the point that late-summer stream flow is reduced, broad negative impacts are foreseen, with species diversity rapidly declining once a critical threshold of roughly 50% glacial cover is crossed (Figure RF-2).

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

[INSERT FIGURE RF-2 HERE
Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16 and 38% of the total species richness in the three study regions in Ecuador, Europe and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.]

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

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

Climate, vegetation and carbon and water cycles are intimately coupled, in particular via the simultaneous transpiration and CO_2 uptake through plant stomata in the process of photosynthesis. Hence, water flows such as runoff and evapotranspiration are affected not only directly by anthropogenic climate change as such (i.e. by changes in climate variables such as temperature and precipitation), but also indirectly by plant responses to increased atmospheric CO_2 concentrations. In addition, effects of climate change (e.g. higher temperature or altered precipitation) on vegetation structure, biomass production and plant distribution have an indirect influence on water flows. Rising CO_2 concentration affects vegetation and associated water flows in two contrasting ways, as suggested by ample evidence from Free Air CO_2 Enrichment (FACE), laboratory and modelling experiments (e.g. Leakey *et al.*, 2009; de Boer *et al.*, 2011; Reddy *et al.*, 2010). On the one hand, a *physiological* effect leads to reduced opening of stomatal apertures, which is associated with lower water flow through the stomata, i.e. lower leaf-level transpiration. On the other hand, a *structural* effect ("fertilization effect") stimulates photosynthesis and biomass production of C3 plants including all tree species, which eventually leads to higher transpiration at regional scales. A key question is to what extent the climate- and CO_2-induced changes in vegetation and transpiration translate into changes in regional and global runoff.

The physiological effect of CO_2 is associated with an increased intrinsic water use efficiency (WUE) of plants, which means that less water is transpired per unit of carbon assimilated. Records of stable carbon isotopes in woody plants (Peñuelas *et al.*, 2011) verify this finding, suggesting an increase in WUE of mature trees by 20.5% between the early 1960s and the early 2000s. Increases since pre-industrial times have also been found for several forest sites (Andreu-Hayles *et al.*, 2011; Gagen *et al.*, 2011; Loader *et al.*, 2011; Nock *et al.*, 2011) and in a temperate semi-natural grassland (Koehler *et al.*, 2010), although in one boreal tree species WUE ceased to increase after 1970 (Gagen *et al.*, 2011). Analysis of long-term whole-ecosystem carbon and water flux measurements from 21 sites in North American temperate and boreal forests corroborates a notable increase in WUE over the two past decades (Keenan *et al.*, 2013). An increase in global WUE over the past century is supported by ecosystem model results (Ito and Inatomi, 2012).

A key influence on the significance of increased WUE for large-scale transpiration is whether vegetation structure and production has remained approximately constant (as assumed in the global modelling study by Gedney *et al.*, 2006) or has increased in some regions due to the structural CO_2 effect (as assumed in models by Piao *et al.*, 2007;

Gerten *et al.*, 2008). While field-based results vary considerably among sites, tree ring studies suggest that tree growth did not increase globally since the 1970s in response to climate and CO_2 change (Peñuelas *et al.*, 2011; Andreu-Hayles *et al.*, 2011). However, basal area measurements at over 150 plots across the tropics suggest that biomass and growth rates in intact tropical forests have increased in recent decades (Lewis *et al.*, 2009). This is also confirmed for 55 temperate forest plots, with a suspected contribution of CO_2 effects (McMahon *et al.*, 2010). Satellite observations analysed in Donohue *et al.* (2013) suggest that an increase in vegetation cover by 11% in warm drylands (1982–2010 period) is attributable to CO_2 fertilization. Owing to the interplay of physiological and structural effects, the net impact of CO_2 increase on global-scale transpiration and runoff remains rather poorly constrained. This is also true because nutrient limitation, often omitted in modelling studies, can suppress the CO_2 fertilization effect (see Rosenthal and Tomeo, 2013).

Therefore, there are conflicting views on whether the direct CO_2 effects on plants already have a significant influence on evapotranspiration and runoff at global scale. AR4 reported work by Gedney *et al.* (2006) which suggested that the physiological CO_2 effect (lower transpiration) contributed to a supposed increase in global runoff seen in reconstructions by Labat *et al.* (2004). However, a more recent analysis based on a more complete dataset (Dai *et al.*, 2009) suggested that river basins with decreasing runoff outnumber basins with increasing runoff, such that a small decline in global runoff is *likely* for the period 1948–2004. Hence, detection of vegetation contributions to changes in water flows critically depends on the availability and quality of hydrometeorological observations (Haddeland *et al.*, 2011; Lorenz and Kunstmann, 2012). Overall, the evidence since AR4 suggests that climatic variations and trends have been the main driver of global runoff change in the past decades; both CO_2 increase and land use change have contributed less (Piao *et al*., 2007; Gerten *et al*., 2008; Alkama *et al.*, 2011; Sterling *et al.*, 2013). Oliveira *et al.* (2011) furthermore pointed to the importance of changes in incident solar radiation and the mediating role of vegetation; according to their global simulations, a higher diffuse radiation fraction during 1960–1990 may have increased evapotranspiration in the tropics by 3% due to higher photosynthesis from shaded leaves.

It is uncertain how vegetation responses to future increases in CO_2 and to climate change will modulate the impacts of climate change on freshwater flows. 21st century continental- and basin-scale runoff is projected by some models to either increase more or decrease less when the physiological CO_2 effect is included in addition to climate change effects (Betts *et al.*, 2007; Murray *et al.,* 2012). This could somewhat ease the increase in water scarcity anticipated in response to future climate change and population growth (Gerten *et al.*, 2011; Wiltshire *et al.*, in press). In absolute terms, the isolated effect of CO_2 has been modelled to increase future global runoff by 4–5% (Gerten *et al.*, 2008) up to 13% (Nugent and Matthews, 2012) compared to the present, depending on the assumed CO_2 trajectory and whether feedbacks of changes in vegetation structure and distribution to the atmosphere are accounted for (they were not in Nugent and Matthews, 2012). In a global model intercomparison study (Davie *et al.*, in press), two out of four models projected stronger increases and, respectively, weaker decreases in runoff when considering CO_2 effects compared to simulations with constant CO_2 concentration (consistent with above findings, though magnitudes differed between the models), but two other models showed the reverse. Thus, the choice of models and the way they represent the coupling between CO_2, stomatal closure and plant growth is a source of uncertainty, as also suggested by Cao *et al.* (2009). Lower transpiration due to rising CO_2 concentration may also affect future regional climate change itself (Boucher *et al.*, 2009) and enhance the contrast between land and ocean surface warming (Joshi *et al.*, 2008). Overall, although physiological and structural effects will influence water flows in many regions, precipitation and temperature effects are *likely* to remain the prime influence on global runoff (Alkama *et al.*, 2010).

An application of a soil-vegetation-atmosphere-transfer model indicates complex responses of groundwater recharge to vegetation-mediated changes in climate, with computed groundwater recharge being always larger than would be expected from just accounting for changes in rainfall (McCallum *et al.*, 2010). Another study found that even if precipitation slightly decreased, groundwater recharge might increase as a net effect of vegetation responses to climate change and CO_2 rise, i.e. increasing WUE and either increasing or decreasing leaf area (Crosbie *et al.*, 2010). Depending on the type of grass in Australia, the same change in climate is suggested to lead to either increasing or decreasing groundwater recharge in this location (Green *et al.*, 2007). For a site in the Netherlands, a biomass decrease was computed for each of eight climate scenarios indicating drier summers and wetter winters (A2 emissions scenario), using a fully coupled vegetation and variably saturated hydrological model. The resulting increase in groundwater recharge up-slope was simulated to lead to higher water tables and an extended habitat for down-slope moisture-adapted vegetation (Brolsma *et al.*, 2010).

Using a large ensemble of climate change projections, Konzmann *et al.* (2013) put hydrological changes into an agricultural perspective and suggested that the net result of physiological and structural CO_2 effects on crop irrigation requirements would be a global reduction (Figure VW-1). Thus, adverse climate change impacts on irrigation requirements and crop yields might be partly buffered as WUE and crop production improve (Fader *et al.*, 2010). However, substantial CO_2-driven improvements will only be realized if proper management abates limitation of plant growth by nutrient availability or other factors.

[INSERT FIGURE VW-1 HERE
Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).]

Changes in vegetation coverage and structure due to long-term climate change or shorter-term extreme events such as droughts (Anderegg *et al.*, 2013) also affect the partitioning of precipitation into evapotranspiration and runoff, sometimes involving complex feedbacks with the atmosphere such as in the Amazon region (Port *et al.*, 2012; Saatchi *et al.*, 2013). One model in the study by Davie *et al.* (in press) showed regionally diverse climate change effects on vegetation distribution and structure, which had a much weaker effect on global runoff than the structural and physiological CO_2 effects. As water, carbon and vegetation dynamics evolve synchronously and interactively under climate change (Heyder *et al.*, 2011; Gerten *et al.*, in press), it remains a challenge to disentangle the individual effects of climate, CO_2 and land cover change on the water cycle.

Box CC-VW References

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Table 4-1: Biome shifts of the 20th century from published field research that examined trends over periods > 30 y for biomes in areas where climate (rather than land-use change or other factors) predominantly influenced vegetation, derived from a systematic analysis of published studies (Gonzalez *et al.*, 2010). Pre-AR4 publications are included to provide a comprehensive review. Shift type: elevational (E), latitudinal (L), examined but not detected (N). The biome abbreviations match those in Figure 4-1. Rate of change in temperature (Temp.) and fractional rate of change in precipitation (Precip.) are derived from linear least squares regression of 1901-2002 data (Mitchell and Jones, 2005; Gonzalez *et al.*, 2010). The table provides general regional climate trends at 50 km spatial resolution because the references do not give uniform site-specific climate data to compare across locations. The regional trends are consistent with local trends reported in each reference. * rate significant at P ≤ 0.05.

	Location	Reference	Plots	Time Period	Shift type	Retracting biome	Expanding biome	Temp. change (ºC century-1)	Precip. change (% century-1)
1.	Alaska Range, Alaska, USA	Lloyd and Fastie, 2003	18	1800-2000	L	UA	BC	1.1*	3
2.	Baltic Coast, Sweden	Walther *et al.*, 2005	7	1944-2003	L	TC	TB	0.6*	8
3.	Becca di Viou, Italy	Leonelli *et al.*, 2011	1	1700-2008	E	UA	BC	0.9*	-6
4.	Garibaldi, British Columbia, Canada	Brink, 1959	1	1860-1959	E	UA	BC	0.7*	16*
5.	Goulet Sector, Québec, Canada	Payette and Filion, 1985	2	1880-1980	E	UA	BC	1.4*	19*
6.	Green Mountains, Vermont, USA	Beckage *et al.*, 2008	33	1962-2005	E	BC	TB	1.6*	6
7.	Jasper, Alberta, Canada	Luckman and Kavanagh, 2000	1	1700-1994	E	UA	BC	0.6	21*
8.	Kenai Mountains, Alaska, USA	Dial *et al.*, 2007	3	1951-1996	E	UA	BC	0.7	6
9.	Kluane Range, Yukon, Canada	Danby and Hik, 2007	2	1800-2000	E	UA	BC	0.7	5
10.	Low Peninsula, Québec, Canada	Payette and Filion, 1985	1	1750-1980	N	-	-	1.4*	19*

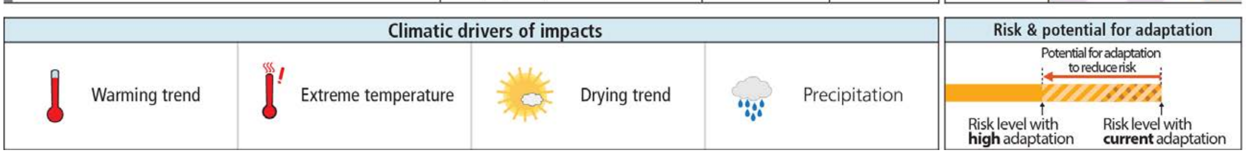
	Location	Reference	Plots	Time Period	Shift type	Retracting biome	Expanding biome	Temp. change (ºC century⁻¹)	Precip. change (% century⁻¹)
11.	Mackenzie Mountains, Northwest Territories, Canada	Szeicz and Macdonald, 1995	13	1700-1990	N	-	-	1.4*	3
12.	Montseny Mountains, Catalonia, Spain	Peñuelas and Boada, 2003	50	1945-2001	E	UA	TB	1.2*	-3
13.	Napaktok Bay, Labrador, Canada	Payette, 2007	2	1750-2000	L	UA	BC	1.1*	5
14.	Noatak, Alaska, USA	Suarez *et al.*, 1999	18	1700-1990	L	UA	BC	0.6	19*
15.	Putorana Mountains, Russia	Kirdyanov *et al.*, 2012	10	1500-2000	E	UA	BC	0.3	10
16.	Rahu Saddle, New Zealand	Cullen *et al.*, 2001	7	1700-2000	N	-	-	0.6*	3
17.	Rai-Iz, Urals, Russia	Devi *et al.*, 2008	144	1700-2002	E	UA	BC	0.3	35*
18.	Sahel, Sudan, Guinea zones; Senegal	Gonzalez, 2001	135	1945-1993	L	RW	RG	0.4*	-48*
19.	Sahel, Burkina Faso, Chad, Mali, Mauritania, Niger	Gonzalez *et al.*, 2012	14	1960-2000	L	RW	RG	-0.01*- to 0.8*	-31*-to 9
20.	Scandes, Sweden	Kullman and Öberg, 2009	123	1915-2007	E	UA	BC	0.8*	25*
21.	Sierra Nevada, California, USA	Millar *et al.*, 2004	10	1880-2002	E	UA	TC	-0.1	21*
22.	South Island, New Zealand	Wardle and Coleman, 1992	22	1980-1990	E	TS	TB	0.6*	3
23.	Yambarran, Northern Territory, Australia	Sharp and Bowman, 2004	33	1948-2000	N	-	-	-0.06	35*

Table 4-2: Summary of drivers and outcomes of LUCC scenarios associated with Representative Concentration Pathways (Hurtt *et al.*, 2011). RCPs are identified with the radiative forcing by 2100 (8.5, 6.0, 4.5 and 2.6 Wm^{-2}) and by the name of the model used to generate the associated land use/cover scenarios (MESSAGE, AIM, GCAM and IMAGE; see Hurtt *et al*. (2011) for further details).

RCP	Model and references	Key assumptions / drivers	Land use / cover outcomes
8.5	MESSAGE, Riahi et al. (2007)	No climate change mitigation actions; radiative forcing still rising at 2100 Strong increase in agricultural resource use driven by the increasing population (rises to 12 billion people by 2100) Yield improvements and intensification assumed to account for most of production increases	Increase in cultivated land by about 305 million hafrom 2000 to 2100 Forest cover declines by 450 million ha from 2000 to 2100 Arable land use in developed countries slightly decreased - all of the net increases occur in developing countries.
6.0	AIM, Fujino *et al*. (2006); Hijioka *et al*. (2008)	Mitigation actions taken late in the century to stabilize radiative forcing at 6 Wm^{-2} after 2100 Population growth and economic growth Increasing food demand drives cropland expansion	Urban land-use increases Cropland area expands Grassland area declines Total forested area extent remains constant
4.5	GCAM, Smith and Wigley (2006); Wise *et al*. (2009)	Mitigation stabilizes radiative forcing at 4.5 Wm^{-2} before 2100 Assumes that global GHG emissions prices are invoked to limit emissions and therefore radiative forcing. Emissions pricing assumes all carbon emissions charged an equal penalty price, so reductions in land-use change carbon emissions available as mitigation Food demand met through crop yield improvements, dietary shifts, production efficiency and international trade.	Preservation of large stocks of terrestrial carbon in forests Overall expansion in forested area Agricultural land declines slightly due to afforestation,
2.6	IMAGE Van Vuuren *et al*., (2007); van Vuuren *et al*. (2006)	Overall trends in land use and land cover mainly determined by demand, trade and production of agricultural products and bio-energy. Expansion of croplands largely due to bioenergy production. Production of animal products met through shift from extensive to more intensive animal husbandry	Much agriculture relocates from high income to low-income regions Increase in bio-energy production, new area for bioenergy crops near current agricultural areas. Pasture largely constant

Table 4-3: Key risks for terrestrial and freshwater ecosystems from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in supporting chapter sections. Each key risk is characterized as very low to very high. Risk levels are presented in three timeframes: the present, near-term (here, assessed over 2030-2040), and longer-term (here, assessed over 2080-2100). For the near-term era of committed climate change, projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options, risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Reduction in terrestrial carbon sink: Carbon stored in terrestrial Medium high ecosystems is vulnerable to loss back into the atmosphere. Key mechanisms include an increase in fire frequency due to climate change and the sensitivity of ecosystem respiration to rising temperatures (*medium confidence*)	Adaptation prospects include managing land-use (including deforestation), fire and other disturbances and non-climatic stressors.	Warming trend; Extreme temperature; Drying trend	4.2.4 4.3.2 4.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Boreal tipping point: Arctic ecosystems are vulnerable to abrupt change related to the thawing of permafrost and spread of shrubs in tundra and increase in pests and fires in boreal forests (*medium confidence*)	There are few adaptation options in the Arctic.	Warming trend; Extreme temperature	4.3.3.1.1 Box 4-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Amazon tipping point: Moist Amazon forests could change abruptly to less carbon-dense drought and fire-adapted ecosystems (*medium confidence*)	Policy and market measures to reduce deforestation and fire.	Warming trend; Extreme temperature; Drying trend	4.3.3.1.3 Box 4-3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Tree mortality and forest loss: Tree mortality has been observed to have increased in many places and has been attributed in some cases to direct climate effects and indirect effects due to pests and diseases. The dead trees increase the risk of forest fires (*medium confidence*)	Adaption options include more effective management of fire, pests and pathogens.	Warming trend; Extreme temperature; Drying trend	4.3.3.1 Box 4-2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Increased risk of species extinction: A large fraction of the species that have been assessed are vulnerable to extinction as a result of climate change, often in interaction with other threats. Species with an intrinsically low dispersal rate, especially when occupying flat landscapes where the projected climate velocity is high, and species in isolated habitats such as mountain tops, islands or small protected areas are especially at risk. Cascading effects through organism interactions, and especially those vulnerable to timing (phenological) changes amplifies the risk (*high confidence*)	Adaptation options include reducing habitat modification, habitat fragmentation, pollution, over-exploitation and invasive species; protected area expansion, assisted dispersal, ex situ conservation.	Warming trend; Extreme temperature; Drying trend	4.3.2.5 4.3.3.3 4.3.2.1 4.4.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Invasion by non-native species: Disruptions of species interactions and the increase in physiological stress as a result of being near the edge or outside of the historical climate niche increases the vulnerability of ecosystems to invasion by non-native (alien) species, especially in the presence of increased long-distance dispersal opportunities. In the extreme this can result in biome shifts, with consequent changes in the spectrum of ecosystem services provided (*high confidence*)	Climate is one driver among many. Adaptation options are limited, largely based on reducing other stresses and measures to slow the unintended arrival of aliens. Intensive direct intervention in controlling emergent invasive species is an option, but could be overwhelmed by the rapidly rising number is cases.	Warming trend; Drying trend; Precipitation	4.2.4.6	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high



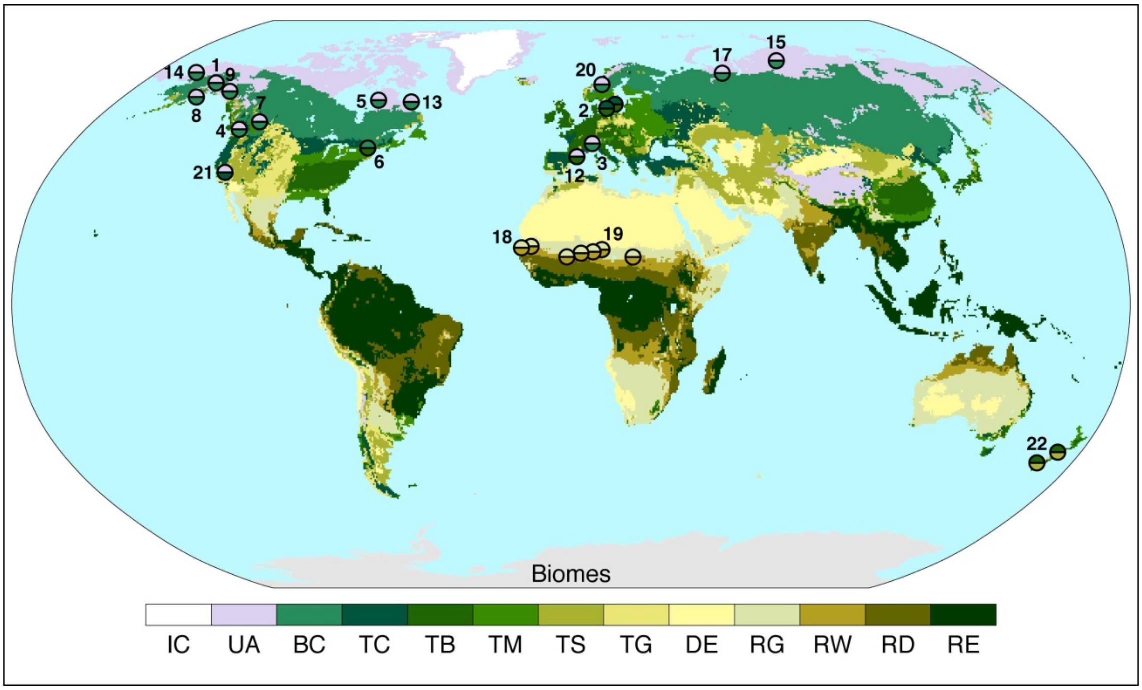


Figure 4-1: Locations of observed biome shifts during the 20th century, listed in Table 4-1, derived from Gonzalez *et al.* (2010). The color of each semi-circle indicates the retracting biome (top for North America, Europe, Asia; bottom for Africa and New Zealand) and the expanding biome (bottom for North America, Europe, Asia; top for Africa and New Zealand), according to published field observations. Biomes, from poles to equator: ice (IC), tundra and alpine (UA), boreal conifer forest (BC), temperate conifer forest (TC), temperate broadleaf forest (TB), temperate mixed forest (TM), temperate shrubland (TS), temperate grassland (TG), desert (DE), tropical grassland (RG), tropical woodland (RW), tropical deciduous broadleaf forest (RD), tropical evergreen broadleaf forest (RE). The background is the potential biome according to the MC1 dynamic global vegetation model under the 1961-1990 climate. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

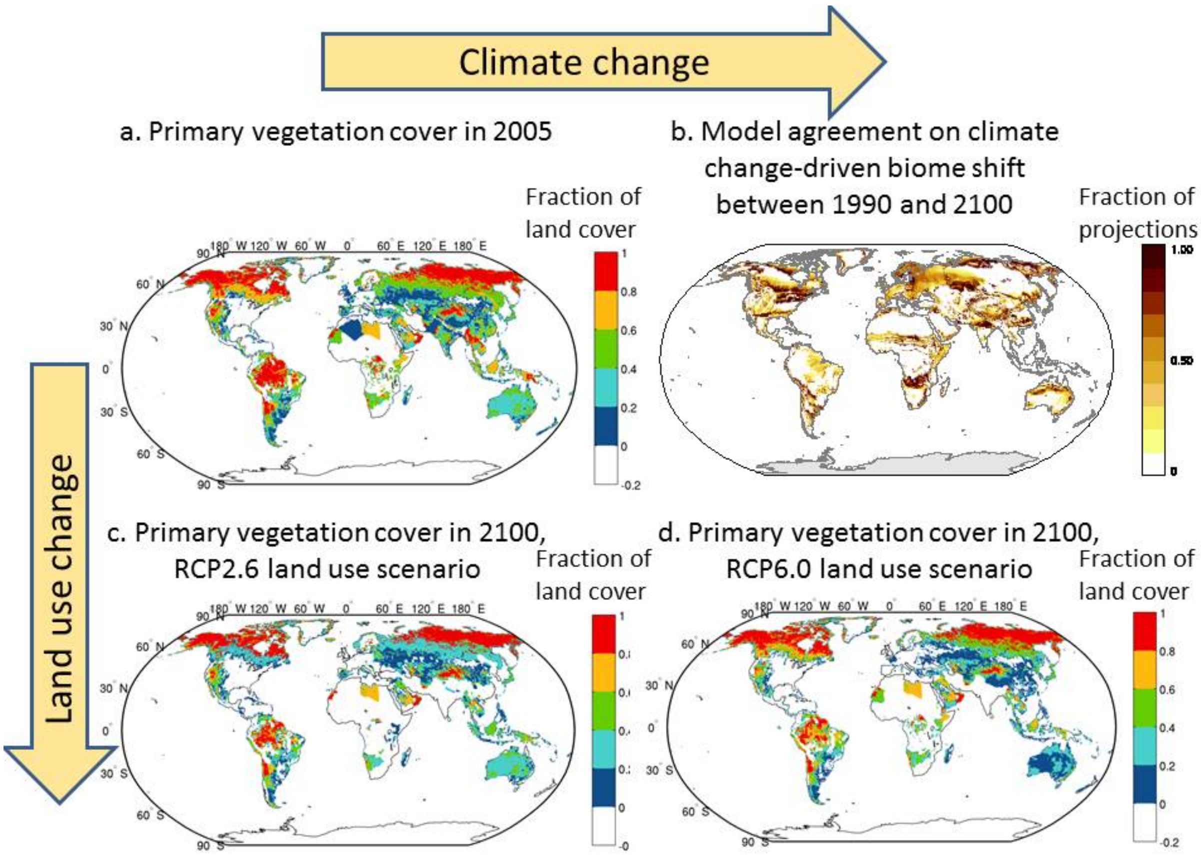


Figure 4-2: Implications of climate change and land use change for biome shifts. (a) Fraction of land covered by primary vegetation in 2005 (Hurtt *et al.*, 2011); (b) Fraction of simulations showing climate change-driven biome shift for any level of global warming between 1990 and 2100, with no direct anthropogenic land use change, using the MC1 vegetation model under 9 CMIP3 climate projections (3 GCMs each forced by the SRES A2, A1B and B1 scenarios; Gonzalez *et al.*, 2010); (c) Fraction of land covered by primary vegetation in 2100 under the RCP2.6 land use scenario with the IMAGE model, with no effect of climate change (Hurtt *et al.*, 2011); (d) Fraction of land covered by primary vegetation in 2100 under the RCP8.5 land use scenario with the MESSAGE model, with no effect of climate change (Hurtt *et al.*, 2011). Comparison of coloured areas in (b) with those in (a) shows where climate- driven biome shifts would occur in current areas of primary vegetation. Comparison of (b) and (d) shows where climate-driven biome shifts would occur in areas of primary vegetation projected under a land use scenario associated with RCP6.0. Comparison of (c) and (a) illustrates a scenario of land use change associated with RCP2.6, in which global climate change is projected to be smaller than that driving the biome shifts in (b) as a result of mitigation measures, some of which involve land use. Further details of the RCP land use / cover scenarios are given in Box 4-1, Figure 4-3 and Table 4-2.
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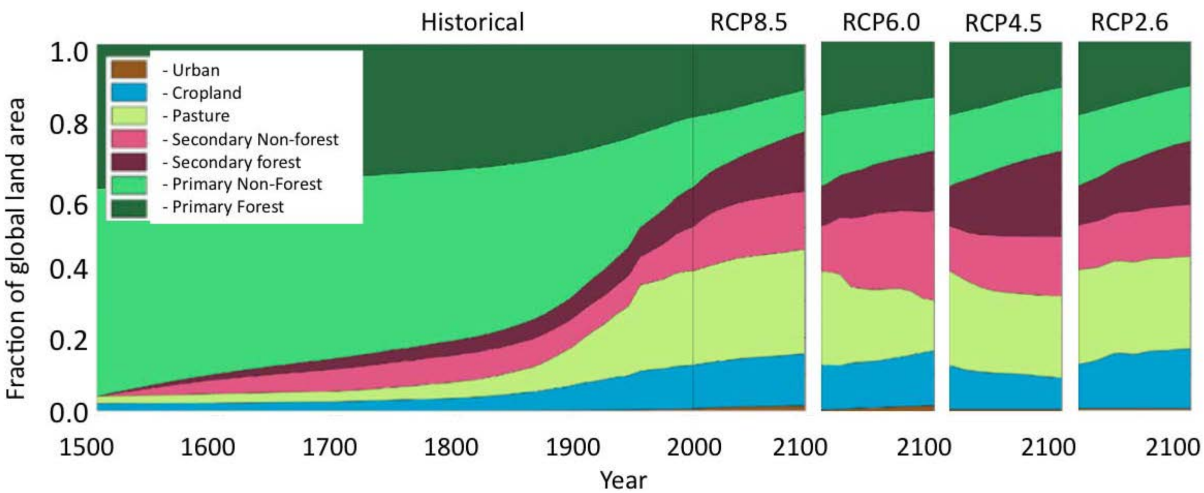

Figure 4-3: Proportion of global land cover occupied by primary and secondary vegetation (forest and non-forest), cropland, pasture and urban land, from satellite data and historical reconstructions up to 2005 (Klein Goldewijk *et al.*, 2010; Klein Goldewijk *et al.*, 2011), and from scenarios associated with the RCPs from 2005 to 2100 (Hurtt *et al.*, 2011)**. [Illustration to be redrawn to conform to IPCC publication specifications.]**

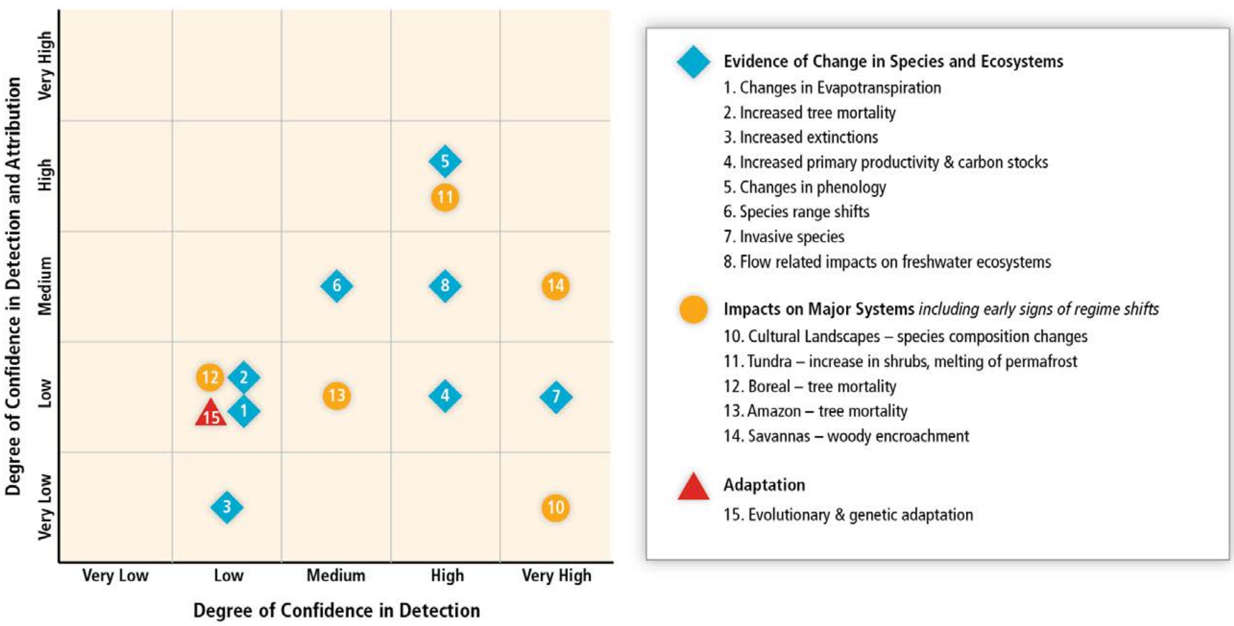

Figure 4-4: Confidence in detection of change and attribution of observed responses of terrestrial ecosystems to climate change. Confidence levels are based on expert judgment of the available literature following the IPCC uncertainty guidance (Mastrandrea *et al.*, 2010), attribution criteria outlined in Chapter 18 and detection criteria defined in the text. The symbols in the figure represent global and cross-taxon assessments; the positioning may be different for specific taxa or regions. The following sections provide the details of the assessments that were used in positioning each of the points Phenology, Section 4.3.2.1; Primary Productivity, Section 4.3.2.2; Biomass and C stocks, Section 4.3.2.3; Evapotranspiration, Section 4.3.2.4; Species distributions, Section 4.3.2.5**;** Global species extinctions, Section 4.3.2.5**;** Invasive and alien species**,** Section 4.2.4.6**;** Tree mortality, Section 4.3.3.1, Box 4-2; Boreal forest regime shift, Section 4.3.3.1.1, Box 4-4; Amazon forest regime shift, Section 4.3.3.1.3, Box 4-3; Tundra regime shift, Section 4.3.3.4, Box 4-4; Woody encroachment, Section 4.3.3.2.2; Cultural landscapes, Section 4.3.3.5.3; Evolutionary and genetic adaptation, Section 4.4.1.2.

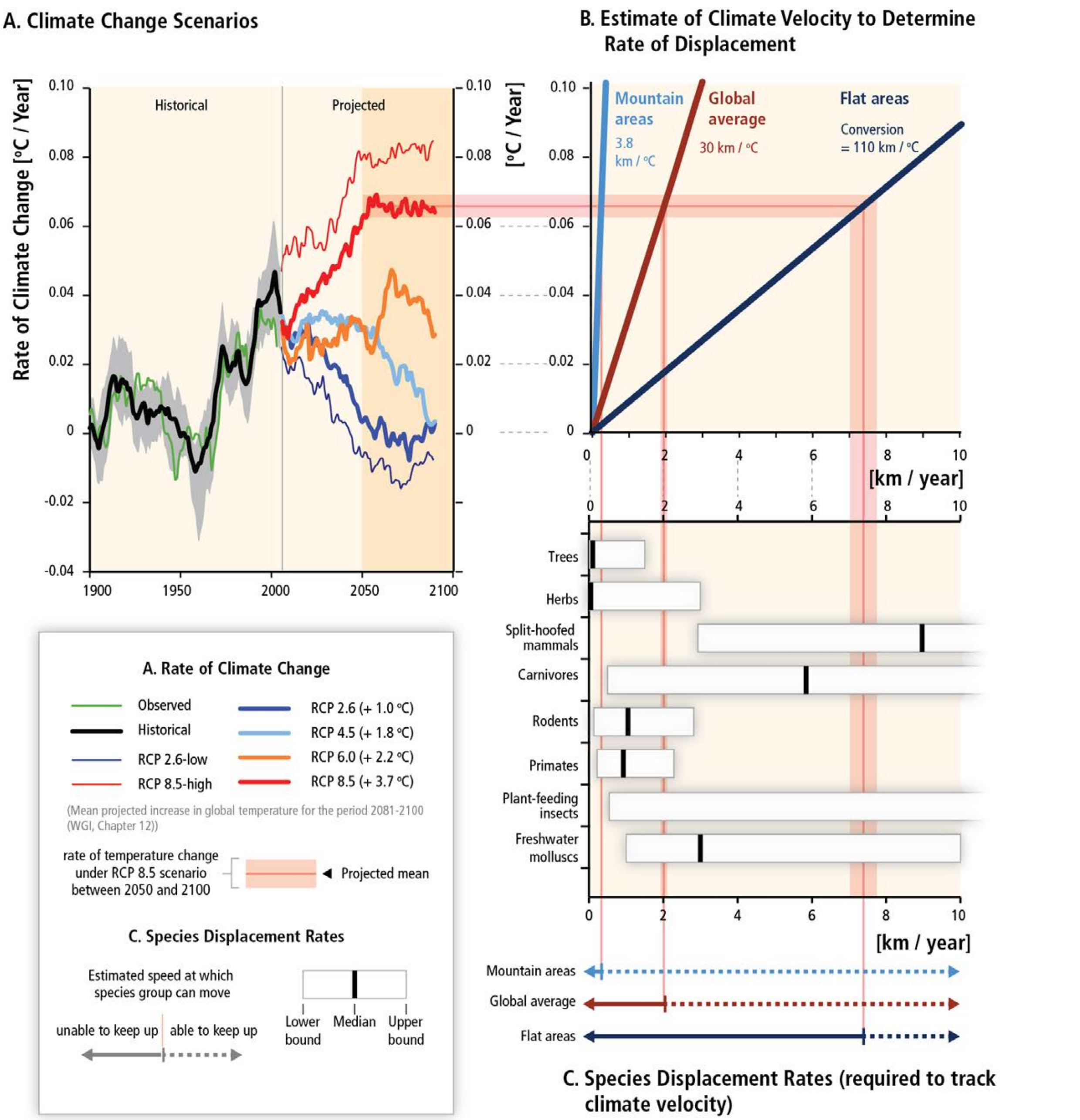

Figure 4-5: (A) Rates of climate change, (B) corresponding climate velocities and (C) rates of displacement of several terrestrial and freshwater species groups in the absence of human intervention. Horizontal and vertical pink bands illustrate the interpretation of this figure. Climate velocities for a given range of rates of climate change are determined by tracing a band from the range of rates in panel A to the points of intersection with the three climate velocity scalars in panel B. Comparisons with species displacement rates are made by tracing vertical bands from the points of intersection on the climate velocity scalars down to the species displacement rates in panel C. Species groups with displacement rates below the band are projected to be unable to track climate in the absence of human intervention. (A) Observed rates of climate change for global land areas are derived from CRUTEM4 climate data reanalysis, all other rates are calculated based on the average of CMIP5 climate model ensembles for the historical period (grey shading indicates model uncertainty) and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window, and rates are means of between 17 and 30 models using one

member per model. Global average temperatures at the end of the 21st century for the four RCP scenarios are from WGI AR5 Chapter 12. (B) Estimates of climate velocity for temperature were synthesized from historical and projected future relationships between rates of temperature change and climate velocity (historical: Burrows *et al.*, 2011; Chen *et al.*, 2011; Dobrowski *et al.*, 2013; projected future: Loarie *et al.*, 2009; Sandel *et al.*, 2011; Feeley and Rehm, 2012). The three scalars are climate velocities that are representative of mountainous areas (left), averaged across global land areas (centre), and large flat regions (right). (C) Rates of displacement are given with an estimate of the median (black bars) and range (boxes = ca. 95% of observations or models for herbaceous plants, trees and plant-feeding insects or median ± 1.5 inter-quartile range for mammals). Displacement rates for herbaceous plants were derived from paleobotanical records, modern plant invasion rates and genetic analyses (Kinlan and Gaines, 2003). Displacement estimates for trees are based on reconstructed rates of tree migration during the Holocene (Clark, 1998; Clark *et al.*, 2003; Kinlan and Gaines, 2003; McLachlan *et al.*, 2005; Nathan, 2006; Pearson, 2006) and modelled tree dispersal and establishment in response to future climate change (Higgins *et al.*, 2003; Iverson *et al.*, 2004; Epstein *et al.*, 2007; Goetz *et al.*, 2011; Nathan *et al.*, 2011; Meier *et al.*, 2012; Sato and Ise, 2012). Displacement rates for mammals were based on modelled dispersal rates of a wide range of mammal species (mean of Schloss *et al.*, 2012 for Western Hemisphere mammals and rates calculated from global assessments of dispersal distance by Santini *et al.*, 2013 and generation length by Pacifici *et al.*, 2013). Displacement rates for phytophagous insects are based on observed dispersal distances and genetic analyses (Peterson and Denno, 1998; Kinlan and Gaines, 2003; Schneider, 2003; Berg *et al.*, 2010; Chen *et al.*, 2011). The estimate of median displacement rate for this group exceeds the highest rates on the axis. These displacement rates do not take into account limitations imposed by host plants. Displacement estimates for freshwater molluscs correspond to the range of passive plus active dispersal rates for upstream movement (Kappes and Haase, 2012).

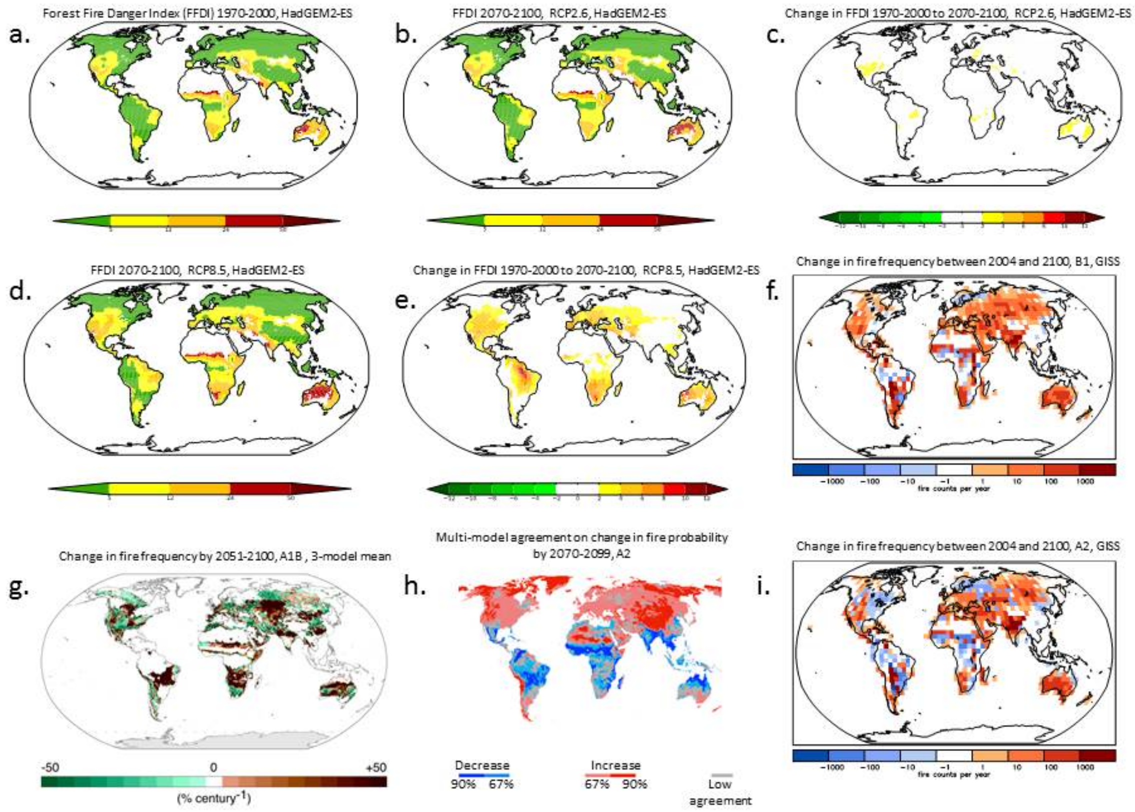

Figure 4-6: Projected changes in meteorological fire danger, fire probability and fire frequency with different methods and climate models. (a)-(e) 30-year annual mean MacArthur Forest Fire Danger Index (FFDI) and change simulated with the HadGEM2-ES Earth System Model, with areas of no vegetation excluded (Betts *et al*., 2013; (a) FFDI 1970-2000; (b) FFDI 2070-2100, RCP2.6; (c) change in FFDI by 2070-2100 relative to 1970-2000, RCP2.6;(d) FFDI 2070-2100; RCP8.5 (e) change in FFDI by 2070-2100 relative to 1970-2000, RCP8.5. (f) Change in fire frequency by 2100 relative to 2004, SRES B1, simulated using climate and land cover projections from the GISS GCM and IMAGE IAM (Pechony and Shindell, 2010). (g) Change in fire frequency by 2051-2100 relative to 1951-2000, SRES A1B, simulated with the MC1 vegetation model driven by 3 GCMs (CSIRO-Mk3.0, HadCM3, MIROC 3.2medres; mean over 3 simulations; Gonzalez et al., 2010). (h) Agreement on changes in fire probability simulated with a statistical model using climate projections from 16 CMIP3 GCMs, SRES A2 (i) Change in fire frequency by 2100 relative to 2004, SRES A2, simulated using climate and land cover projections from the GISS GCM (AR4 version) and IMAGE IAM (Pechony and Shindell, 2010). Changes in FFDI (a)-(e) and fire probability (h) arise entirely from changes in meteorological quantities, whereas changes in fire frequency (f) (g) (i) depend on both meteorological quantities and vegetation.
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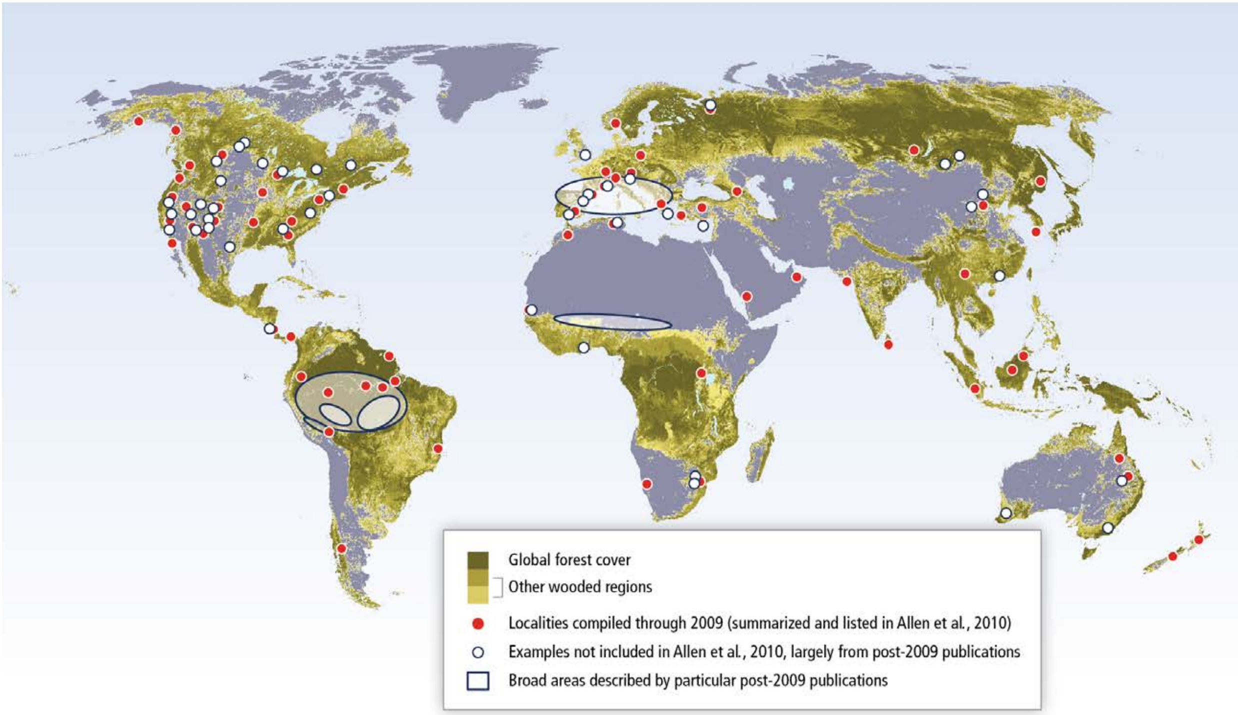

Figure 4-7: Locations of substantial drought- and heat-induced tree mortality around the globe since 1970 (global forest cover and other wooded regions based on FAO, 2005). Studies compiled through 2009 (red dots) are summarized and listed in Allen *et al.* (2010a). Localities and measurement networks not included in Allen *et al.* (2010a), which are largely from post-2009 publications, have been added to this map (white dots and shapes). New locality references by region: Africa – Mehl *et al.*, 2010, van der Linde *et al.*, 2011; Fauset *et al.*, 2012; Gonzalez *et al.*, 2012; Kherchouche *et al.*, 2012; Asia – Dulamsuren *et al.*, 2009; Kharuk *et al.*, 2013; Liu *et al.*, 2013; Zhou *et al.*, 2013; Australasia – Brouwers *et al.*, 2012; Fensham *et al.*, 2012; Keith *et al.*, 2012; Matusick *et al.*, 2012; Brouwers *et al.*, 2013; Matusick *et al.*, 2013; Europe – Innes, 1992; Peterken and Mountford, 1996; Linares *et al.*, 2009; Galiano *et al.*, 2010; Vennetier and Ripert, 2010; Aakala *et al.*, 2011; Carnicer *et al.*, 2011; Linares *et al.*, 2011; Sarris *et al.*, 2011; Marini *et al.*, 2012; Cailleret *et al.*, 2013; Vilà-Cabrera *et al.*, 2013; North America – Fahey, 1998; Minnich, 2007; Klos *et al.*, 2009; Ganey and Vojta, 2011; Michaelian *et al.*, 2011; Peng *et al.*, 2011; DeRose and Long, 2012; Fellows and Goulden, 2012; Kaiser *et al.*, 2012; Millar *et al.*, 2012; Garrity *et al.*, 2013; Kukowski *et al.*, 2013; Williams *et al.*, 2013; Worrall *et al.*, 2013; South America – Enquist and Enquist, 2011; Lewis *et al.*, 2011; Saatchi *et al.*, 2013.

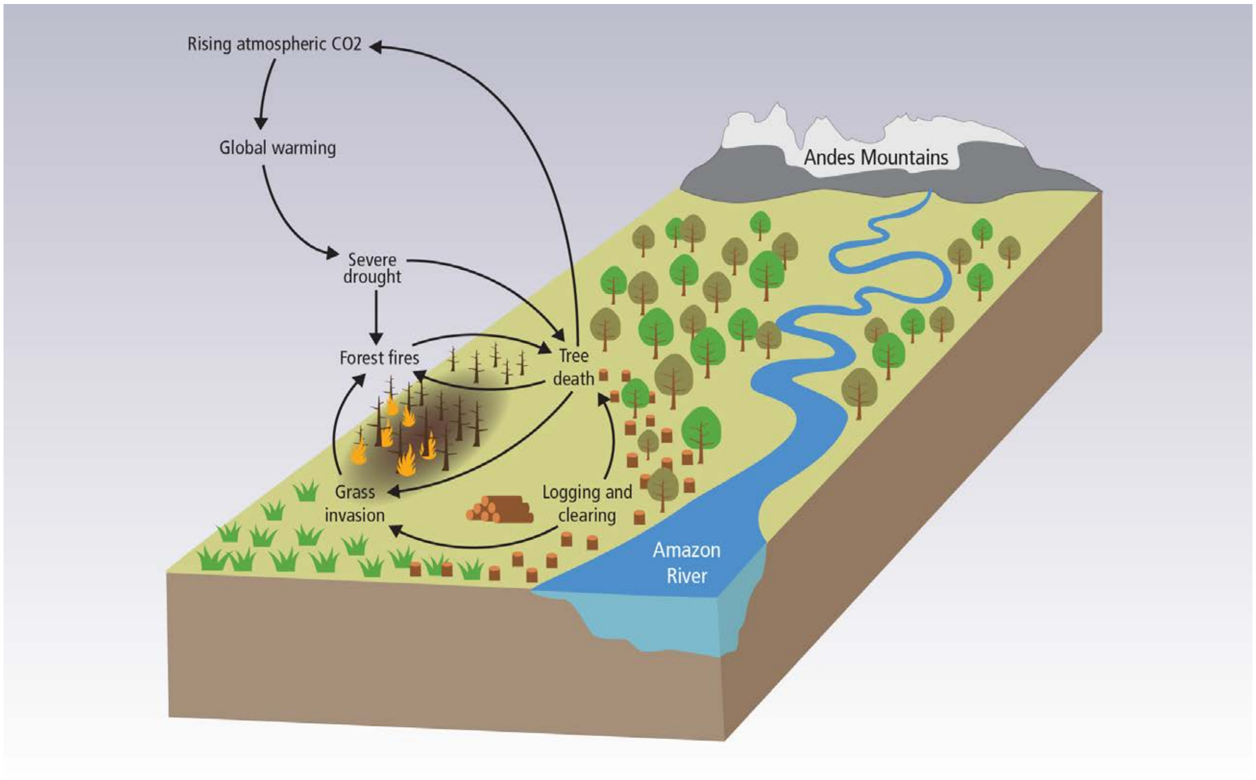

Figure 4-8: The forests of the Amazon Basin are being altered through severe droughts, land use (deforestation, logging), and increased frequencies of forest fire. Some of these processes are self-reinforcing through positive feedbacks, and create the potential for a large-scale tipping point. For example, forest fire kills trees, increasing the likelihood of subsequent burning. This effect is magnified when tree death allows forests to be invaded by flammable grasses. Deforestation provides ignition sources to flammable forests, contributing to this dieback. Climate change contributes to this tipping point by increasing drought severity, reducing rainfall and raising air temperatures, particularly in the eastern Amazon Basin (*medium confidence; medium evidence, medium agreement).*]

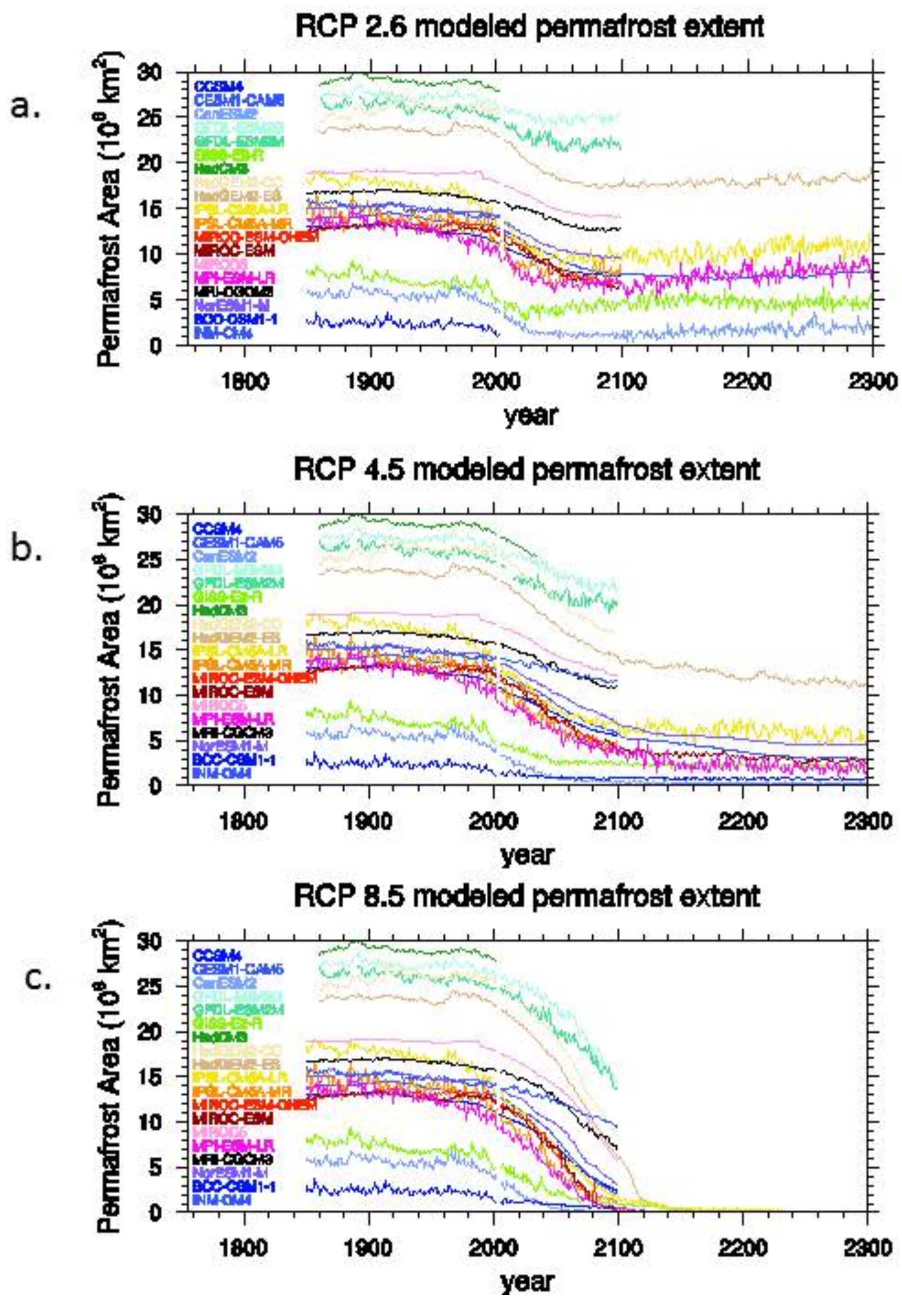

Figure 4-9: CMIP5 multi-model simulated area of Northern Hemisphere permafrost in the upper 3m of soil, from 1850 to 2100 or 2300 depending on extent of individual simulations. Each panel shows historical (1850-2005) and projected (2005 to 2100 or 2300) simulations for (a) RCP2.6, (b) RCP4.5, and (c) RCP8.5. The observed current permafrost extent is 15×10^6 km^2. (Based on Koven *et al.*, 2013, with analysis extended to 2300 following Caesar *et al.*, 2013). **[Illustration to be redrawn to conform to IPCC publication specifications.]**

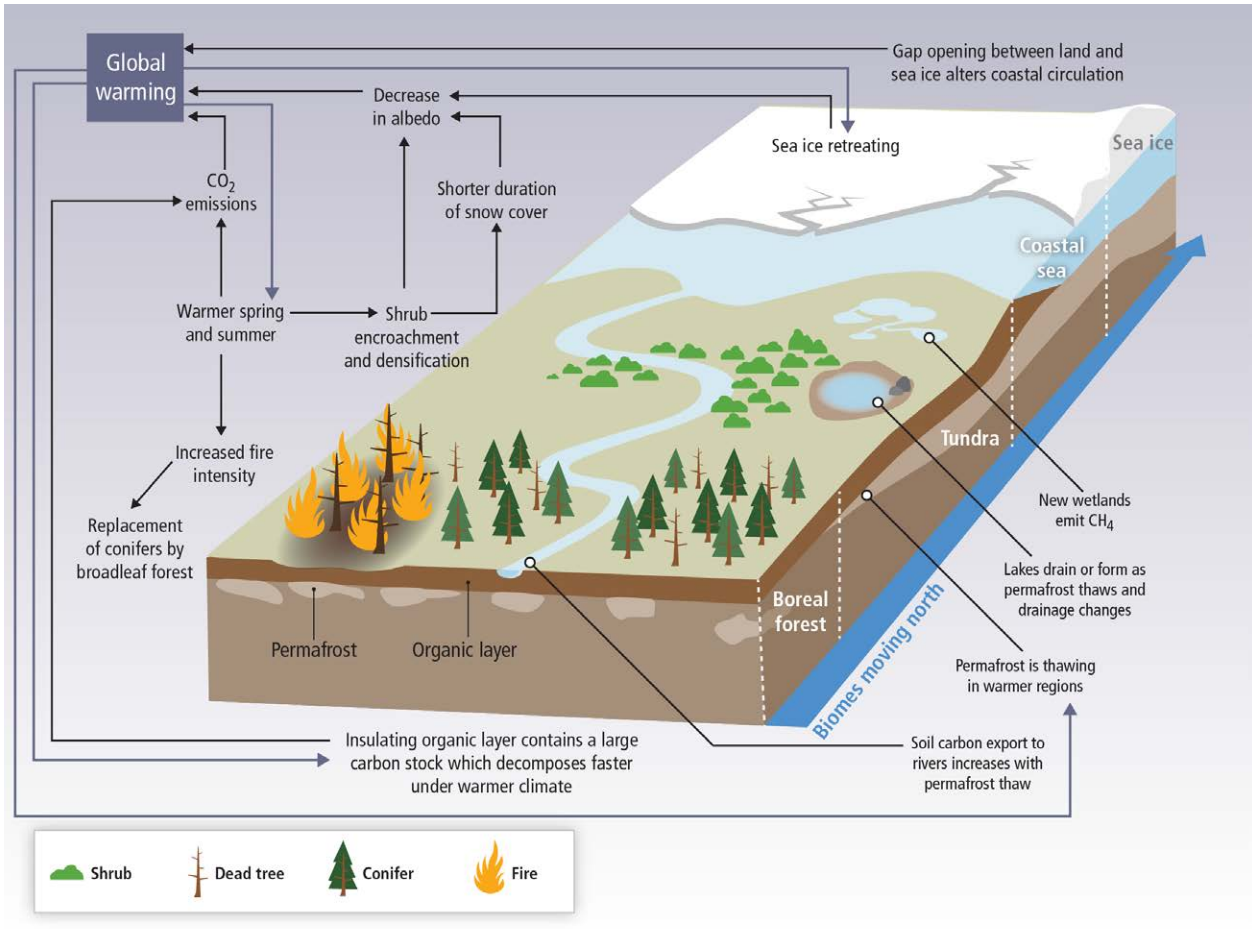

Figure 4-10: Tundra-Boreal Biome Shift. Earth system models predict a northward shift of Arctic vegetation with climate warming, as the boreal biome migrates into what is currently tundra. Observations of shrub expansion in tundra, increased tree growth at the tundra-forest transition, and tree mortality at the southern extent of the boreal forest in recent decades are consistent with model projections. Vegetation changes associated with a biome shift, which is facilitated by intensification of the fire regime, will modify surface energy budgets, and net ecosystem carbon balance, permafrost thawing and methane emissions, with net feedbacks to additional climate change.

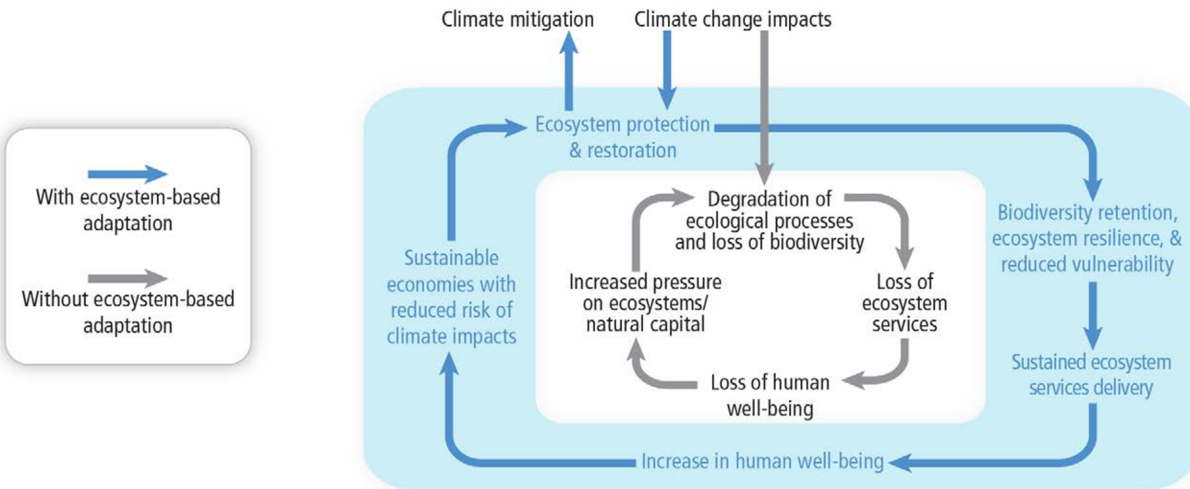

Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

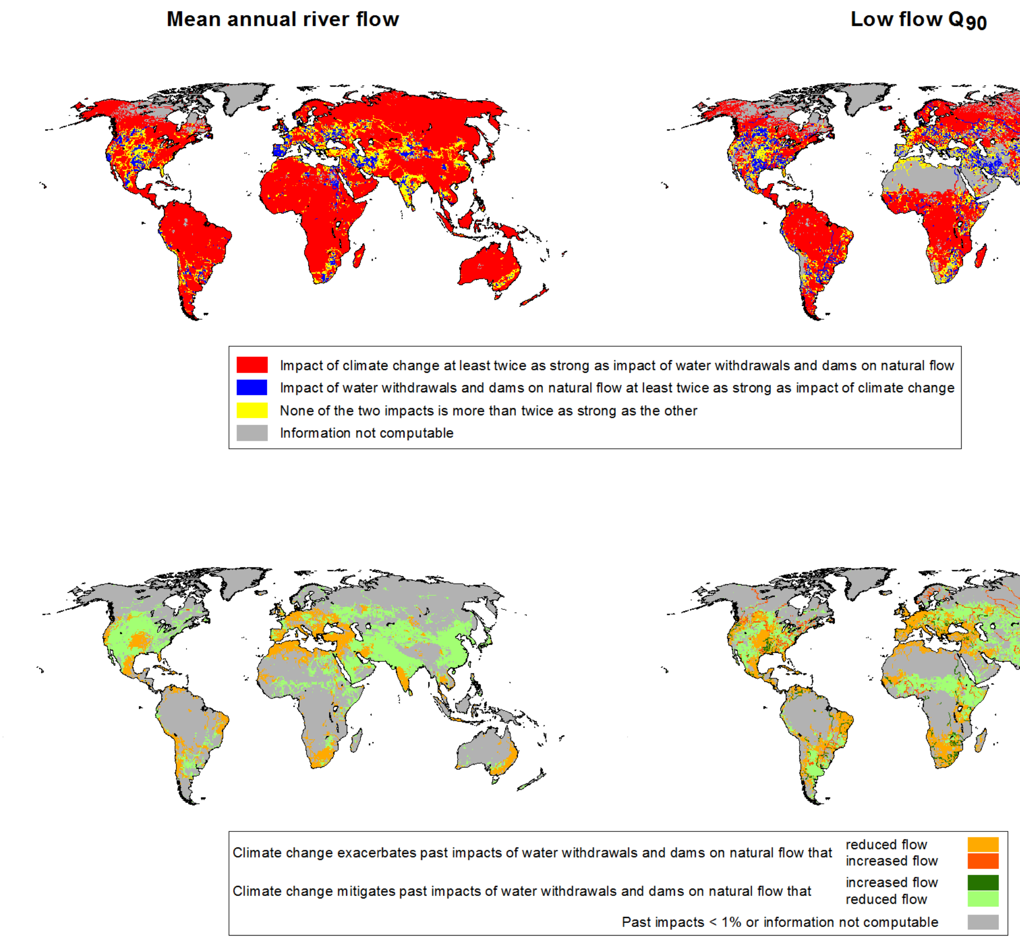

Figure RF-1: Impact of climate change relative to the impact of water withdrawals and dams on natural flows for two ecologically relevant river flow characteristics (mean annual river flow and monthly low flow Q_{90}), computed by a global water model (Döll and Zhang, 2010). Monthly Q_{90} was defined as the flow that is exceeded in 9 out 10 months. Impact of climate change is the percent change of flow between 1961-1990 and 2041-2070 according to the emissions scenario A2 as implemented by the global climate model HadCM3. Impact of water withdrawals and reservoirs is computed by running the model with and without water withdrawals and dams that existed in 2002. Please note that the figure does not reflect spatial differences in the magnitude of change.
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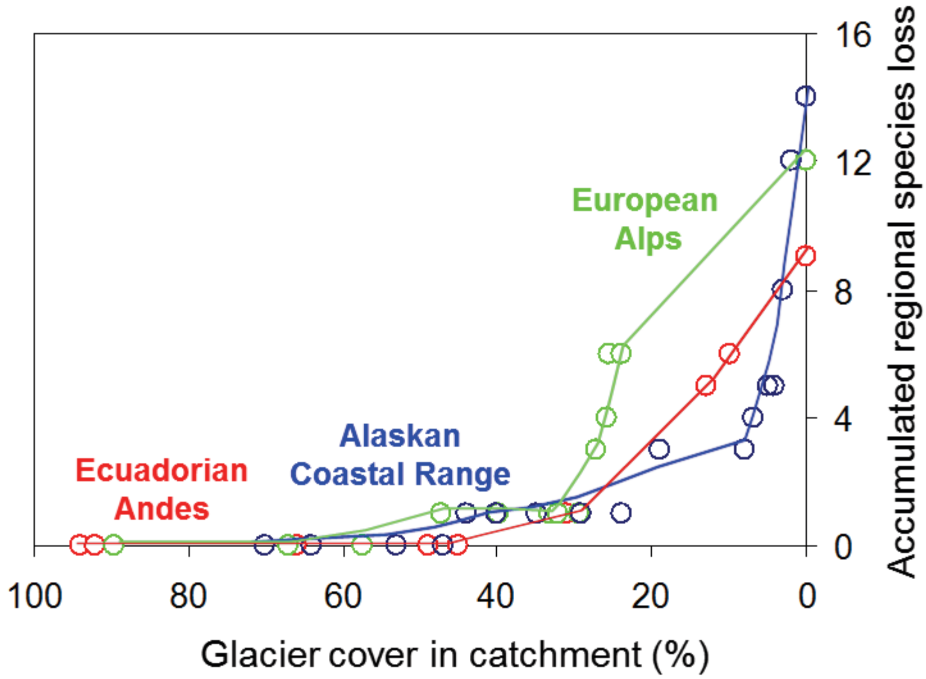

Figure RF-2: Accumulated loss of regional species richness (gamma diversity) of macroinvertebrates as a function of glacial cover in catchment. Obligate glacial river macroinvertebrates begin to disappear from assemblages when glacial cover in the catchment drops below approximately 50%, and 9-14 species are predicted to be lost with the complete disappearance of glaciers in each region, corresponding to 11, 16 and 38% of the total species richness in the three study regions in Ecuador, Europe and Alaska. Data are derived from multiple river sites from the Ecuadorian Andes and Swiss and Italian Alps, and a temporal study of a river in the Coastal Range Mountains of southeast Alaska over nearly three decades of glacial shrinkage. Each data point represents a river site or date (Alaska), and lines are Lowess fits. Adapted by permission from Macmillan Publishers Ltd: *Nature Climate Change*, Jacobsen *et al.*, 2012, © 2012.
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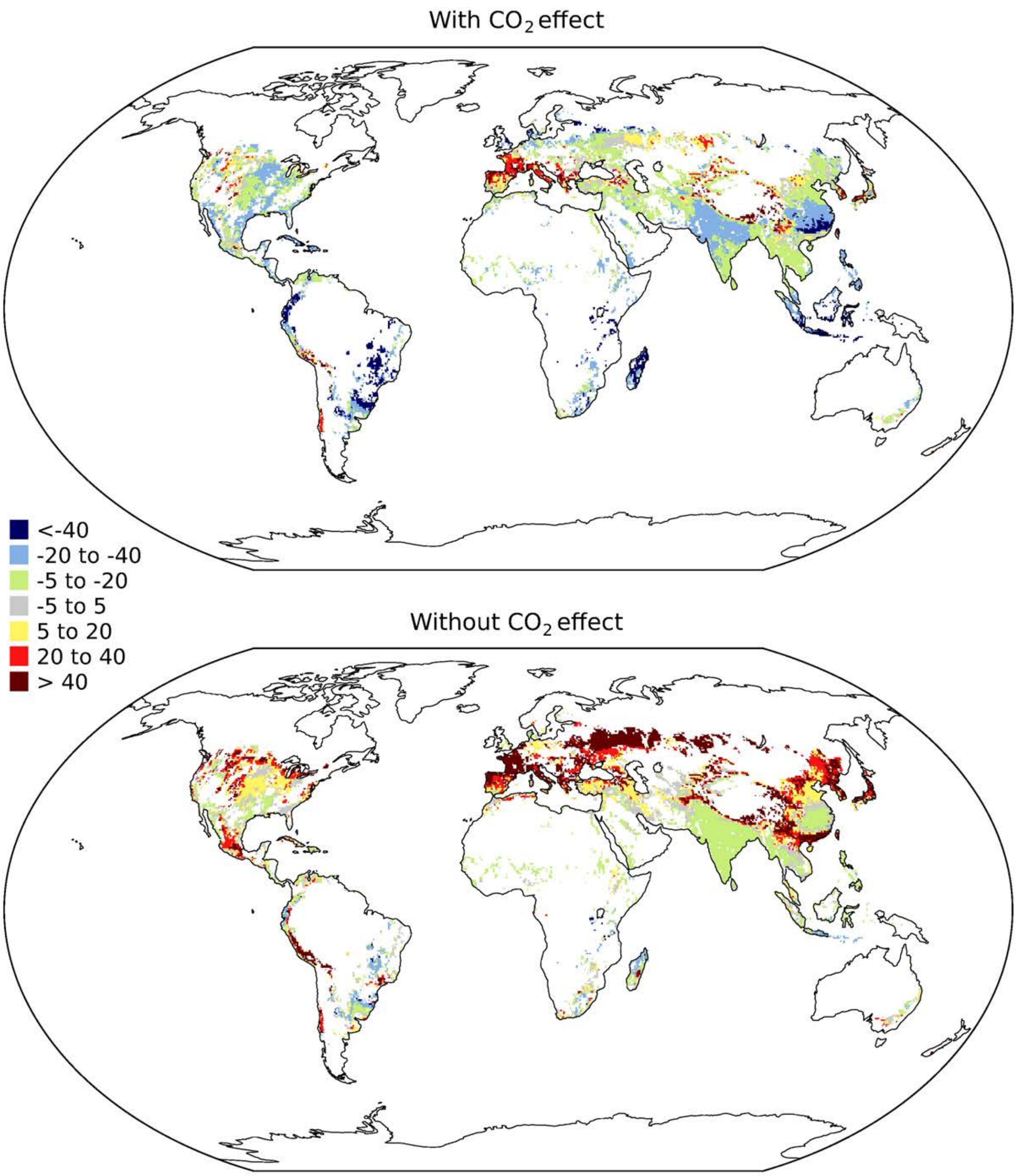

Figure VW-1: Percentage change in net irrigation requirements of 11 major crops from 1971–2000 to 2070–2099 on areas currently equipped for irrigation, assuming current management practices. Top: impact of climate change including physiological and structural crop responses to increased atmospheric CO_2 concentration (maximum effect in the absence of co-limitation by nutrients). Bottom: impact of climate change only. Shown is the median change derived from climate change projections by 19 GCMs (based on the SRES A2 emissions scenario) used to force a vegetation and hydrology model. Modified after Konzmann *et al.* (2013).
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Chapter 5. Coastal Systems and Low-Lying Areas

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Contents

Executive Summary

Coastal systems are particularly sensitive to three key drivers related to climate change: sea level, ocean temperature and ocean acidity (*very high confidence*) [5.3.2, 5.3.3.4, 5.3.3.5]. Despite the lack of attribution of observed coastal changes, there is a long-term commitment to experience the impacts of sea level rise because of a delay in its response to temperature [5.5.8] (*high agreement*). In contrast, coral bleaching and species ranges can be attributed to ocean temperature change and ocean acidity [5.4.2.4, 5.4.2.2]. For many other coastal changes, the impacts of climate change are difficult to tease apart from human-related drivers (e.g. land-use change, coastal development, pollution) (*high agreement, robust evidence*).

Coastal systems and low-lying areas will increasingly experience adverse impacts such as submergence, coastal flooding and coastal erosion due to relative sea level rise (*very high confidence*). Beaches, sand dunes and cliffs currently eroding will continue to do so under increasing sea level (*high confidence*) [5.4.2.1, 5.4.2.2]. Large

spatial variations in the projected sea level rise together with local factors means relative sea level rise at the local scale can vary considerably from projected Global Mean Sea Level (GMSL) rise (*very high confidence*) [5.3.2]. The storms related impacts and associated storm surges will be worsened by GMSL rise although uncertainty related to changes in tropical and mid-latitude cyclones at the regional scale will signify that there is *low confidence* in projections of storm surge change [5.3.3.2]. Both relative sea level rise and impacts are also influenced by a variety of local processes unrelated to climate (e.g. subsidence, glacial isostatic adjustment, sediment transport, coastal development) (*very high confidence*).

Acidification and warming of coastal waters will continue with significant negative consequences for coastal ecosystems (*high confidence*). The increase in acidity will be higher in areas where eutrophication or coastal upwellings are an issue. It will have negative impacts for many calcifying organisms (*high confidence*) [5.4.2.2]. Warming and acidification will lead to coral bleaching, mortality and decreased constructional ability (*high confidence)* making coral reefs the most vulnerable marine ecosystem with little scope for adaptation [5.4.2.4, Box CC-OA]. Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and sea temperature extremes as well as through the impact of invasive subtropical species *(high confidence*) (5.4.2.3).

The population and assets exposed to coastal risks as well as human pressures on coastal ecosystems will increase significantly in the coming decades due to population growth, economic development and urbanization (*high confidence*)**.** The exposure of people and assets to coastal risks has been rapidly growing and this trend is expected to continue [5.3.4.1, 5.4.3.1]. Humans have been the primary drivers of changes in coastal aquifers, lagoons, estuaries, deltas and wetlands (*very high confidence*) and are expected to further exacerbate human pressures on coastal ecosystems resulting from excess nutrient input, changes in run-off and reduced sediment delivery (*high confidence*) [5.3.4.2, 5.3.4.3, 5.3.4.4].

For the 21st century, the benefits of protecting against increased coastal flooding and land loss due to submergence and erosion at the global scale are larger than the social and economic costs of inaction (*high agreement, limited evidence***).** Without adaptation, hundreds of millions of people will be affected by coastal flooding and will be displaced due to land loss by year 2100; the majority of those affected are from East, Southeast and South Asia (*high confidence*) [5.3.4.1, 5.4.3.1]. At the same time, protecting against flooding and erosion is considered economically rational for most developed coastlines in many countries under all socio-economic and sea level rise scenarios analyzed, including for the 21st century GSML rise of above 1 m (*high agreement, low evidence*) [5.5.5].

The relative costs of adaptation vary strongly between and within regions and countries for the 21st century (*high confidence***).** Some low-lying developing countries (e.g. Bangladesh, Vietnam) and small island states are expected to face very high impacts and associated annual damage and adaptation costs of several percentage points of GDP [5.5.5]. Developing countries and small island states within the tropics dependent on coastal tourism will be impacted directly not only by future sea level rise and associated extremes but also by coral bleaching and ocean acidification and associated reductions in tourist arrivals **(***high confidence*) [5.4.3.4].

The analysis and implementation of coastal adaptation has progressed more significantly in developed countries than in developing countries towards climate resilient and sustainable coasts (*high confidence***).** Given ample adaptation options, more proactive responses can be made and based on technological, policy related, financial and institutional support. Observed successful adaptations include major projects (e.g. Thames Estuary, Venice Lagoon, Delta Works) and specific practices in both developed countries (e.g. Netherlands, Australia) and developing countries (e.g. Bangladesh) [5.5.4.2]. More countries and communities carry out coastal adaptation measures including those based on integrated coastal zone management, local communities, ecosystems and disaster reduction, and these measures are mainstreamed into relevant strategies and management plans [5.5.4, 5.5.5] (*high confidence*).

5.1. Introduction

This chapter presents an updated picture of the impacts, vulnerability and adaptation of coastal systems and low-lying areas to climate change, with sea level rise perceived as most important risk for the human systems. Unlike the coastal chapter in the previous assessment (Fourth Assessment Report, AR4), materials pertinent to the oceans are not covered here but in two new ocean chapters (Chapters 6 and 30). As in AR4, polar coasts are in another chapter (chapter 28); small islands area also considered separately (chapter 29) and an in depth presentation will not be found herein.

The topics covered in this chapter follow the outline for sectoral chapters approved by the IPCC. An Executive Summary summarizes the key messages with a line of sight to the supporting sections in the chapter.

This chapter comprises six sections with this first section dealing with progress in knowledge from AR4 to AR5 (Fifth Assessment Report), scope of chapter and new developments. Section 2 defines the coastal systems and climate and non-climate drivers. The coastal systems include both natural systems and human systems and this division is generally followed throughout the chapter. The climate and non-climate drivers are assessed in section 3, followed by the impacts, vulnerabilities and risks in section 4. Section 5 deals with adaptation and managing risks. Information gaps, data gaps and research needs are assessed in section 6. There is one box on a specific example and three cross-chapter boxes, distributed within the chapter.

In AR4, the coastal chapter assessed the impact of climate change and a global sea level rise up to 0.59 m in 2090s. The coastal systems were considered to be affected mainly by higher sea levels, increasing temperatures, changes in precipitation, larger storm surges and increased ocean acidity. Human activities had continued to increase their pressure on the coasts with rapid urbanization in coastal areas and growth of megacities with consequences on coastal resources. Regionally, South, Southeast and East Asia, Africa and small islands were identified as most vulnerable. The AR4 chapter offered a range of adaptation measures, many under the ICZM (Integrated Coastal Zone Management) framework that could be carried out in both developed and developing countries, but recognized that the latter would face more challenges. Various issues on increasing the adaptive capacity or increasing the resilience of coastal communities were discussed. The unavoidability of sea level rise in the long term, even with stringent mitigation was noted, with adaptation becoming an urgent issue.

A number of key issues related to the coasts have arisen since AR4. There is now better understanding of the natural systems, their ecosystem functions, their services and benefits to humanity and how they can be affected by climate change. Their linkages landward to the watersheds and seaward to the seas and oceans need to be considered for a more integrated assessment of climate change impacts. The GMSL (global mean sea level) rise is projected to be 0.28-0.98 m by 2100 (Table 5-2) although with regional variations and local factors the local sea level rise can be higher than the projected for the GMSL. This has serious implications for coastal cities, deltas and low-lying states. While higher rates of coastal erosion are generally expected under rising sea levels, the complex inter-relationships between the geomorphological and ecological attributes of the coastal system (Haslett, 2009; Gilman *et al*., 2007) and the relevant climate and oceanic processes need to be better established at regional and local scales. Such complex inter-relationships can be influenced by different methods and responses of coastal management.

Also of concern is ocean acidification. Together with warming, it causes coral reefs to lose their structural integrity with negatively implicating reef communities and shore protection (Sheppard *et al.*, 2005; Manzello *et al.*, 2008; see Boxes CC-OA and CC-CR). Acidification has potential impacts of reduced calcification in shellfish and impacts on commercial aquaculture (Barton *et al.*, 2012). Since AR4, a significant number of new findings regarding the impacts of climate change on human settlements, key coastal systems such as rocky coasts, beaches, estuaries, deltas, salt marshes, mangroves, coral reefs and submerged vegetation have become available and are reviewed in this chapter. However, uncertainties regarding projections of potential impacts on coastal systems remain generally high.

This chapter also provides advances in both vulnerability assessments and the identification of potential adaptation actions, costs, benefits and tradeoffs. A large number of new studies estimate the costs of inaction versus potential adaptation. Coastal adaptation has become more widely used, with a wider range of approaches and frameworks such as integrated coastal management, ecosystem-based adaptation, community-based adaptation and disaster risk reduction and management.

Climate change will interact differently with the variety of human activities and other drivers of change along coastlines of developed and developing countries. For example, on the coastlines of developed countries, changes in weather and climate extremes and sea level rise may impact the demand for housing, recreational facilities and construction of renewable energy infrastructure on the coast (Hadley, 2009) including critical infrastructures such as transportation, ports and naval bases. Along the coasts of developing countries, weather and climate extremes impact on a wide range of economic activities supporting coastal communities and pose an additional risk to many of the fastest-growing low-lying urban areas, such as in Bangladesh and China (McGranahan *et al.*, 2007; Smith, 2011).

5.2. Coastal Systems

Coastal systems and low-lying areas, further referred to as coasts in this assessment, include all areas near mean sea level. Generally, there is no single definition for the coast and the coastal zone/area where the latter emphasizes the area or extent of the coastal ecosystems. In relation to exposure to potential sea level rise, the LECZ (low-elevation coastal zone) has been used in recent years with reference to specific area and population up to 10 m elevation (Vafeidis *et al.*, 2011).

Coastal systems are conceptualized to consist of both natural and human systems (Figure 5-1). The natural systems include distinct coastal features and ecosystems such as rocky coasts, beaches, barriers and sand dunes, estuaries and lagoons, deltas, river mouths, wetlands and coral reefs. These elements help define the seaward and landward boundaries of the coast. In spite of providing a wide variety of regulating, provisioning, supporting and cultural services (MEA, 2005), they have been altered and heavily influenced by human activities, with climate change constituting only one amongst many pressures these systems are facing. The human systems include the built environment (e.g. settlements, water, drainage, as well as transportation infrastructure and networks), human activities (e.g. tourism, aquaculture, fisheries) as well as formal and informal institutions that organize human activities (e.g. policies, laws, customs, norms and culture). The human and natural systems form a tightly coupled social-ecological system (Berkes and Folke, 1998; Hopkins *et al.*, 2012).

[INSERT FIGURE 5-1 HERE
Figure 5-1: Climate, just as anthropogenic or natural changes, affects both climate and human related drivers. Risk on coastal systems is the outcome of integrating drivers and exposure and vulnerability. Adaptation options can be implemented either to modify the drivers or exposure and vulnerability or both.]

5.3. Drivers

5.3.1. Introduction

In AR4, changes in climate drivers (any climate-induced factor that directly or indirectly causes a change), including sea level rise, were projected for different SRES (Special Report on Emissions Scenarios) emissions scenarios (Nakicenovic and Swart, 2000). Consequently, to date, most of the impacts and vulnerability assessments of climate change in coastal areas are based on SRES A2, A1B, B2 and A1F1 scenarios. Since AR4 a new scenario process has been initiated to replace the SRES scenarios with Representative Concentration Pathways (RCPs) and Shared Socio-economic Pathways (SSPs) (Moss *et al.*, 2010). The RCPs are scenarios specifying concentrations, rather than emissions, thereby avoiding differences in concentrations of Long-Lived Greenhouse Gas and aerosol concentrations for the same emissions scenarios that can arise from the use of different models (van Vuuren *et al.*, 2011). For a comparison between RCP and SRES scenarios see WG1, Chapter 1, Box 1.2. In addition, Extended Concentration Pathways (ECPs) have been introduced for the 2100-2300 period (Meinhausen *et al.*, 2009) providing the opportunity to assess the long-term commitment to sea level rise, which is *very likely* to continue beyond 2500 unless global temperature declines (WG1, Chapter 1, 13.5.2).

The SSPs provide representative qualitative story lines (narratives) of world development together with quantitative pathways of key socio-economic variables such as GDP and population. A preliminary list of five SSPs has been proposed (Arnell *et al.*, 2011; O'Neill *et al.*, 2012) and work to further refine it is ongoing (Kriegler *et al.* 2012; Van Vuuren *et al.*, 2012). SSPs do not include assumptions on mitigation policy and are thus independent from RCPs in the sense that the same SSP may lead to different concentration levels and consequently rises in sea level depending on the level of mitigation reached (Arnell *et al.*, 2011; O'Neill *et al.*, 2012). Table 5-1 summarizes the main climate-related drivers for the coastal systems.

[INSERT TABLE 5-1 HERE
Table 5-1: Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects.]

5.3.2. Relative Sea Level Rise

Assessments of coastal impacts, vulnerability and adaptation need to consider relative sea level (RSL) rise, which includes climate-induced GMSL rise (5.3.2.1) and regional variations (5.3.2.2) as well as local non-climate related sea level changes (5.3.2.3). Relative sea level rise poses a significant threat to coastal systems and low-lying areas around the globe leading to inundation and erosion of coastlines, contamination of freshwater reserves and food crops (Nicholls, 2010). sea level rise due to thermal expansion as the oceans warm, together with meltwater from glaciers, icecaps and ice sheets of Greenland and Antarctica are the major factors that contribute to relative sea level rise globally. However, regional variations in the rate of rise occur because of ocean circulation patterns and inter-annual and decadal variability (e.g. Zhang and Church, 2012; Ganachaud *et al*., 2013) and glacial isostatic rebound and tectonic movement. Subsidence of coastal land from sediment compaction due to building loads, harbor dredging, changes in sediment supply that cause erosion/accretion, subsurface resource extraction (e.g. groundwater, gas and petroleum; Syvitski *et al.*, 2009), may also contribute to relative sea level rise locally and therefore requires consideration in coastal impact studies. sea level impacts are most pronounced during episodes of extreme sea levels and these are discussed in 5.3.3.

5.3.2.1. Global Mean Sea Level

It is *very likely* that GMSL rose at a mean rate of 1.7 [1.5 to 1.9] mm yr^{-1} between 1900 and 2010 and at a rate 3.2 [2.8 to 3.6] mm yr^{-1} from 1993 to 2010 (WG1, 13.2.2). Ocean thermal expansion and melting of glaciers have been the largest contributors, accounting for over 80% of the GMSL rise over the latter period (WG1, 13.3.1). Future rates of GMSL rise during the 21st century are projected to exceed the observed rate for the period 1971–2010 of 2.0 [1.7 to 2.3] mm yr^{-1} for all RCP scenarios (WG1, Table 13.1). Table 5-2 summarizes the *likely* ranges of 21st century GMSL rise as established by the Working Group 1 (WG1) contribution to this Assessment Report.

From a coastal risk management perspective (Nicholls *et al*., 2013) assessments of impacts, vulnerabilities and adaptation have been using GMSL rise scenarios above the ranges put forward by WG1 reports of AR4 (Meehl *et al*., 2007, Table 10.7) and AR5 (WG1 Table 13.5). The ranges estimated by WG1 of AR4 and AR5 only include those components of GMSL rise that can be quantified using process-based models (i.e. models derived from the laws of physics; WG1 Glossary). The ranges given in AR4 thus explicitly excluded contributions to GMSL rise resulting from changes in ice flows from the ice sheets of Greenland and Antarctica because at that time process-based models were not able to assess this with sufficient confidence (Meehl *et al*., 2007; WG1, 4.4.5). Since then, understanding has increased and the *likely* range of GMSL given in AR5 now includes ice sheet flow contributions. Likely, however, means that there is still a 0-33% probability of GMSL rise beyond this range and coastal risk management needs to consider this. WG1 does not assign probabilities to GMSL rise beyond the *likely* range, because this cannot be done with the available process-based models. WG1, however, assigns *medium confidence* that 21st century GMSL rise does not exceed the *likely* range by several tenths of a meter (WG1, 13.5.1). When using other approaches such as semi-empirical models, evidence from past climates and physical constraints on ice-sheet dynamics GMSL rise upper bounds of up to 2.4m by 2100 have been estimated, but there is *low agreement* on these higher estimates and no consensus on a 21st century upper bound (WG1, 13.5.3). Coastal risk management is thus left to choose an upper bound of GMSL rise to consider based on which level of risk is judged to be acceptable in the specific case. The Dutch Delta Programme, for example, considered a 21st century global mean sea level rise of 1.3m as upper bound.

It is *virtually certain* that sea level rise will continue beyond the 21st Century although projections beyond 2100 are based on fewer and simpler models that include lower resolution coupled climate models for thermal expansion and ice sheet models coupled to climate models to project ice sheet contributions. The basis for the projections are the Extended Concentration Pathways (ECPs) and projections are provided for low, medium and high scenarios which relate to atmospheric GHG concentrations <500 ppm, 500-700 and > 700 ppm respectively (WG1, 13.5.2). Projections of GMSL up to 2500 are also summarized in Table 5-2.

[INSERT TABLE 5-2 HERE
Table 5-2: Projections of global mean sea level rise in meters relative to 1986–2005 are based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5-95% range are given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available. Source: WGI AR5 SPM and Sections 12.4.1, 13.5.1, and 13.5.4.]

5.3.2.2. Regional Sea Level

Sea level rise will not be uniform in space and time. Natural modes of climate variability influence sea levels in different regions of the globe and this will affect the rate of rise on interannual and interdecadal time periods. For example in the equatorial Pacific, sea levels can vary from the global mean by up to 40 cm due to ENSO (e.g. Walsh *et al*., 2012) and this can strongly influence trends on decadal scales. Regional variations in the rate of sea level rise on the coast can arise from climate and ocean dynamic processes such as changes in winds and air pressure, air-sea heat and freshwater fluxes, ocean currents and their steric properties (Timmermann *et al*., 2010; WG1, FAQ 13.1). Although the vast majority of coastlines are experiencing sea level rise, coastlines near current and former glaciers and ice sheets are experiencing relative sea level fall (Milne *et al*., 2009; WG1, FAQ 13.1). This is because the gravitational attraction of the icesheet reduces as it melts and exerts less pull on the oceans and also because the land tends to rise as the ice melts, the shape of the sea floor changes under the reduced load of the ice sheets and the change in mass distribution alters the Earths rotation (WG1, FAQ 13.1, Gomez *et al*., 2010). In terms of absolute sea level change, approximately 70% of the global coastlines are projected to experience sea level change that is within 20% of the global mean sea level change (WG1, 13.6.5).

5.3.2.3. Local Sea Level

Besides the effect of long-term vertical land movement on regional sea level, relative sea level rise can occur locally due to subsidence or uplifts of coastal plains as well as due to other natural causes. Natural subsidence can occur because of sediment compaction and loading, as in the Mississippi River, and other deltas (Törnqvist *et al*., 2008; Dokka, 2011; Marriner *et al*., 2012). Tectonic movements, both sustained and abrupt, have brought about relative sea level changes. The Great East Japan Earthquake in 2011 caused subsidence of up to 1.2 m of the Pacific coast of northeast Japan (Geospatial Information Authority of Japan, 2011). The Sumatra-Andaman earthquake in 2004 and subsequent earthquakes in 2005 produced vertical deformation ranging from uplift of 3 m to subsidence of 1 m (Briggs *et al.*, 2006). These movements are especially important in coastal zones located near active plate margins.

Anthropogenic causes of relative sea level rise include sediment consolidation from building loads, reduced sediment delivery to the coast and extraction of subsurface resources such as gas, petroleum and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal (e.g. Kolker *et al*., 2011). Syvitski *et al*. (2009) estimate that the majority of the world’s largest deltas are currently subsiding at rates that are considerably larger than the current rates of sea level rise because of coastal sediment starvation due to substantial dam building over the 20th century or sediment compaction through natural or anthropogenic activities. Many large cities on deltas and coastal plains have subsided during the last 100 years ~4.4 m in eastern Tokyo, ~3 m in the Po delta, ~2.6 m in Shanghai, and ~1.6 m in Bangkok (Syvitski *et al*., 2009; Teatini *et al*., 2011). Loads from massive buildings and other large structures can also increase sediment compaction and subsidence (Mazzotti *et al.*, 2009). Relative sea level rise can exceed GMSL rise by an order of magnitude, reaching more than 10 cm yr^{-1} and it is estimated that the delta surface area vulnerable to flooding could increase by 50% for 33 deltas around the world under the sea level rise as projected for 2100 by the IPCC AR4 (Syvitski *et al*., 2009).

Clearly large regional variations in the projected sea level rise, together with local factors such as subsidence indicates that relative sea level rise can be much larger than projected GMSL rise and therefore is an important consideration in impact assessments (*very high confidence*).

5.3.3. Climate-Related Drivers

Increasing greenhouse gases in the atmosphere produce changes in the climate system on a range of time scales that impact the coastal physical environment. On shorter time scales, physical coastal impacts such as inundation, erosion and coastal flooding arise from severe storm-induced surges, wave overtopping and rainfall runoff. On longer time scales, wind and wave climate change can cause changes in sediment transport at the coast and associated changes in erosion or accretion. Natural modes of climate variability, which can affect severe storm behavior and wind and wave climate, may also undergo anthropogenic changes in the future. Ocean and atmospheric temperature change can affect species distribution with impacts on coastal biodiversity. CO_2 uptake in the ocean increases ocean acidity and reduces the saturation state of carbonate minerals, essential for shell and skeletal formation in many coastal species. Changes in freshwater input can alter coastal ocean salinity concentrations. Past and future changes to these physical drivers are discussed in this section (see also Table 5-1).

5.3.3.1. Severe Storms

Severe storms such as tropical and extratropical cyclones can generate storm surges over coastal seas. The severity of these depends on the storm track, regional bathymetry, nearshore hydrodynamics and the contribution from waves. Globally there is *low confidence* regarding changes in tropical cyclone activity over the 20th century due to changes in observational capabilities, although it is *virtually certain* that there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic since the 1970s (WG1, 2.6). In the future, it is *likely* that the frequency of tropical cyclones globally will either decrease or remain unchanged, but there will be a *likely* increase in global mean tropical cyclone precipitation rates and maximum wind speed (WG1, 14.6).

Extratropical cyclones occur throughout the mid-latitudes of both hemispheres and their development is linked to large-scale circulation patterns. Assessment of changes in these circulation features reveals a widening of the tropical belt, poleward shift of storm tracks and jet streams and contraction of the polar vortex; this leads to the assessment that it is *likely* that, in a zonal mean sense, circulation features have moved poleward (WG, 2.7.5-2.7.8) but there is *low confidence* regarding regional changes in intensity of extratropical cyclones (e.g. Seneviratne *et al*., 2012). With regards to future changes, a small poleward shift is *likely* in the Southern Hemisphere but changes in the Northern Hemisphere are basin specific and of *lower confidence* (WG1, 14.6.3). Globally, it is *unlikely* that the number of extratropical cyclones will fall by more than a few percent due to anthropogenic climate change (*high confidence*; WG1, 14.6.3).

5.3.3.2. Extreme Sea Levels

Extreme sea levels discussed here are those that arise from combinations of factors including astronomical tides, storm surges, wind waves and swell, and interannual variability in sea levels. Storm surges are caused by the falling atmospheric pressures and surface wind stress associated with storms such as tropical and extratropical cyclones and therefore may change if storms are affected by climate change. To date however, observed trends in extreme sea levels are mainly consistent with MSL trends (e.g. Menendez and Woodworth, 2010; Marcos *et al.*, 2009; Haigh *et al.*, 2010, Losada *et al.*, 2013) indicating that Mean Sea Level (MSL) trends rather than changes in weather patterns are responsible.

Assuming that sea level extremes follow a simple extreme value distribution (i.e. a Gumbel distribution), and accounting for the uncertainty in projections of future sea level rise, Hunter (2012) has developed a technique for estimating a sea level allowance, i.e. the minimum height that structures would need to be raised in a future period so that the number of exceedences of that height remains the same as under present climate conditions (Figure 5-2). Such an allowance can be factored into adaptive responses to rising sea levels. It should be noted however that extreme sea level distributions might not follow a simple Gumbel distribution (e.g. Tebaldi *et al.* 2012) due to different factors influencing extreme levels that may not be measured by tide gauges (e.g. Hoeke *et al.*, 2013).

[INSERT FIGURE 5-2 HERE
Figure 5-2: The estimated increase in height (m) that flood protection structures would need to be raised in the 2081-2100 period to preserve the same frequency of exceedences that was experienced for the 1986-2005 period, shown for 182 tide gauge locations and assuming regionally-varying relative sea level rise projections under an RCP4.5 scenario (adapted from Hunter *et al*., 2013).]

Regarding future changes to storm surges, hydrodynamic models forced by climate models have been used in several extratropical regional studies such as the northeast Atlantic (e.g. Debenard and Roed, 2008; Wang *et al*., 2008; Sterl *et al*., 2009) and southern Australia (Colberg and McInnes, 2012). These studies show strong regional variability and sensitivity to the choice of Global Climate Model (GCM) or Regional Climate Model (RCM). The effect of future tropical cyclone changes on storm surges has also been investigated in a number of regions using a range of different methods. These include methods to stochastically generate and/or perturb cyclones within background environmental conditions that represent historical (e.g. Harper *et al*., 2009) and GCM-represented future conditions (e.g. Mousavi *et al*., 2011; Lin *et al*., 2012). Regional studies include Australia's tropical east coast (Harper *et al*., 2009), Louisiana (Smith *et al*., 2010), Gulf of Mexico, (Mousavi *et al*., 2011), India, (Unnikrishnan *et al*., 2011) and New York (Lin *et al*., 2012) and the details of the methods and findings vary considerably between the studies. While some studies indicate for some regions increase to extreme sea levels due to changes in storms, others indicate the opposite. In general, the small number of regional storm surge studies together with the different atmospheric forcing factors and modeling approaches means that there is *low confidence* in projections of storm surges due to changes in storm characteristics. However, observed upward trends in MSL together with projected increases for 2100 and beyond indicate that coastal systems and low-lying areas will increasingly experience extreme sea levels and their adverse impacts (*high confidence*). (see also WGI, 13.7).

5.3.3.3. Winds and Waves

Changes in wind climate affect large-scale wave climate. Winds also influence longshore current regimes and hence upwelling systems (Narayan *et al.*, 2010; Miranda *et al.*, 2012; see also 6.3.3, 6.3.5). Energy dissipation via wave breaking contributes to longshore and cross-shore currents, elevated coastal sea levels through wave set-up and run-up and beach erosion. Changes to wind and wave climate therefore can affect sediment dynamics and shoreline processes (e.g. Aargaard *et al*., 2004; Reguero *et al.*, 2013) and extreme winds and waves are a threat to coastal populations. The coastal impacts of wave climate change are also a function of wave direction and period as well as the coastline itself, which can influence shoaling and refraction. Long period swell, which dominates the wave energy field, poses a significant danger to coastal and offshore structures and shipping (e.g. Semedo *et al.*, 2011) and can causes significant flooding of coastlines with steep shelf margins (Hoeke *et al*., 2013).

There is *low confidence* in trends calculated from measurements of mean and extreme winds and their causes due to the limited length of records and uncertainties associated with different wind measurement techniques (Seneviratne *et al*., 2012). However, there is increasing evidence for a strengthening wind stress field in the Southern Ocean since the early 1980s from atmospheric reanalyses, satellite observations and island station data (WG1, 3.4.5). Positive trends in wave height have been detected in the Northeast Atlantic over the 1958-2002 period based on reanalyses and ship observations and in the Southern Ocean between 1985–2008 based on satellite data (*medium confidence*) (WG1, 3.4.6, see Table 5-2).

Projected changes in mean and extreme winds and waves were assigned *low confidence* (Seneviratne *et al*., 2012) owing to limited studies. Although there has been an increase in studies addressing future wave climate change (Hemer *et al.,* 2013), generally *low confidence* remains in projected wave climate change (except for *medium confidence* over the southern ocean) and this is due to uncertainties in future winds, particularly those associated with storms (see WG1, 13.7).

5.3.3.4. Sea Surface Temperature

Sea surface temperature (SST) has significantly warmed during the past 30 years along more than 70% of the world's coastlines, with highly heterogeneous rates of change both spatially and seasonally (Lima and Wethey, 2012). The average rate is 0.18 ± 0.16°C per decade and the average change in seasonal timing was -3.3 ± 4.4 days per decade. These values are larger than in the global ocean where the average of change is about 0.1°C per decade in the upper 75 m of the ocean during the 1970-2009 period (WG1, Chapter 3) and the seasonal shift is -2.3 days per decade (Lima and Wethey, 2012). Extreme events have also been reported. For example, the record high ocean temperatures along the Western Australian coast during the austral summer of 2010/2011, with nearshore temperatures peaking at about 5 °C above average, were unprecedented (Pearce and Feng, 2013). In summary, positive trends in coastal SST's are seen on the majority of coastlines and the rate of rise along coastlines is higher on average than the oceans (*high confidence*). Based on projected temperature increases there is *high confidence* that positive coastal SST trends will continue.

5.3.3.5. Ocean Acidification

Anthropogenic ocean acidification refers to the changes in the carbonate chemistry primarily due to the uptake of atmospheric CO_2 (Box CC-OA). Seawater pH exhibits a much larger spatial and temporal variability in coastal waters compared to open ocean due to the variable contribution of processes other than CO_2 uptake (Duarte *et a*l., 2013a) such as upwelling intensity (Feely *et al*., 2008; Box CC-UP), deposition of atmospheric nitrogen and sulphur (Doney *et al*., 2007), carbonate chemistry of riverine waters (Salisbury *et al*., 2008; Aufdenkampe *et al*., 2011), as well as inputs of nutrients and organic matter (Borges, 2011; Cai *et al*., 2011). For example, pH (NBS scale) ranges from 6 to 9 in 24 estuaries (Borges and Abril, 2011) and short-term (hours to weeks) changes of up to 0.5 pH units are not unusual in coastal ecosystems (Hofmann *et al.*, 2011).

Few high-quality ocean acidification time series exceed 5 years in the coastal ocean (Wootton *et al*., 2008; Provoost *et al*., 2010; Waldbusser *et al*., 2010). Some exhibit considerable differences compared to open ocean stations illustrating that anthropogenic ocean acidification can be lessened or enhanced by processes such as primary production, respiration and calcification (Borges and Gypens, 2010; Kleypas *et al*., 2011).

Under the IS92a CO_2 emission scenario, the global pH (total scale) of coastal waters has been projected to decrease from about 8.16 in the year 1850 to 7.83 in 2100 (Lerman *et al*., 2011) but with considerable spatial variability. For example, using the same CO_2 emission scenario, Cai *et al.* (2011) projected an overall decline of pH in the Northern Gulf of Mexico of 0.74 over the same period a value which is much greater than that of the open ocean (Box CC-OA).

To summarize, seawater pH exhibits considerable temporal and spatial variability in coastal areas compared to open ocean due to additional natural and human influences (*very high confidence*). Coastal acidification is projected to continue but with large and uncertain regional and local variations (*high confidence*).

5.3.3.6. Freshwater Input

Changes in river runoff arise from changes in climate drivers such as precipitation, complex interactions between changing levels of CO_2, plant physiology and, consequently, evapotranspiration (e.g. Gedney *et al*., 2006; Betts *et al*., 2007) as well as human drivers such as land-use change, water withdrawal, dam building and other engineered modifications to waterways (see more detailed discussion in Chapter 3). An assessment of run-off trends in 925 of the world's largest ocean-reaching rivers, which account for about 73% of global total runoff, indicates that from 1948–2004 statistically significant trends were present in only one third of the top 200 rivers, and of these, two thirds exhibited downward trends and one third upward trends (Dai *et al.*, 2009). While precipitation changes dominate freshwater flows, decreasing trends in river discharges may be further enhanced due to human pressures (Dai *et al.*, 2009; 3.2.3).

Average annual runoff is generally projected to increase at high latitudes and in the wet tropics and to decrease in most dry tropical regions (3.4.5). Shifts to earlier peak flows are also projected in areas affected by snowmelt (Adam *et al*, 2009). However, there are some regions where there is considerable uncertainty in the magnitude and direction of change, specifically south Asia and large parts of South America. Both the patterns of change and the uncertainty are largely driven by projected changes in precipitation.

To summarize, there is *medium confidence (high agreement, limited evidence)* in a net declining trend in freshwater input globally although large regional variability exists. Trends are dominated by precipitation changes although human pressures on water supply may enhance downward trends (*medium confidence*). Uncertainty in future changes in run-off is linked to precipitation uncertainty. Runoff is generally projected to increase in high latitudes with earlier peak flows and in the wet tropics and decrease in other tropical regions however with large uncertainty (*medium confidence*).

5.3.4. Human-Related Drivers

Coastal systems are subject to a wide range of human-related or anthropogenic drivers (e.g. Crain *et al.*, 2009) which interact with climate-related drivers and confound efforts to attribute impacts to climate change. Some of the major terrestrially based human drivers that directly or indirectly cause changes are briefly reviewed below. Related drivers in the marine environment are discussed in 6.4 and 30.6.

5.3.4.1. Socioeconomic Development

Socio-economic development (SED) drives coastal impacts in several ways. SED influences the number of people and the value of assets exposed to coastal hazards. Since AR4, a number of studies have estimated the influence of future sea level rise and associated hazards on coastal population and assets. Although these estimates are subject to uncertainties associated with global elevation and population datasets (Lichter *et al.*, 2011; Mondal and Tatem, 2012), all the studies indicate high and growing exposure of low-lying coastal areas. The Low Elevation Coastal Zone (LECZ) constitutes 2% of the world's land area but contains 10% of world's population (600 million) and 13% of world's urban population (360 million) based on year 2000 estimates (McGranahan *et al.*, 2007). About 65% of the world's cities with populations of over 5 million are located in the LECZ (McGranahan *et al.*, 2007). The global population exposed to the 1-in-100 year extreme sea level (i.e. the sea level that has a 1% chance of being exceeded every year) has increased by 95% from 1970 to 2010 with about 270 million people and 13 trillion US$ worth of assets being exposed to the 1-in-100 year extreme sea level in 2010 (Jongman *et al*., 2012). In 2002, about 1.9 trillion US$ worth of assets below the 1-in-100 year extreme sea level were concentrated in the following 10 port cities: Miami (USA), New York-Newark (USA), New Orleans (USA), Osaka-Kobe (Japan), Tokyo (Japan), Amsterdam (Netherlands), Rotterdam (Netherlands), Nagoya (Japan), Virginia Beach (USA) and Guangzhou (China) (Hanson *et al.*, 2011). Compared to other regions, Asia exhibits the greatest exposure in terms of population and assets (Jongman *et al*. 2012).

For many locations population and assets exposure is growing faster than the national average trends due to coastward migration, coastal industrialization and urbanization (e.g. McGranahan *et al.*, 2007; Smith, 2011; Seto, 2011; Chapter. 8; *high confidence*). Coastal net migration has largely taken place in flood- and cyclone-prone areas, which poses a challenge for adaptation (de Sherbinin *et al.*, 2012). These processes and associated land use changes are driven by a combination of many social, economic, and institutional factors including taxes, subsidies, insurance schemes, aesthetic and recreational attractiveness of the coast and increased mobility (Bagstad *et al.*, 2007; Palmer *et al.*, 2011). In China, the country with the largest exposed population, urbanization and land reclamation are the major drivers of coastal land-use change (Zhu *et al.*, 2012). Although coastal migration is expected to continue in the coming decades, it is difficult to capture this process in global scenarios as the drivers of migration and urbanization are complex and variable (Black *et al.* 2011).

SED also influences the capacity to adapt. Poor people living in urban informal settlements, of which there are about 1 billion worldwide, are particularly vulnerable to weather and climate impacts (Handmer *et al.*, 2012; de Sherbinin *et al.*, 2012). The top five nations classified by population in coastal low-lying areas are developing and newly industrialized countries: Bangladesh, China, Vietnam, India and Indonesia (McGranahan *et al*., 2007; Bollman *et al.*, 2010; Jongman *et al*. 2012). SED and associated land reclamation are also major drivers of the destruction of coastal wetlands, which also makes human settlements more vulnerable since wetlands act as natural buffers reducing wave and storm impacts on the coast (e.g. Crain *et al.*, 2009; Shepard *et al.*, 2011; Duarte et al., 2013b; Arkema *et al.*, 2013). Finally, socio-economic development is expected to further exacerbate a number of human pressures on coastal systems related to nutrient loads, hypoxia and sediment delivery, which will be discussed in the following sub-sections.

5.3.4.2. Nutrients

Increased river nutrient (N, P) loads to coasts in many regions are observed, and simulated by regional and global models (Alexander *et al.*, 2008; Seitzinger *et al.*, 2010). Anthropogenic global loads of dissolved inorganic nutrients (DIN, DIP) are 2-3 times larger than those of natural sources (Seitzinger *et al.*, 2010) causing coastal ecosystem degradation (5.3.4.3, 5.4.2.6). Large variations exist in magnitude and relative sources of nutrient loads. Anthropogenic sources are primarily related to fertilizer use in agriculture and fossil fuel emissions (NOx) (Bouwman *et al.*, 2009; Galloway *et al.*, 2004).

Future trends depend on measures available to optimize nutrient use in crop production and minimize loss to rivers from agriculture (crop, livestock), sewage, and NOx emissions. In scenarios with little emphasis on nutrient management, global nutrient discharge increases (DIN 30%, DIP 55%) between 2000 and 2050 (Seitzinger *et al.*, 2010). With ambitious nutrient management, global DIN loads decrease slightly and DIP increases (35%). Climate change is projected to change water runoff (Chapter 3) that influences river nutrient loads. Studies of climate change effects related to increased watershed nutrient sources are needed. In summary, nutrient loads have increased in many world regions (*high confidence*); future increases will largely depend on nutrient management practices (*medium confidence*).

5.3.4.3. Hypoxia

The presence of excessive nutrients in coastal waters, which causes eutrophication and the subsequent decomposition of organic matter, is the primary cause of decreased oxygen concentration (hypoxia). Globally, upwelling of low oxygen waters (e.g. Grantham *et al.*, 2004) and ocean warming, which decreases the solubility of oxygen in seawater (Shaffer *et al.*, 2009) are secondary drivers but can be locally important. The oxygen decline rate is greater in coastal waters than in the open ocean (Gilbert *et al.*, 2010). Hypoxia poses a serious threat to marine life, which is exacerbated when combined with elevated temperature (Vaquer-Sunyer and Duarte, 2011; 6.3.3). The number of so-called “dead zones” has approximately doubled each decade since 1960 (Diaz and Rosenberg, 2008). Fishery catches from these areas are generally lower than predicted from nutrient loading alone (Breitburg *et al.*, 2009). Although non-climate anthropogenic factors are responsible for virtually all hypoxia in estuaries and inner continental shelves, climate drivers such as ocean warming, altered hydrological cycles and coastal currents shifts and changes in upwellings may interact with eutrophication in the next decades (Rabalais *et al.*, 2010; Meire *et al.*, 2013; *high confidence*).

5.3.4.4. Sediment Delivery

Human activities in drainage basins and coastal plains have impacted the coastal zone by changing the delivery of sediment to the coast. Sediment trapping behind dams, water diversion for irrigation, and sand and gravel mining in river channels all contribute to decrease sediment delivery, whereas soil erosion due to land-use changes help increase it (Syvitski, 2008; Walling, 2006). It is estimated that the global discharge of riverine sediment was 16-–19 Gt yr-1 in the 1950s before widespread dam construction (e.g. Syvitski *et al.*, 2005; Milliman and Farnsworth, 2011) and it has decreased to 12–13 Gt yr-1 (Syvitski and Kettner, 2011). Out of 145 major rivers with mostly more than 25-year record, only 7 showed evidence of an increase in sediment flux while 68 showed significant downward trends (Walling and Fang, 2003). The number of dams has increased continuously and their distribution has expanded globally. As of early 2011, the world has an estimated 16.7 million reservoirs larger than 0.01 ha (Lehner *et al.*, 2011). Globally, 34 rivers with drainage basins of 19 million km2 in total show a 75% reduction in sediment discharge over the past 50 years (Milliman and Farnsworth, 2011). Reservoir trapping of sediments is estimated globally as 3.6 Gt yr-1 to more than 5 Gt yr-1 (Syvitski *et al.*, 2005; Walling, 2012; Milliman and Farnsworth, 2011). Human pressure is the main driver of the observed declining trend in sediment delivery to the coast (*high agreement*).

5.4. Impacts, Vulnerabilities, and Risks

5.4.1. Introduction

This subsection briefly introduces the diverse approaches and methods applied in the literature on coastal impact, vulnerability and risk. The following subsections then assess this literature related to coastal natural systems (5.4.2) and coastal human systems (5.4.3). Much of this literature focuses on relative sea level rise and extreme sea level events as the main drivers. The main biophysical impacts of this driver are increasing flood damage, dry-land loss due to submergence and erosion, wetland loss and change, saltwater intrusion into surface and ground waters and rising water tables and impeded drainage (Table 5-3).

Impacts and risks are assessed using a wide variety of approaches from the local to global scale. *sea level rise exposure approaches* are applied at all scales to assess values exposed to sea level rise (e.g. people, assets, ecosystems or geomorphological units). *Submergence exposure approaches* assess exposure to permanent inundation under a given sea level rise (e.g. Dasgupta *et al.*, 2009; Boateng, 2012) whereas *flood exposure approaches* assess exposure to temporary inundation during a coastal flood event by combining the extreme water level of the flood event with a given level of sea level rise (e.g. Dasgupta *et al.*, 2011; Kebede and Nicholls, 2012).

Indicator-based approaches are also used at all scales to aggregate data on the current state of the coastal systems into vulnerability indices (Gornitz, 1991; Hinkel, 2011), based on either biophysical exposure or hazard variables (e.g. Yin *et al.*, 2012; Bosom and Jimenez, 2011), socioeconomic variables representing a social group's capacity to adapt (e.g. Cinner *et al.*, 2012) or both kinds of variables (e.g. Bjarnadottir *et al.*, 2011; Yoo *et al.*, 2011; Li and Li, 2011).

At local scales (<100 km coastal length), *process-based models* are applied to assess flooding, erosion and wetland impacts. Approaches include assessments of *flood damage* of single extreme water level events using numerical *inundation models* (e.g. Xia *et al.*, 2011; Lewis *et al.*, 2011). Erosion impacts are assessed using either numerical *morphodynamic models* (e.g. Jiménez *et al., 2009;* Ranasinghe *et al., 2012)* or simple geometric profile relationships such as the Bruun Rule (Bruun, 1962). For ecosystem impacts *ecological landscape simulation models* are used to predict habitat change due to sea level rise and other factors (e.g. Costanza *et al.*, 1990).

At regional to global scales, numerical process-based models are not available for assessing the impacts of relative sea level rise and extreme sea level events due to data and computational limits. Global scale assessments of coastal impacts have been conducted with the models FUND (Climate Framework for Uncertainty, Negotiation and Distribution) and DIVA (Dynamic and Interactive Coastal Vulnerability Assessment). FUND is an integrated assessment model with a coastal impact component that includes country-level cost functions for dry land loss, wet land loss, forced migration and dike construction (Tol, 2002). DIVA is a dedicated coastal impact model employing subnational coastal data (Vafeidis *et al*., 2008) and considering additional impacts such as coastal flooding and erosion as well as adaptation in terms of protection via dikes and nourishment (Hinkel and Klein, 2009). DIVA assesses coastal flood risk based on hydrologically connected elevation and extreme water level distributions (Hinkel *et al.*, 2013) and erosion based on a combination of the Bruun Rule and a simplified version of the ASMITA model for tidal basins (Nicholls *et al.*, 2011). The results of these models are discussed in Sections 5.4.3.1 and 5.5.5.

For impacts on natural systems, the key climate-related drivers considered are temperature, ocean acidification and sea level. A variety of approaches are applied including field observations of ecosystem features (e.g. biodiversity, reproduction) and functioning (e.g. calcification, primary production), remote sensing (e.g. extent of coral bleaching, surface area of vegetated habitats) and perturbation experiments in the laboratory and in the field.

[INSERT TABLE 5-3 HERE
Table 5-3: Main impacts of relative sea level rise. Source: Adapted from Nicholls et al., 2010.]

5.4.2. Natural Systems

Coastal ecosystems are experiencing large cumulative impacts related to human activities (Halpern *et al.*, 2008) arising from both land- and ocean-based anthropogenic drivers. Anthropogenic drivers associated with global climate change are distributed widely and are an important component of cumulative impacts experienced by coastal ecosystems. There is no wetland, mangrove, estuary, rocky shore or coral reef which is not exhibiting some degree of impact. Overexploitation and habitat destruction are often the primary causes of historical changes in coastal systems leading to declines in diversity, structure and functioning (Lotze *et al.*, 2006). Furthermore, extreme climate events generate changes to both the mean and the variance of climatic variables over ecological time scales.

5.4.2.1. Beaches, Barriers, and Sand Dunes

Beaches, barriers and sand dunes are about half as common as rocky coasts (Bird, 2000; Davis and FitzGerald, 2004) but often exhibit distinct and seasonal changes. Due to their aesthetic qualities, they are highly valued for recreation and residences.

Observed impacts

Globally beaches and dunes have in general undergone net erosion over the past century or longer (e.g. see Bird, 2000 for an overview). A number of studies have investigated shoreline change by comparing historical maps and imagery, available since about the mid-19th century with more recent maps and imagery to quantify combined climate and non-climate changes. For example, along the U.S. Mid-Atlantic and New England coasts the long-term rate of erosion, based on 21,184 transects equally spaced along more than 1000 km of coast, is 0.5 ± 0.09 m yr^{-1} with 65% of transects showing net erosion (Hapke *et al.*, 2011). A similar study by Webb and Kench (2010) in the central Pacific utilized historical aerial photographs and satellite images to show physical changes in 27 islets located in 4 atolls over a 19 to 61 year period. The analysis highlighted the dynamic nature of sea level rise response in the recent past, with physical changes in shoreline progradation and displacement influencing whether the island area increased (46%), remained stable (46%) or decreased (14%).

Attributing shoreline changes to climate change is still difficult due to the multiple natural and anthropogenic drivers contributing to coastal erosion. For example, rotation of pocket beaches (i.e. where one end of the beach accretes while the other erodes and then the pattern reverses) in southeast Australia is closely related to interannual changes in swell direction (Harley *et al.*, 2010). Additional processes, unrelated to climate change, that contribute to coastal change, include dams capturing fluvial sand (e.g. in Morocco, Chaibi and Sedrati, 2009). Statistically linking sea level rise to observed magnitudes of beach erosion has had some success although the coastal sea level change signal is often small when compared to other processes (e.g. Sallenger *et al*., 2000; Leatherman *et al*., 2000a; 2000b; Zhang *et al*., 2004). A Bayesian network incorporating a variety of factors affecting coastal change including relative sea level rise, has been successful in hindcasting shoreline change, and can be used to evaluate the probability of future shoreline change (Gutierrez *et al*., 2011).

While some coastal systems may be able to undergo landward retreat under rising sea levels, others will experience coastal squeeze, which occurs when an eroding shoreline approaches hard, immobile, structures such as seawalls or resistant natural cliffs. In these instances the beaches will narrow due to the resulting sediment deficit and produce adverse impacts such as habitat destruction, impacting the survivability of a variety of organisms (Jackson and McIlvenny, 2011). With such a manifestation of coastal squeeze, sand dunes will ultimately be removed as the beach erodes and narrows. Extreme storms can erode and completely remove dunes, degrading land elevations and exposing them to inundation and further change if recovery does not occur before the next storm (Plant *et al*., 2010). Even in the absence of hard obstructions, barrier island erosion and narrowing can occur, as a result of rising sea level and recurrent storms, as in the Chandeleur Islands and Isles Dernieres, Louisiana, U.S.A. (Penland *et al*., 2005).

Projected impacts

With projected GMSL rise (see 5.3.3), inundation and erosion may become detectable and progressively important. The impacts will *likely* be first apparent by sea level rise adding to storm surge, making extreme water levels higher and more frequent to attack beaches and dunes (Tebaldi *et al.*, 2012).

The Bruun rule, (a simple rule based on the assumption that to maintain an equilibrium cross-shore profile under rising sea levels, the coastline will move landwards a distance of approximately 100 times the vertical sea level rise; Bruun, 1962), has been used by many researchers to calculate erosion by sea level rise. However there is disagreement about whether the Bruun rule is appropriate (Cooper and Pilkey, 2004; Woodroffe and Murray-Wallace, 2012) and how to calculate the amount of retreat remains controversial (Gutierrez *et al.*, 2011; Ranasinghe *et al.*, 2012). An increase in storm intensity and ocean swell may accelerate erosion of beaches, barriers and dunes although in some places beach response to sea level rise could be more complex than just a simple retreat (Irish *et al.*, 2010).

Coastal squeeze is expected to accelerate with a rising sea level. In many locations, finding sufficient sand to artificially rebuild beaches and dunes will become increasingly difficult and expensive as present supplies near project sites are depleted (*high confidence*). New generation models are emerging to estimate the costs of saving oceanfront homes through beach nourishment relative to the structures cost (McNamara *et al.*, 2011). In the absence of adaptation measures, beaches and sand dunes currently affected by erosion will continue to do so under increasing sea levels (*high confidence*).

5.4.2.2. Rocky Coasts

Rocky coasts with shore platforms form about ¾ of the world's coasts (Jackson and McIIvenny, 2011; Davis and FitzGerald, 2004) and are characterized by very strong environmental gradients, especially in the intertidal zone where challenges are posed by both aquatic and aerial climatic regimes, such as temperature and desiccation.

Observed impacts

Cliffs and platforms are erosional features and any change that increases the efficiency of processes acting on them, such as relative sea level rise, storminess, wave energy and weathering regimes, increases erosion (Naylor *et al.*, 2010). Their responses vary, due to different lithology (e.g. hard rock vs. non-lithified soft rock) and profiles (e.g. plunging cliffs or cliffs with shore platforms). Cliffs and platforms have reduced resilience to climate change impacts; once platforms are lowered or cliffs have retreated, it is difficult to rebuild them (Naylor *et al.*, 2010). On the decadal scale for example, the retreat of soft rock cliffs in East Anglia, UK, has been linked to the NAO phases with high energetics (Brooks and Spencer, 2013).

Changes in the abundance and distribution of rocky shore animals and algae have long been recognized (Hawkins *et al.*, 2008) and perturbation experiments provide information about environmental limits, acclimation and adaptation, particularly to changes in temperature (Somero, 2012). The challenge is to attribute the changes to climate-related drivers, human-related drivers and to natural fluctuations.

The range limits of many intertidal species have shifted by up to 50 km per decade over the past 30 years in the North Pacific and North Atlantic, much faster than most recorded shifts of terrestrial species (Helmuth *et al.*, 2006; Box CC-MB). However, the distribution of some species has not changed in recent decades, which may be due to weak local warming (Rivadeneira and Fernández, 2005) or overriding effects of variables such as timing of low tide, hydrographic features, lack of suitable substrate, poor larval dispersal, and effects of food supply, predation and competition (Helmuth *et al.*, 2002, 2006; Poloczanska *et al.*, 2011).

The dramatic decline of biodiversity in mussel beds of the Californian coast has been attributed to large-scale processes associated with climate-related drivers (59% loss in species richness, 1960s to 2002; Smith *et al.*, 2006) (*high confidence*). Warming reduced predator-free space on rocky shores, leading to a decrease of the vertical extent of mussel beds by 51% in 52 years in the Salish Sea, and to the disappearance of reproductive populations of mussels (Harley, 2011). Unusually high air or water temperature led to mass mortalities, for example, of mussels on the Californian coast (Harley, 2008) and gorgonians in the Northwestern Mediterranean (Garrabou, 2009).

Rocky shores are one of the few ecosystems for which field evidence of the effects of ocean acidification is available. Observational and modeling analysis have shown that the community structure of a site of the NE Pacific shifted from a mussel to an algal-barnacle dominated community between 2000 and 2008 (Wootton *et al.*, 2008), in relation with rapidly declining pH (Wootton and Pfister, 2012).

Projected impacts

Modeled relationships suggest that soft-rock recession rates depends on the relative change in sea level rise while cliff retreat depends both on total elevation change of sea level and on the rate of sea level rise (Ashton *et al.*, 2011). In a modelling study, Trenhaile (2010) found sea level rise to trigger faster rates of cliff recession, especially in coasts that are already retreating fast. Additionally, based on modelling cliff dynamics with contemporary and historic data of soft cliff retreat along Suffolk Coast, UK, rapid retreat is associated with accelerating sea level rise (Brooks and Spencer, 2013). However, coasts currently retreating slowly would experience the largest proportional increase in retreat rates. Increases in storminess have smaller effects on rocky shores (Trenhaile, 2011; Dawson *et al.*, 2009).

Few projections of the effect of climate change on rocky shores have considered the effects of direct and indirect species interactions (Poloczanska *et al.*, 2008; Harley, 2011) and the effects of multiple drivers (Helmuth *et al.* 2006). The abundance and distribution of rocky shore species will continue to change in a warming world (*high confidence*). For example, the long-term consequences of ocean warming on mussel beds of the NE Pacific are both positive (increased growth) and negative (increased susceptibility to stress and of exposure to predation) (Smith *et al.*, 2006; Menge *et al.*, 2008; *medium confidence)*. Extrapolations of ecosystem change based on temperature-focused studies alone are likely to be conservative, as hypoxia (Grantham *et al.*, 2004) or ocean acidification (Feely *et al.*, 2008) are also known to occur in this region.

Observations performed near natural CO_2 vents in the Mediterranean Sea show that diversity, biomass, and trophic complexity of rocky shore communities will decrease at future pH levels (Barry *et al.*, 2011; Kroeker *et al.*, 2011; *high confidence*). An abundant food supply appears to enable mussels of the Baltic Sea to tolerate low pH (Thomsen *et al*., 2010; 2013) at the cost of increased energy expenditure. Model projections that include the interactive effects of ocean warming and acidification suggest that a population of barnacle of the English Channel will become extinct 10 years earlier than it would with warming alone (Findlay *et al.*, 2010; *medium confidence*). Ocean acidification may also exacerbate mass mortality events in the Mediterranean Sea (Rodolfo-Metalpa *et al*., 2011; *limited evidence).*

In summary, rocky shores are among the better-understood coastal ecosystems in terms of potential impacts of climate variability and change. The most prominent effects are range shifts of species in response to ocean warming (*high confidence*) and changes in species distribution and abundance (*high confidence*) mostly in relation to ocean warming and acidification.

5.4.2.3. Wetlands and Seagrass Beds

Vegetated coastal habitats and coastal wetlands (mangrove forests, salt marshes, seagrass meadows and macroalgal beds) extend from the intertidal to the subtidal areas in coastal areas, where they form key ecosystems.

Observed impacts

Vegetated coastal habitats are globally declining globally (Duarte *et al.*, 2005), rendering shorelines more vulnerable to erosion due to increased sea level rise and increased wave action (e.g. Alongi, 2008) and leading to the loss of carbon stored in sediments. Together, the loss of coastal wetlands and seagrass meadows results in the release of 0.04 to 0.28 Pg C annually from organic deposits (Pendleton *et al.*, 2012). Recognition of the important consequences of the losses of these habitats for coastal protection and carbon burial (Duarte *et al*., 2013a), has led to large-scale reforestation efforts in some nations (e.g. Thailand, India, Vietnam).

The response of saltmarshes to sea level rise involves landward migration of salt-marsh vegetation zones, submergence at lower elevations, and drowning of interior marshes. Ocean warming is leading to range shifts in vegetated coastal habitats. The poleward limit of mangrove forests is generally set by the 20 ºC mean winter isotherm (Duke *et al.*, 1998). Accordingly, migration of the isotherm with climate change (Burrows *et al.*, 2011) should lead to a poleward expansion of mangrove forests, as observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux *et al.*, 2011; Raabe *et al.* 2012), and New Zealand (Stokes *et al.*, 2010),leading to increased sediment accretion (*medium confidence*).

Seagrass meadows are already under stress due to climate change (*high confidence*), particularly where maximum temperatures already approach their physiological limit. Heat waves lead to widespread seagrass mortality, as documented for *Zostera* species in the Atlantic (Reusch *et al.*, 2005), and *Posidonia* meadows in the Mediterranean Sea (Marbà and Duarte, 2010) and Australia (Rasheed and Unsworth, 2011; *high confidence*). Warming also favors flowering of *P. oceanica* (Diaz-Almela *et al.*, 2007), but the increased recruitment rate is insufficient to compensate for the losses resulting from elevated temperatures (Diaz-Almela *et al.*, 2009).

Kelp forests have been reported to decline in temperate areas in both hemispheres (Johnson *et al.*, 2011, Wernberg *et al.*, 2011a,b, Fernández *et al.*, 2011), a loss involving climate change (*high confidence*). Decline in kelp populations attributed to ocean warming has been reported in southern Australia (Johnson *et al.*, 2011; Wernberg *et al.*, 2011a,b) and the North Coast of Spain (Fernández *et al.*, 2011). The spread of subtropical invasive macroalgal species may be facilitated by climate change, adding to the stresses experienced by temperate seagrass meadows due to ocean warming (*medium evidence, high agreement*).

Projected impacts

Ocean acidification (5.3.3.5; Box CC-OA) is expected to enhance the production of seagrass, macroalgae, salt-marsh plants and mangrove trees through the fertilization effect of CO_2 (Hemminga and Duarte, 2000; Wu *et al.*, 2008;

McKee *et al.*, 2012; *high confidence*). Increased CO_2 concentrations may have already increased seagrass photosynthetic rates by 20% (Hemminga and Duarte, 2000; Hendriks *et al.*, 2010; *limited evidence, high agreement*).

Coupling of downscaled model projections using the SRES A1B scenario in the Western Mediterranean with relationships between mortality rates and maximum seawater temperature led Jordá *et al.* (2012) to conclude that seagrass meadows may become functionally extinct by 2050 to 2060 (*high confidence*). Poleward range shifts in vegetated coastal habitats are expected to continue with climate change (*high confidence*).

Although elevated CO_2 and ocean acidification are expected to increase productivity of vegetated coastal habitats in the future, there is *limited evidence* that elevated CO_2 will increase seagrass survival or resistance to warming (Alexandre *et al.*, 2012; Jordá *et al.*, 2012).

Coastal wetlands and seagrass meadows experience coastal squeeze in urbanized coastlines, with no opportunity to migrate inland with rising sea levels. However, increased CO_2 and warming can stimulate marsh elevation gain, counterbalancing moderate increases in sea level rise rates (Langley *et al.*, 2009; Kirwan and Mudd, 2012). Climate change is expected to increase carbon burial rates on salt-marshes during the first half of the twenty-first century, provided sufficient sediment supply, with carbon–climate feedbacks diminishing over time (Kirwan and Mudd, 2012; *medium confidence*).

In summary, climate change will contribute to the continued decline in the extent of seagrasses and kelps in the temperate zone (*medium confidence*) and the range of seagrasses, mangroves and kelp in the northern hemisphere will expand poleward (*high confidence*). The limited positive impact of warming and increased CO_2 on vegetated ecosystems will be insufficient to compensate the decline of their extent resulting from other human drivers such as land use change (*very high confidence*).

5.4.2.4. Coral Reefs

Coral reefs are shallow-water ecosystems made of calcium carbonate secreted by reef-building corals and algae. They are among the most diverse ecosystems and provide key services to humans (Box CC-CR).

Observed impacts

Mass coral bleaching coincided with positive temperature anomalies over the past 30 years, sometimes followed by mass mortality (Kleypas *et al.*, 2008; *very high confidence*). Over 80% of corals bleached during the 2005 event in the Caribbean and over 40% died (Eakin *et al.*, 2010). Bleaching events and their recovery are variable in time and space: 7% of the reef locations exhibited at least one bleaching between 1985-1994 compared to 38% in the 1995-2004 period, most of which occurred during the 1997-98 El Niño event (Figure 5-3). Recovery from the 1998 global bleaching event was generally slow in the Indian Ocean (about 1% yr^{-1}), absent in the western Atlantic and variable elsewhere (Baker *et al.*, 2008). Warming has caused a poleward range expansion of some corals (Greenstein and Pandolfi, 2008; Yamano *et al.*, 2011; *high confidence)*.

[INSERT FIGURE 5-3 HERE
Figure 5-3: Percent of reef locations (1°x1° grid cells which have at least one reef) that experience no bleaching, at least one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are summarized from the ReefBase dataset (Kleypas *et al.*, 2008). In the observations, some of the “no bleaching” cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the SRES A1B CO_2 scenario and the standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are not shown.]

Persistence of coral reefs depends on the balance between the production and erosion of calcium carbonate and on coral settlement, both of which are affected by ocean acidification (5.3.3.5, Box CC-OA). Experimental data show that ocean acidification generally decreases calcification (Andersson *et al*., 2011; Kroeker *et al.*, 2013) and promotes dissolution of calcium carbonate and bioerosion (Tribollet *et al.*, 2009; Wisshak *et al.*, 2012), leading to poorly cemented reefs (Manzello *et al.*, 2008); it also negatively affects early life history stages which could reduce the number of larval settlers (Albright, 2011).

Coral cover and calcification have decreased in recent decades (e.g., Gardner *et al.*, 2003; De'ath *et al.*, 2009, 2012; Manzello, 2010; Box CC-CR; *very high confidence)* but attribution to climate-related and human-related drivers is difficult. Globally, the primary climate-related driver appears to be ocean warming rather than ocean acidification, cyclonic activity and changes in freshwater input (Cooper *et al.*, 2012; De'ath *et al.*, 2012; *medium confidence)*. sea level rise also controls reef growth but, within the uncertainties of past sea level rise and coral reef growth, most coral reefs seem to have kept pace with the recent sea level rise (Buddemeier and Smith, 1988; Brown *et al*., 2011).

Projected impacts

Coral bleaching and mortality will increase in frequency and magnitude over the next decades (*very high confidence*). Under the A1B CO_2 emission scenario, 99% of the reef locations will experience at least one severe bleaching event between 2090-2099 (Figure 5-3), with *limited evidence* and *low agreement* that coral acclimation and/or adaptation will limit this trend (Logan *et al.*, 2013). The onset of annual bleaching event under RCP 8.5 is delayed by more than two decades in about 23% of reef locations compared to RCP 6.0 (van Hooidonk *et al*., 2013).

Ocean warming and acidification have synergistic effects in several reef-builders (Reynaud *et al.*, 2003; Anthony *et al.*, 2008). They will increase coral mortality, reduce calcification and the strength of calcified organisms, and enhance skeletal dissolution (Manzello *et al.*, 2008; *high confidence*). Reefs will transition from a condition of net accretion to one of net erosion (Andersson and Gledhill, 2013; *high confidence*) and will be more susceptible to breakage. The onset of global dissolution is an atmospheric CO_2 of 560 ppm (Silverman *et al.*, 2009; *medium confidence*) and dissolution will be widespread in 2100 (RCP 8.5 emission scenario, Dove *et al*., 2013; *medium confidence*). The observed poleward range extension will be limited by ocean acidification (Yara *et al*., 2012; Couce *et al.*, 2013) and may be followed by equatorial range retractions (Kiessling *et al.*, 2012).

The maximum rate of vertical accretion has been variable regionally during the last deglaciation (about 20 mm yr^{-1}; Dullo, 2005; Montaggioni *et al.*, 2005) and has not enabled all coral reefs to keep-up with sea level rise. Some reefs kept up, even when the eustatic sea level rise exceeded 40 mm yr^{-1} (Camoin *et al.*, 2012). A number of coral reefs could therefore keep up with the maximum rate of sea level rise of 15.1 mm yr^{-1} projected at the end of the century (WGI, Table 13.5; *medium confidence*) but a lower net accretion than during the Holocene (Perry *et al.*, 2013) and increased turbidity (Storlazzi *et al.*, 2011) will weaken this capability (*very high confidence*)

In summary, ocean warming is the primary cause of mass coral bleaching and mortality (*very high confidence*), which, together with ocean acidification, deteriorates the balance between coral reef construction and erosion (*high confidence*). The magnitude of these effects depends on future rates of warming and acidification (*very high confidence*), with a limited moderating role due to biological acclimation and adaptation (*medium confidence*).

5.4.2.5. Coastal Aquifers

Coastal aquifers are of strategic importance for the water supply of highly populated coastal areas, especially in small islands (29.3).

Observed impacts

Temperature and evaporation rise, precipitation changes and extended droughts affecting aquifer recharge can contribute to saltwater intrusion (3.2.4). Rising sea levels and overwash from waves or storm surge are also relevant, especially in low-lying areas and islands (Terry and Falkland, 2010, White and Falkland, 2010) (29.3).

Aquifers on the coasts of the US have experienced increased levels of salinity largely due to excessive water extraction (Barlow and Reichard, 2010). Natural drivers combined with over-extraction, pollution, mining and erosion compound groundwater supply problems in small islands in the Pacific, Indian and Atlantic Oceans (White *et al.*, 2007; White and Falkland, 2010). This increased usage of groundwater resources globally has, over the last century, led to a reduction in groundwater quality, including increased salinization (*very high confidence*).

Attribution of saline intrusion to incremental sea level rise is still not sufficiently supported (Rozell and Wong, 2010; White and Falkland 2010). In small islands, observed saltwater intrusion due to flooding and overwash under storm events cannot be attributed to climate change (29.3.2; *high agreement)*.

Projected impacts

Available information on projected impacts on coastal aquifers is limited (3.4.6). Rozell and Wong (2010) assessed the impact of rising sea levels on fresh water resources on Shelter Island (USA) for two different combinations of precipitation change and sea level rise. Projected impacts were highly dependent on local conditions. Ferguson and Gleeson (2012) concluded that the direct impact of groundwater extraction in the US has been and will be much more significant than the impact of a 0.59 m sea level rise by the end of the 21st century under a wide range of hydrogeological conditions and population densities.

Saltwater intrusion is generally a very slow process; as a consequence reaching equilibrium may take several centuries limiting the reversibility of the process in the near-term (Webb and Howard, 2011).

Human-induced pressure will continue to be the main driver for aquifer salinization during the next century (*high confidence*). Changing precipitation, increased storminess and sea level rise will exacerbate these problems (*high agreement, limited evidence*).

5.4.2.6. Estuaries and Lagoons

Coastal lagoons are shallow water bodies separated from the ocean by a barrier and connected at least intermittently to the ocean, while estuaries, where fresh and saltwater mix, are the primary conduit for nutrients, particulates and organisms from land to the sea.

Observed impacts

Sediment accumulation in estuaries is high, heterogeneous and habitat-specific and directly affected by human drivers, such as dredging and canalization, and indirectly via habitat loss, changes in sea level, storminess and freshwater and sediment supply by rivers (Syvitski *et al.*, 2005; Swanson and Wilson, 2008). Coastal lagoons are also susceptible to alterations of sediment input and erosional processes driven by changes in sea level, precipitation, and storminess (Pickey and Young, 2009). Droughts, floods and other runoff events, as well as sea level rise impact estuarine circulation, tidal characteristics, suspended matter, and consequently the light climate, and biological communities, in particular in microtidal systems. Climate change and habitat modification (e.g., dams and obstructions) impact fish species such as salmon and eels that pass through estuaries (Lassalle and Rochard 2009).

Enhanced nutrient delivery (5.3.4.3) has resulted in major changes in biogeochemical processes, community structure, metabolic balance, and carbon dioxide exchange (Howarth *et al.* 2011 Canuel *et al.*, 2012; Statham, 2012), including enhanced primary production which has affected coastal fishery yield (Nixon, 1982; Savage *et al.*, 2012). Eutrophication has modified the food-web structure (*high confidence*) and led to more intense and long lasting hypoxia (5.3.4.4), more frequent occurrence of harmful algal blooms (Breitburg *et al.*, 2009; Howarth *et al.*, 2011; *medium confidence)* and to enhanced emission of nitrous oxide (Kroeze *et al.*, 2010; de Bie *et al.*, 2002; *high confidence)*.

In summary, there is very high confidence that humans have impacted lagoons and estuaries.

Projected impacts

The increase of atmospheric carbon dioxide levels will reduce the efflux of CO_2 from estuaries (Borges, 2005; Chen and Borges, 2009; *high confidence*). Its impact on the pH of estuarine and lagoon waters will generally be limited because other drivers are usually more important (5.3.3.4 and Box CC-OA; *high confidence*). For example, freshwater flow in the Scheldt estuary was the main factor controlling pH, directly via a decreased supply of dissolved inorganic carbon and total alkalinity, and, indirectly, via decreased input ammonia loadings and lower rates of nitrification (Hofmann *et al.*, 2009).

Changes in sea level and hydrology could affect lagoons and estuaries in multiple ways. sea level rise will impact sediment redistribution, the partitioning of habitats within estuaries, salinity, tidal range and submergence periods (Anthony *et al.*, 2009; *high confidence*). Lagoons may shrink because landward migration is restricted due to human occupation or extend due to the drowning of marshes (Pilkey and Young, 2009: Anthony *et al.*, 2009; Stutz and Pilkey, 2011). Salinity, primary production, biodiversity, fisheries and aquaculture may be impacted by changes in water discharge, withdrawals and precipitation-evaporation balance (Anthony *et al.*, 2009: Smith *et al.*, 2005; Webster and Harris, 2004; Canu *et al.*, 2010). Altered riverine discharge and warming may lead to enhanced thermal and/or salinity stratification of estuaries and lagoons. This has consequences for biogeochemical processes, organism distribution patterns and frequency and duration of hypoxia (Diaz and Rosenberg, 2008; Rabalais *et al.*, 2009; Hong and Shen, 2012; *medium confidence*). However, stronger winds and droughts may reduce the extent, duration and frequency of estuarine stratification, counteracting the decrease in oxygen concentration (Rabalais *et al.*, 2009; *medium confidence*).

Changes in storm events may also alter the sediment deposition-erosion balance of lagoons and estuaries (Pilkey and Young, 2009), the structure and functioning of biological communities via the transport of communities and/or of their resources, and the underwater light climate (Wetz and Paerl, 2008; Canuel *et al.*, 2012; *medium confidence*). Changes in precipitation extremes and freshwater supply may induce fluctuations in salinity with the associated adverse impacts on biodiversity, benthic macrofauna and ecosystem functions (Pollack *et al.*, 2011; Levinton *et al.*, 2011; Fujii and Raffaelli, 2008; Jeppesen *et al.*, 2007). Warming may directly affect most biological processes and the trophic status of coastal ecosystems, and higher carbon dioxide emission (Canuel *et al.*, 2012; *limited evidence, medium agreement*). Warming may lengthen the duration of phytoplankton production season (Cloern and Jassby, 2008; *medium confidence*).

Any change in the primary production of lagoons might impact fisheries, as primary production and fisheries yield are correlated (Nixon, 1982; *limited evidence, medium agreement*). For example, seawater warming and changes in seasonal patterns of precipitations projected in the Venice lagoon using the SRES A2 CO_2 emission scenario for the period 2071-2100, may lead to a reduction in plankton production, with a decline of habitat suitability for clam growth and aquaculture (Canu *et al.*, 2010).

Finally, projected changes in climate-related drivers such as warming, storms, sea level and run-off will interact with non-climate human drivers (e.g. eutrophication, damming) and will have consequences for ecosystem functioning and services of lagoons and estuaries (*high confidence*).

In summary, the primary drivers of change in lagoons and estuaries are human-related rather than climate-related drivers (*very high confidence*). Future changes in climate-related drivers such as warming, acidification, waves, storms, sea level and run-off will have consequences on the functions and services of ecosystems in lagoons and estuaries (*high confidence*) but the impacts cannot be assessed at the global scale as the key drivers operate at a local to regional scale.

5.4.2.7. Deltas

Characterized by the interplay between rivers, lands and oceans and influenced by a combination of river, tidal and wave processes, deltas are coastal complexes that combine natural systems in diverse habitats (e.g. tidal flats, salt marshes, mangroves, beaches, estuaries, low-lying wetlands) and human systems (e.g. houses, agriculture, aquaculture, industry and transport). They are low-lying coastal landforms formed by riverine sediments in the areas around river mouths, mostly during the last 6000–8000 years of relatively stable sea level and have a population density more than 10 times the world average (Ericson *et al*., 2006; Foufoula-Georgiou *et al*., 2011). As low-lying plains, deltas are highly sensitive to changes in sea level. They are subject to climatic impacts from rivers upstream (e.g. freshwater input) and oceans downstream (e.g. sea level changes, waves) as well as within the deltas themselves. At the same time, they are affected by human activities such as land-use changes, dam construction, irrigation, mining, extraction of subsurface resources and urbanization (Nicholls *et al*., 2007).

Observed impacts

The combined impact of sediment reduction, relative sea level rise, land-use changes in delta and river management on channels and banks has led to the widespread degradation of deltas (*very high confidence*). The changes of sediment delivery from rivers due to dams, irrigation and embankments/dykes create an imbalance in sediment budget in the coastal zones. Degradation of beaches, mangroves, tidal flats, and subaqueous delta fronts along deltaic coasts has been reported in many deltas (e.g. Nile and Ebro, Sanchez-Arcilla *et al*., 1998; Po, Simeoni and Corbau, 2009; Krishna-Godavari, Nageswara Rao *et al*., 2010; Changjiang, Yang *et al*., 2011; Huanghe, Chu *et al*., 1996; *very high confidence*). Deltaic coasts naturally evolve by seaward migration of the shoreline, forming a delta plain. However, decreasing sediment discharge during the last 50 years has decreased the growth of deltaic land, even reversing it in some locations (e.g. Nile, Godavari, Huanghe). Artificial reinforcement of natural levees also has reduced the inter-distributory basin sedimentation in most deltas, resulting in wetland loss.

The major impacts of sea level rise are changes in coastal wetlands, increased coastal flooding, increased coastal erosion, and saltwater intrusion into estuaries and deltas (Mcleod *et al*., 2010), which are exacerbated by increased human-induced drivers (*very high confidence*). Ground subsidence amplifies these hazards in farms and cities on deltaic plains through relative sea level rise (Day and Giosan, 2008; Mazzotti *et al*., 2009). Relative sea level rise due to subsidence has induced wetland loss and shoreline retreat (e.g. the Mississippi delta, Morton *et al*., 2005; Chao Phraya delta, Saito *et al*., 2007; *high confidence*). Episodic events superimpose their effects on these underlying impacts and accelerate land loss (*high confidence*) (e.g., Hurricanes Katrina and Rita in 2005, Barras *et al*., 2008). To forestall submergence and frequent flooding, many delta cities now depend on a substantial infrastructure for flood defense and water management (Nicholls *et al*., 2010).

Deltas are impacted by river floods and oceanic storm surges (*very high confidence*). Tropical cyclones are noteworthy for their damages to deltas, for example, the Mississippi delta by Hurricane Katrina in 2005 (Barras *et al*., 2008), the Irrawaddy delta by Cyclone Nargis in 2008, and the Ganges-Brahmaputra delta by Cyclone Gorky in 1991 and Cyclone Sidr in 2007 (Murray *et al*., 2012) (Box CC-TC). A detailed study of 33 deltas around the world found that 85% of them had experienced severe flooding in the past decade, causing the temporary submergence of 260,000 km2 (Syvitski *et al*., 2009).

Projected impacts

The projected natural impacts on deltas under changing global climate are caused mainly by extreme precipitation induced floods and sea level rise. These will result in increased coastal flooding, decreased wetland areas, increased coastal erosion, and increased salinization of cultivated land and groundwater (McLeod *et al*., 2010; Day *et al*., 2011; Box CC-TC; *high confidence)*. The surface area of flooding in 33 deltas around the world is estimated to increase by 50% under sea level rise estimations as projected for 2100 by the IPCC AR4 (Syvitski *et al*., 2009). Non-climatic drivers (e.g. reduction in sediment delivery, subsidence, and land-use changes) rather than climatic drivers have affected deltas for the last 50 years (Syvitski, 2008; *very high confidence*). Densely populated deltas are particularly vulnerable due to further population growth together with the above-described impacts. The impacts of further sea level rise beyond 2100 show a more complex and enhanced flood risk on deltas (e.g. Katsman *et al*., 2011).

In summary, increased human drivers have been primary causes in changes of deltas (e.g. land-use, subsidence, coastal erosion) for at least for the last 50 years (*very high confidence*). There is *high agreement* that future sea level rise will exacerbate the problems of increased anthropogenic degradation in deltas.

5.4.3. Human Systems

5.4.3.1. Human Settlements

Important direct effects of climate change on coastal settlements include dry land loss due to erosion and submergence, damage of extreme events (such as wind storms, storm surges, floods, heat extremes and droughts) on built environments, effects on health, food and water-borne disease, effects on energy use, effects on water availability and resources and loss of cultural heritage (Hunt and Watkiss, 2010). Since AR4, a large number of regional, national and sub-national scale studies on coastal impacts have been conducted. These are covered in the respective regional chapters. At the global scale, studies have focused either on exposure to sea level rise or extreme water levels or on the physical impacts of flooding, submergence and erosion.

Projected exposure

Coastal flood risks are strongly influenced by the growing exposure of population and assets. The population exposed to the 1 in 100 year coastal flood is projected to increase from about 270 million in 2010 to 350 million in 2050 due to socio-economic development only (UN medium fertility projections) (Jongman *et al.*, 2012). Population growth, economic growth and urbanization will be the most important drivers of increased exposure in densely populated areas (Seto, 2011; Hanson *et al.*, 2011; Chapter 14; *high confidence*). For 136 port cities above one million inhabitants the number of people exposed to a 1-in-100 year extreme sea level is expected to increase from 39 million in 2005 to 59 million by 2070 through 0.5 m GMSL rise alone and to 148 million if socio-economic development (UN medium population projections) is considered on top of this (Hanson *et al.*, 2011). Human-induced subsidence alone is expected to increase the global economic exposure of 136 major port cities by around 14% from 2005 to 2070 although this driver only applies to 36 of the cities (Hanson *et al.*, 2011). Due to socio-economic development Asia is expected to continue to have the largest exposed population and Sub-Saharan Africa the largest increases in exposure (Dasgupta *et al.*, 2009; Vafeidis *et al.*, 2011; Jongman *et al.*, 2012).

Projected impacts and risks

Exposure estimates however give an incomplete picture of coastal risks to human settlements because they do not consider existing or future adaptation measures that protect the exposed population and assets against coastal hazards (Hallegatte *et al*., 2013; Hinkel *et al*., 2013). While the global potential impacts of coastal flood damage and land loss on human settlements in the 21st century are substantial, these impacts can be reduced substantially through coastal protection (*limited evidence, high agreement*). Nicholls *et al.* (2011) estimate that without protection 72 to 187 million people would be displaced due to land loss due to submergence and erosion by 2100 assuming GMSL increases of 0.5 to 2.0 m by 2100. Upgrading coastal defenses and nourishing beaches would reduce these impacts roughly by three orders of magnitude. Hinkel *et al.* (2013) estimate the number of people flooded annually in 2100 to reach 170 to 260 million per year in 2100 without upgrading protection and two orders of magnitude smaller with dike (levee) upgrades, if GMSL rises 0.6 to 1.3 m by 2100. The major driver of increasing risks to human settlements in the next decades is socio-economic development. When upgrading flood defenses to maintain a constant probability of flooding, average annual losses (AAL) in the 136 largest coastal cities are expected to increase 9-fold from 2005 to 2050 due to socio-economic development only another 12% due to subsidence and 2 to 8% due to GMSL rises of 0.2 to 0.4 m (Hallegate *et al*., 2013;Figure 5-4).

[INSERT FIGURE 5-4 HERE
Figure 5-4: The 20 cities where average annual losses (AAL) increase most (in relative terms in 2050 compared with 2005) in the case of optimistic sea level rise, if adaptation maintains only current defense standards or flood probability (PD). Source: Hallegatte *et al*., 2013.]

Despite the delayed response of sea level rise to global warming levels (WG1, 13.5.40) mitigation may limit 21st century impacts of increased coastal flood damage, dry land loss and wetland loss substantially (*limited evidence, medium agreement*) albeit numbers are difficult to compare due to differences in scenarios, baselines and adaptation assumptions. Tol (2007) finds that stabilizing CO_2 concentration at 550 ppm reduces global impacts on wetlands and drylands by about 10% in 2100 compared to a scenario of unmitigated emissions. Hinkel *et al.* (2013) report that stabilizing emissions at 450 ppm-CO_2-eq reduces the average number of people flooded in 2100 by about 30% compared to a baseline where emissions increase to about 25 Gt C-eq in 2100. Arnell *et al.* (2013) find that an emissions pathway peaking in 2016 and declining at 5% per year thereafter reduces flood risk by 58-66% compared to an unmitigated A1B scenario. All three studies only consider the effects of mitigation during the 21st century and assume low or no contribution of ice sheets to GMSL rise. Mitigation is expected to be more effective when considering impacts beyond 2100 and higher contributions of ice sheets (5.5.8).

Global studies confirm AR4 findings that there are substantial regional differences in coastal vulnerability and expected impacts (*high confidence*). Most countries in South, South East and East Asia are particularly vulnerable to sea level rise due to rapid economic growth and coastward migration of people into urban coastal areas together with high rates of anthropogenic subsidence in deltas where many of the densely populated areas are located (Nicholls and Cazenave, 2010). At the same time, economic growth in these countries increases the monetary capacity to adapt (Nicholls *et al.*, 2010). In contrast, while many African countries experience a similar trend in rapid urban coastal growth, the level of economic development is generally lower and consequently the monetary capacity to adapt is smaller (Hinkel *et al.*, 2012; Kebede and Nicholls, 2012).

In summary, while there is *high agreement* on some general findings, only a small fraction of the underlying uncertainty has been explored, which means *evidence is limited*. Gaps remain with respect to impacts of possible large contributions of the ice sheets of Greenland and Antarctica to GMSL rise (WG1, 13.4.3, 13.4.4), regional patterns of climate-induced sea level rise, subsidence and socio-economic change and migration. Many studies rely on few or only a single socio-economic scenario. Few studies consider adaptation and those that do generally ignore the wider range of adaptation measures beyond hard protection options. Integrated studies considering the interactions between a wide range of relative sea level rise impacts (Table 5-3) as well as trade-offs between diverse adaptation options are missing.

5.4.3.2. Industry, Infrastructure, Transport, and Network Industries

Coastal industries, their supporting infrastructure including transport (ports, roads, rail, airports), power and water supply, storm water and sewerage are highly sensitive to a range of extreme weather and climate events including temporary and permanent flooding arising from extreme precipitation, high winds, storm surges and sea level rise (Handmer *et al.* 2012, Horton *et al.* 2010, Hanson and Nicholls, 2012, Aerts *et al*. 2013; *high confidence*). Most industrial facilities, infrastructure and networks are designed for service lives extending over several decades. In fact, many bridges, ports, road and railway lines remain in their original design location for centuries even if the infrastructure on them has been rehabilitated or replaced several times. Besides, certain facilities, such as new nuclear power plants are designed to last even well beyond the twenty-second century (Wilby *et al*. 2011).

Since the need to locate most of these industries and networks in coastal areas will remain and probably increase due to human coastal development (5.4.3.1), considering climate variability and climate change drivers in life cycle assessment of industry, infrastructure, transport and network industries is of utmost importance (*high agreement*).

Observed impacts

Climate impacts on coastal industries and infrastructures vary considerably depending on geographical location, associated weather and climate and specific composition of industries within particular coastal regions (*high confidence*).

Over the last 10 years an extensive number of climate related extreme events (Coumou and Rahmstorf, 2012) have served as an example to evidence impacts on coastal industry, infrastructure, transport and network industry. Severe storms with associated winds, waves, rain, lightning and storm surges have been particularly disruptive to transport and power and water supplies (USCCSP, 2008; Horton *et al*., 2010; Jacob *et al*., 2007; *high confidence*). In such network configurations, flooding of even the smallest component of an intermodal system can result in a much larger system disruption. Even though a transportation terminal may not be affected, the access roads to it could be, thus forcing the terminal to cease or reduce operation. Disruption to port activities in one location can disrupt supply chains, which can have far reaching consequences (Becker *et al*. 2012, Becker *et al*. 2013). Existing experience has also shown that impacts of hurricanes and flooding on underground infrastructure can have long-term effects (Chisolm and Matthews, 2012).

Hurricanes like Katrina (2005), causing US$100 Million of damage to Mississippi's ports Irene (2011) and Sandy (2012), leading to a week-long shut-down of the Port of New York, generating economic damages reaching US$ 50 billion (Becker *et al*. 2012), have shown the critical need to better prepare coastal human settlements and associated network infrastructures and industries for future extreme weather impacts and climate change (Aerts *et al.* 2013; *high agreement*).

Projected impacts

While there is *robust evidence* of the impacts and consequences of extreme events on coastal infrastructure and industrial facilities, there are limited assessments on projected impacts of long-term changes (*high agreement*). Besides, while there is an important amount of grey literature on projected impacts of sea level rise and increasing flooding levels on certain coastal infrastructures (USCCSP, 2008; USACE, 2011; McEvoy and Mullet, 2013), limited peer review information is available.

Vulnerability to flooding of railroads, tunnels, ports, roads and industrial facilities at low-lying areas will be exacerbated by rising sea levels or more frequent or intense storms, causing more frequent and more serious disruption of services and damages under extreme sea levels unless adaptation is enforced (Aerts *et al*, 2013,Wilby *et al.* 2011, Esteban et al. 2012, Esteban et al. 2010; *high agreement*).

Furthermore, sea level rise will reduce the extreme flood return periods and will lower the design critical elevations of infrastructure such as airports, tunnels, coastal protections and ship terminals requiring adaptation (Jacob *et al.*, 2007, Becker *et al*. 2013).

It is estimated that a hypothetical 1 m rise in relative sea level projected for the Gulf Coast region between Alabama and Houston over the next 50-100 years would permanently flood a third of the region's roads as well as putting more than 70% of the region's ports at risk (USCCSP, 2008).

The projected impacts of climate change, considering different possible levels and adaptation, to Alaska's public infrastructure including, but not limited to coastal erosion, inundation and flooding, could add US$3.6-6.1 billion (+10% to 20% above normal wear and tear) from 2006 to 2030 and US$5.6-7.6 billion (+10% to 12%) to 2080 to future costs (Larsen *et al*., 2008).

Hanson *et al*. (2011) presents a first estimate of the exposure of the world's large port cities to coastal flooding due to sea level rise and storm surge in the 2070s. The analysis suggests that the total value of assets exposed in 2005 across all cities considered is estimated to be US$3,000 billion; corresponding to around 5% of global GDP in 2005. By the 2070s, and assuming a homogeneous global sea level rise of 0.5 m, increased extreme water levels up to a 10% and a fixed subsidence rate in susceptible cities with respect to today's values, asset exposure is estimated to increase to approximately 9% of projected global GDP in this period.

Coastal infrastructural instability may result from natural hazards triggered by groundwater-level (GWL) variations resulting from rising sea level. For earthquake-prone coasts, this could be exacerbated by earthquake liquefaction if GWL increases with sea level rise (Yasuhara *et al.*, 2007). Increasing sea levels, surges and waves can also lead to a stability loss of coastal structures (Mori *et al*., 2013, Headland *et al.*, 2011).

Other impacts may arise in coastal industries in high latitudes affected by permafrost thaw causing ground instability and erosion thereby affecting transport safety and the industries that rely on such travel in these regions (e.g., Pearce *et al*., 2010).

5.4.3.3. Fisheries, Aquaculture, and Agriculture

Fisheries and aquaculture and the associated post-harvest activities globally create millions of jobs (Daw *et al.*, 2009; Sumaila *et al*., 2011); and contribute significantly to the dietary animal protein of millions of people and to the world merchandise trade (FAO, 2010 and 2012; Chap 6: 6.4.1.1.). In addition to small-scale fisheries and aquaculture, which are important for the food security and economy of coastal communities (Bell *et al*., 2009), coastal zones also support significant agricultural activities, e.g., rice production in the low-lying deltaic regions of Asia (Wassmann *et al.*, 2009).

Observed impacts

Climate variability and change impact both fishers' livelihoods (Badjeck *et al.*, 2010) and fish production (Barange and Perry, 2009) (6.5.3). In the North Sea, ocean warming over the 1977-2002 period led to relatively increased distribution ranges of some fish species (Hiddink and Hofstede, 2008); and demersal fish assemblage deepened in response to climate change (Dulvy *et al.*, 2008). In southeastern Australia, Last *et al.* (2011) found an increasing abundance of some fish species of warm temperate origin (Ridgeway, 2007) and a decline in abundance for fewer other species. A study (Sherman *et al.* , 2009) of the impact of sea surface temperature changes on the fisheries yields of 63 large marine ecosystems over a 25-year period shows a positive relationship for the Northeast Atlantic large marine ecosystems, due to zooplankton biomass increases (6.5.3). Distributional effects are very important for migratory pelagic fisheries, such as tuna (Chap. 29, Table 29-2). Impacts of climate change on aquaculture (*Mytilus edulis and Salmo salar*) in the UK and Ireland have been difficult to discern from natural environmental variability (Callaway *et al.*, 2012).

Seawater inundation has become a major problem for traditional agriculture in Bangladesh (Rahman *et al.*, 2009), and in low-lying island nations (e.g. Lata and Nunn, 2012). The combination of rice yield reduction induced by climate change and inundation of lands by seawater causes an important reduction in production (Chen *et al.*, 2012).

Projected impacts

Fisheries may be impacted either negatively or positively (Cinner *et al.*, 2012; Meynecke and Lee, 2011; Hare *et al.*, 2010) depending on the latitude, location and climatic factors. Climate change can impact the pattern of marine biodiversity through changes in species' distributions, and may lead to large-scale redistribution of global catch potential depending on regions (Cheung *et al*., 2009; Cheung *et al*., 2010). Narita *et al.* (2012) estimated that the global economic costs of production loss of mollusks due to ocean acidification (5.3.3.5) by the year 2100 could be over 100 billion US$. As a result of increased sea temperatures, the reduction in coral cover and its associated fisheries production is expected to lead in the Caribbean basin to a net revenue loss by 2015 (Trotman *et al.*, 2009). Economic losses in landed catch value and the costs of adapting fisheries resulting from a 2°C global temperature increase by 2050 have been estimated at US$ 10-31 billion globally (Sumaila *et al*., 2011).

For aquaculture, negative impacts of rising ocean temperatures will be felt in the temperate regions whereas positive impacts will be felt in the tropical and subtropical regions (De Silva and Soto, 2009). Changes to the atmosphere–ocean in the Pacific Island countries are *likely* to affect coral reef fisheries by a decrease of 20% by 2050 and coastal aquaculture may be less efficient (Bell *et al.*, 2013).

In summary, changes have occurred to the distribution of fish species (*medium confidence*) with evidence of poleward expansion of temperate species (*high agreement, limited evidence*). Tropical and subtropical aquaculture has not been adversely affected by rising ocean temperatures to date *(high agreement, limited evidence)*. Coastal agriculture has experienced negative impacts (*medium confidence)* due mainly to increased frequency of submersion of agricultural land by saltwater inundation (*high agreement, limited evidence).*

5.4.3.4. Coastal Tourism and Recreation

Coastal tourism is the largest component of the global tourism industry. More than 60% of Europeans opt for beach holidays and beach tourism provides more than 80% of US tourism receipts (UNEP, 2009). More than 100 countries benefit from the recreational value provided by their coral reefs, which contributed US$11.5 billion to global tourism (Burke *et al.*, 2011).

Observed impacts

Observed significant impacts on coastal tourism have occurred from direct impacts of extreme events on tourist infrastructure (e.g. beach resorts, roads), indirect impacts of extreme events (e.g. coastal erosion, coral bleaching) and short-term tourist-adverse perception after the occurrence of extreme events (e.g. flooding, tropical storms, storm surges) (IPCC 2012, 4.3.5.3; Scott *et al*., 2008; Phillips and Jones, 2006). Recent observed climate change impacts on the Great Barrier Reef include coral bleaching in the summers of 1997-98, 2001-02 and 2005-06 and extreme events including floods and cyclones (Tropical cyclones Larry in 2006, Hamish in 2009 and Yasi in 2011). The stakeholders show a high level of concern for climate change and various resilience initiatives have been proposed and developed by the Great Barrier Reef Marine Park Authority (Biggs, 2011; GBRMPA, 2012).

Projected impacts

In order to provide some idea of climate change impacts on coastal destinations, many studies have been carried out on projecting tourism demand, for example, in Europe (Perch-Nielson *et al.*, 2010), the Baltic region (Haller *et al.*, 2011) and beach tourism in the Mediterranean (Moreno and Amelung, 2009a) and in 51 countries worldwide (Perch-Nielson, 2010). The studies provide varying details although it is difficult to draw overarching conclusions on tourism demand for coastal destinations. With increased temperature in mid-latitude countries and coupled with increased storms in tropical areas, tourist flows could decrease from mid-latitude countries to tropical coastal regions with large developing countries and small islands most affected (Perch-Nielson, 2010). The Mediterranean would likewise be affected in summer (Moreno and Amelung, 2009a). In contrast, less is known about the relationship between the impacts of climate change and specific tourist behavior, activities or flows to coastal destinations (Moreno and Amelung, 2009b) (see 10.6.2). Usually tourists do not consider climate variability or climate change in their holidays (Hares *et al.*, 2009) although there are a few studies to show the contrary (Alvarez-Diaz *et al.*, 2010; Cambers, 2009).

As for future impacts on coastal tourism, there is *high confidence* in the impacts of extreme events and sea level rise aggravating coastal erosion. A scenario of 1 m sea level rise by 2100 would be a potential risk to Caribbean tourism

(Scott *et al.*, 2012). The presence of coastal tourism infrastructure will continue to exacerbate beach reduction and coastal ecosystems squeeze under rising sea levels, as exemplified in Martinique (Schleupner, 2008). Carbonate reef structures would degrade under a scenario of at least 2ºC by 2050 to 2100 with serious consequences for tourism destinations in Australia, the Caribbean and other small island nations (Hoegh-Gulberg *et al.*, 2007, see Box CC-CR).

The costs of future climate change impacts on coastal tourism are enormous. For example, in the Caribbean community countries, rebuilding costs of tourist resorts are estimated US$10-US$23.3 billion in 2050. A hypothetical 1-m sea level rise would result in the loss or damage of 21 airports, inundation of land surrounding 35 ports and at least 149 multi-million dollar tourism resorts damaged or lost from erosion to the coastal beach areas (Simpson *et al.*, 2010).

In summary, while coastal tourism can be related to climate change impacts, it is more difficult to relate tourism demand directly to climate change. Coastal tourism continues to be highly vulnerable to weather, climate extremes and rising sea levels with the additional sensitivity to ocean temperature and acidity for the sectors that rely on reef tourism *(high confidence*). Developing countries and small island states within the tropics relying on coastal tourism, are most vulnerable to present and future weather and climate extremes, future sea level rise and the added impacts of coral bleaching and ocean acidification (*high confidence*).

5.4.3.5. Health

The relationship between health of coastal populations and climate change include direct linkages (e.g. floods, droughts, storm surges and extreme temperatures) and indirect linkages (e.g. changes in the transmission of vector, food and water borne infectious diseases and increased salinization of coastal land that affects food production and freshwater supply and ecosystem health). Coastal and particularly informal settlements, concentrate injury risk and death from storm surges and rainfall flooding (Handmer *et al.*, 2012). This section deals with human health in the context of the coastal zone, while Chapter 11 addresses general health issues and 6.4.2.3 deals with health issues associated with ocean changes. Understanding the relationship between climate and health is often confounded by socio-economic factors that influence coastal settlement patterns and the capacity of authorities to respond to health-related issues (Baulcomb, 2011).

Observed impacts

Mortality risk in coastal areas is related to exposure and vulnerability of coastal populations to climate hazards (e.g. Myung and Jang, 2011). A regional analysis of changes in exposure, vulnerability and risk indicates that although exposure to flood and cyclone hazards has increased since 1980, the risk of mortality has generally fallen. The reductions reflect a strengthening of the countries' capacity to respond to disasters (Box 5-1). However, mortality is still rising in the countries with the weakest risk governance capacities (UNISDR, 2011).

Coastal regions face a range of climate-sensitive diseases. Increased saline intrusion is linked to increased hypertension disease (Vineis *et al*., 2011), with greater occurrence in pregnant women living in coastal regions compared to further inland (Khan *et al*., 2008). Increasing temperature, humidity and rainfall can increase vector-borne diseases such as malaria, dengue, leishmaniasis and chikungunya. (Stratten *et al.*, 2008; van Kleef *et al.*, 2010; Pialoux *et al.*, 2007; Kolivras, 2010) and diarrhoea, infectious gastrointestinal disease, rotovirus and salmonella (e.g. Chou *et al.*, 2010; Hashizume *et al.*, 2007, 2008a; Zhang *et al.*, 2007, 2010; Onozuka *et al.*, 2010). The parasitic disease, Schistosomiasis, endemic in many tropical and small island coastal regions, (29.3.3.2) is also sensitive to temperature increase (Mangal *et al.*, 2008). Vibrio outbreaks (e.g. cholera) are sensitive to rainfall and SST (e.g. Koelle *et al*., 2005) and recent increased vibrio outbreaks in the Baltic have been linked to heat waves and low salinity (Baker-Austin *et al*., 2013). Harmful Algal Blooms (HABs) outbreaks (e.g. ciguatera) have been linked to SST variability (e.g. Jaykus *et al.*, 2008; Erdner *et al.*, 2008). However, in general there is *limited evidence* and *low confidence* in how global climate change will impact HABs (6.4.2.3) suggesting the need for increased monitoring

(Hallegraeff, 2010). Nontoxic blooms of high biomass can reduce biodiversity through oxygen depletion and shading (Erdner *et al.*, 2008) with consequences for ecosystem and human nutrition and health.

Projected impacts

Under future climate conditions, expansion of brackish and saline water bodies in coastal areas under projected sea level rise may increase the incidence of vector-borne diseases (Ramasamy and Surendran, 2011), diarrhea and hypertension (Vineis *et al*., 2011). Human responses to climate change may also influence outcomes on health however limited empirical climate-health data increases uncertainties on such projections (Kolstad and Johansson, 2011).

Evidence continues to emerge of the relation between climate and diseases that affect human health in the coastal zone including air and water temperature, rainfall, humidity and coastal salinity. However, the relations are often complex and vary between diseases and even regionally for the same disease. The interplay between climate and human systems with regards to health impacts is poorly understood and this continues to confound reliable projections of health impacts (*high agreement, robust evidence*).

5.4.4. Summary: Detection and Attribution

There is *high confidence* in the attribution to climate change of observed coastal impacts that are sensitive to ocean temperature change, such as coral bleaching and movements in species ranges. However, for many other coastal changes, the impacts of climate change are difficult to tease apart from human related drivers (e.g. land-use change, coastal development, pollution).

Figure 5-5 shows changes of major phenomena observed in coastal systems and low-lying areas. Horizontal and vertical axes indicate the degree of confidence in detection of trends for phenomena, which are elements sensitive to climate change, and the degree of confidence in attribution of phenomena to climate change, respectively. Phenomena with high and *very high degree of confidence* in trend detection are mainly selective in this figure.

The increase of coral bleaching and the shift in range limits of some species distribution are attributed to climate change with *high degree of confidence*. Mass coral bleaching coincided with positive temperature anomalies over the past 30 years. A poleward expansion of mangrove forests and some corals, and shifts of range limits of many intertidal species are also attributed. Vegetated coastal habitats are declining globally. Coral cover and calcification have decreased in recent decades. Elevated temperatures along with ocean acidification reduce the calcification rate of corals. However attribution to climate-related and human-related drivers for decrease calcification is difficult. Its attribution is *medium confidence* because the primary climate-related driver appears to be ocean warming globally. Seagrass meadows are already under stress due to climate change, particularly where maximum temperatures already approach their physiological limit. However the decline of the distribution of mangroves and salt marshes is mainly linked with human activities, e.g. deforestation and reclamation. Therefore the degree of their attribution to climate change is *very low*.

Globally beaches and shorelines have, in general, undergone net erosion over the past century or longer. There is *high confidence* in detection of increased beach erosion globally. However attributing shoreline changes to climate change is still difficult due to the multiple natural and human related drivers contributing to coastal erosion (e.g., subsidence, decreased sediment delivery, land-use change). There is *high confidence* that human pressures, e.g., increased usage of surface-water and groundwater resources for agriculture and coastal settlements, and river-channel deepening, have led to increased saltwater intrusion, and *low confidence* in attribution of saltwater intrusion to climate change.

The population living in coastal lowlands is increasing and more than 270 million people in 2010 are already exposed to flooding by the 1-in-100 year coastal flood. Population growth and land subsidence in coastal lowlands are the major causes; therefore there is *very low attribution* to climate change.

[INSERT FIGURE 5-5 HERE
Figure 5-5: Summary of detection and attribution in coastal areas.]

5.5. Adaptation and Managing Risks

5.5.1. Introduction

Coastal adaptation and risk management refer to a wide range of human activities related to the social and institutional processes of framing the adaptation problem, identifying and appraising adaptation options, implementing options, and monitoring and evaluating outcomes (chapters 2, 14, 15, 16 and 17). The governance of this process is challenging due to the complex, non-linearity dynamics of the coastal socio-ecological systems (Rosenzweig *et al*., 2011) as well as the presence of multiple management goals, competing preferences of stakeholders and social conflicts involved (Hopkins *et al*., 2012). In many instances, coastal adaptation may thus be characterized to be a "wicked problem" (Rittel and Webber, 1973), in the sense that there is often *no clear agreement* about what exactly the adaptation problem is and there is uncertainty and ambiguity as to how improvements might be made (Moser *et al.*, 2012).

Since AR4, the set of adaptation measures considered has been expanded specifically towards ecosystem-based measures (5.5.2); novel approaches for appraising coastal adaptation decisions have been applied (5.5.3.1) and the analysis of adaptation governance and the institutional context in which decisions are taken has progressed (5.5.3.2). Progress has also been made in better integrating adaptation practices within existing policy frameworks (5.5.4.1) as well as in implementing adaptation and identifying good practices (5.5.4.2). A number of studies have also explored the global costs and benefits of coastal adaptation (5.5.5), opportunities, constraints and limits of coastal adaptation (5.5.6), linkages between coastal adaptation and mitigation (5.5.7) and the long-term commitment to coastal adaptation (5.5.8).

5.5.2. Adaptation Measures

A detailed discussion on general adaptation needs and measures can be found in chapter 14. As a first approximation, adaptation measures were classified into: institutional and social measures (14.3.2.1), technological and engineered measures (14.3.2.2) and ecosystem-based adaptation measures (14.3.2.3). In terms of coastal adaptation, most of the existing measures can be included within this classification.

The IPCC classification of coastal adaptation strategies consisting of retreat, accommodation and protection (Nicholls *et al.*, 2007) is now widely used and applied in both developed and developing countries (Boateng, 2010; Linham and Nicholls, 2012). This trilogy of strategies has expanded into broad approaches of retreat, defend and attack (Peel, 2010). Protection aims at advancing or holding existing defense lines by means of different options such as: land claim, beach and dune nourishment, the construction of artificial dunes, hard structures such as seawalls, sea dikes and storm surge barriers or removing invasive and restoring native species. Accommodation is achieved by increasing flexibility, flood proofing, flood-resistant agriculture, flood hazard mapping, the implementation of flood warning systems or replacing armored with living shorelines. Retreat options include allowing wetlands to migrate inland, shoreline setbacks and managed realignment by, for example, breaching coastal defenses allowing the creation of an intertidal habitat. The appropriate measure may depend on several factor requiring a careful decision-making and governance process (5.5.3).

Since AR4, coastal adaptation options have been revised and summarized in several guidebooks (USAID, 2009; EPA, 2009; UNEP, 2010) including best practice examples. Especially relevant has been the growth of Community Based Adaptation (CBA) measures (*robust evidence*). Table 5-4 compiles different examples of CBA measures in countries such as Bangladesh, India or the Philippines.

Ecosystem-based adaptation is increasingly attracting attention (Munroe *et al*., 2011). Adaptation measures based on the protection and restoration of relevant coastal natural systems such as mangroves (Schmitt *et al.*, 2013), oyster reefs (Beck *et al.*, 2011) and salt marshes (Barbier *et al*., 2011) are seen as no- or low-regret options irrespective of the future of climate change (Cheong *et al*., 2013; *high agreement, medium evidence*). Further work is still needed in order to make reliable quantitative estimates and predictions of the capability of some of these ecosystems to reduce wave, storm surge and sea level rise impacts and in order to provide reliable cost-benefit analysis of how they compare to other measures based on traditional engineering approaches.

5.5.3. Adaptation Decision-Making and Governance

Since AR4, progress has been made in understanding coastal adaptation decisions and governance. For a general treatment of adaptation decision-making and governance see Chapters 2 and 15, 17.

5.5.3.1. Decision Analysis

One specific quality of many coastal adaptation decisions is that these involve options with long (i.e. 30 and more years) investment time scales (e.g. land-use planning, flood defenses, construction of housing and transportation infrastructure; 5.5.2). For such decisions, standard methods that rely on probability distribution on outcomes, such as cost-benefit analysis under uncertainty, cannot be applied because of the difficulties, both in theory and practice, to associate probabilities to future levels of greenhouse gas emissions, which determine the level of impacts and outcomes (Lempert and Schlesinger, 2001; Hallegate, 2009; 17.3.6.2).

Alternative approaches that represent uncertainty not through a single probability distribution but through a range of scenarios have thus been applied to long-term coastal adaptation. Robust decision-making (RDM), for example, refers to approaches where options that work well over a wide range of these scenarios are preferred (Lempert and Schlesinger, 2000; Lempert and Collins, 2007). RDM in this sense has been applied to, e.g., the Port of Los Angeles infrastructure (Lempert *et al.*, 2012).

Another set of approaches uses the criterion of flexibility to decide between alternative strategies. Flexible and reversible options are favored over non-flexible and non-reversible ones and decisions are delayed to keep future options open (Hallegate, 2009). The adaptation pathways approach, for example, implements the criterion of flexibility by characterizing alternative strategies in terms of two attributes: i) adaptation tipping points (ATP), which are points beyond which strategies are no longer effective (Kwadijk *et al.*, 2010), and ii) what alternative strategies are available once a tipping point has been reached (Haasnoot *et al.*, 2013). Importantly, the exact time when an ATP is reached does not matter; it is rather the flexibility of having alternative strategies available that is driving the decision. Prominent applications of this approach include the Thames Estuary 2100 Plan (Penning-Roswell *et al.* 2012; Box 5-1), the Dutch Delta Programme (Kabat *et al.*, 2009) and the New York City Panel on Climate Change (Rosenzweig *et al.*, 2011).

_____ START BOX 5-1 HERE _____

Box 5-1. London's Thames Estuary 2100 Plan: Adaptive Management for the Long Term

The Environment Agency in Britain has recently developed the Thames Estuary 2100 plan (TE2100) to manage future flood threat to London (Environment Agency, 2012). The motivation was a fear that due to accelerated climate change induced sea level rise the time could already be too short for replacing the Thames Barrier (completed in 1982) and other measures that protect London, because such major engineering schemes take 25 to 30 years to plan and implement. An adaptive plan that manages risk in an iterative way was adopted based on the adaptation pathway approach (Penning-Rowsell *et al.*, 2012; 5.5.3.1; Figure 5-6). This plan includes maintaining the existing system in the first 25 years, then enhancing the existing defenses in a carefully planned way over the next 25-60 years, including selectively raising defenses and possibly over-rotating the Barrier to raise protection standards. Finally, in the longer term (beyond 2070) there will be the need to plan for more substantial measures if sea level rise accelerates. This might include a new barrier, with even higher protection standards, probably nearer to the sea, or even a coastal barrage. In the meantime the adaptive approach requires careful monitoring of the drivers of risk in the Estuary to ensure that flood management authorities are not taken by surprise and forced into emergency measures.

[INSERT FIGURE 5-6 HERE
Figure 5-6: Adaptation measures and pathways considered in the TE2100 project. The boxes show the measures and the range of sea level rise over which the measures are effective. The blue arrows link to alternative measures that may be applied once a measure is no longer effective. The red lines show the various 21st century sea level rise scenarios used in the analysis including a conservative estimate of about 0.9 m by the UK Department for Environment Food and Rural Affairs (Defra), a high-level scenario of 2.6 m (H+) and an extreme scenario of over 4 meters (H++). The fat green line shows a possible future adaptation pathway that allows for lower-end sea level rises but also for the unlikely event of extreme change.]

_____ END BOX 5-1 HERE _____

5.5.3.2. Institution and Governance Analysis

Decisions are made within a context. Institution and governance analysis comprise a variety of approaches that aim at describing this context as well as at explaining the emergence and performance of institutions and governance structures (GS). Institution analysis is particularly relevant to coastal adaptation, because deciding between options and implementing them is an ongoing process involving complex inter-linkages between public and private decisions at multiple levels of decision-making and in the context of other issues, existing policies, conflicting interests and diverse GS (e.g, Few *et al.*, 2007; Urwin and Jordan, 2008; Hinkel *et al.*, 2009; 2.2.2 and 2.2.3). The non-consideration of this context may hinder or mislead adaptation decisions and implementations as reported by the emerging literature on barriers to adaptation (5.5.5). Institution analysis strives to understand how this context shapes decisions, and insights gained may be employed to craft effective institutions and policies for adaptation.

For coastal adaptation, the effectiveness of existing GS is often hindered due to a lack of horizontal (i.e., within the same level of decision-making) and vertical (i.e. between different levels of decision-making) integration of organizations and policies (*high confidence*). Storbjörk and Hedren (2011), for example, report on a weak vertical administrative interplay in coastal GS in Sweden. In the UK, the effectiveness of local GS of Coastal Partnership is found to be limited because these are poorly integrated with higher-level policies (Stojanovic and Barker, 2008). In the UK, national level coastal recommendations are difficult to translate into local level actions (Few *et al.*, 2007) and in the United States, coastal policies often have ambiguous or contradictory goals (Bagstad *et al.*, 2007). In a number of African cases, coastal policies are found not to take into account longer-term climate change (Bunce *et al.*, 2010).

Governance issues are particularly challenging when considering planned retreat (*medium evidence)*. While managed realignment is on the political agenda in Germany and the UK, the political costs of doing so are high as both the existing GS as well as public opinion are geared towards protection (e.g. Tunstall and Tapsell, 2007), so that short election cycles do not provide incentives for politicians to undertake actions that may produce benefits in the long term (Few *et al.*, 2007; Rupp-Armstrong and Nicholls, 2007). Along the Queensland coast in Australia the option of planned retreat is disappearing because of rapid coastal development and liability laws favoring development. To prevent this, risks and responsibilities would need to be redistributed from the governments to the beneficiaries of this development (Abel *et al.*, 2011).

While institutional factors are decisive in enabling coastal adaptation (*high confidence*), the role of institutions in coastal adaptation is generally under-researched. The majority of studies are descriptive. Institutional analysis striving to understand which GS emerge and are effective depending on both biophysical and social system characteristics as found in the fields of social-ecological systems (Dietz *et al.*, 2003; Folke *et al.*, 2005; Ostrom 2007, 2009) and institutional economics (Hagedorn *et al.*, 2002; Bougherara *et al.*, 2009) are practically non-existent.

5.5.4. Implementation and Practice

Since AR4, more experiences have been gained in coastal adaptation implementation and practice. Generally, adaptation is not carried out stand-alone but in the context of already existing policy and practice frameworks. Section 5.5.4.1 assesses frameworks that are particularly relevant for coastal adaptation and Section 5.5.4.2 assesses the experiences made as well as principles and compiled best practice guidelines.

5.5.4.1. Frameworks

The issues for coastal adaptation are not radically different from issues encountered within integrated coastal zone management (ICZM), which offers an enabling environment for adaptation practice (Celliers *et al*., 2013). ICZM is a long-term, institutionalized and iterative process that promotes the integration of coastal activities, relevant policy makers, practitioners and scientists across coastal sectors, space and organizations with a view to use coastal resources in a sustainable way (Kay and Alder 2005; Christie *et al.*, 2005; Sales, 2009; WG2 Glossary). Considering climate change in this framework does not mean radical changes to ICZM, because ICZM already emphasizes the integration of coastal issues across sectors and policy domains as well as the long-term perspective (e.g., Hofstede, 2008; Falaleeva *et al.*, 2011). The major difference of coastal adaptation from ICZM is coping with greater uncertainty, longer time frames in planning (beyond 30 years), and long-term commitments inherent to climate change (Tobey *et al.* 2010).

So far, however, there is *limited evidence* and *low agreement* on the effectiveness of ICZM alone or combined with climate change adaptation. Even though ICZM has been applied throughout the world for over 40 years, many obstacles to its successful implementation still remain (*high confidence*). Generally, there is a lack of empirical research evaluating ICZM (Stojanovic *et al*., 2004; Stojanovic and Ballinger, 2009). A recent review of ICZM in Europe concluded that the complexity of coastal regulations, demographic deficits, lack of sustainable finance and a failure to involve communities, business and industry hinder its implementation (Shipman and Stojanovic, 2007).

Developing countries in particular struggle to meet the goals of ICZM due to a lack of qualified human resources, a lack of human, legal and institutional capacities (Isager, 2008; González-Riancho *et al*., 2009); difficulties in integrating policy across multiple coastal agencies (Ibrahim and Shaw, 2012; Martinez *et al*., 2011); power (abuse) of the majority political party or political leaders (Tabet and Fanning, 2012; Isager, 2008), the lack of long-term financial commitment of donors (González-Riancho *et al*., 2009; Ibrahim and Shaw, 2012), and a lack of knowledge regarding the coastal system (González-Riancho *et al*., 2009).

Another prominent framework used for coastal adaptation practice is adaptive management (AM), which has been developed as a response to the deep uncertainty characterizing ecosystem management, where it is often impossible to predict outcomes of management interventions. AM thus aims to test management hypothesis by implementing them, monitoring their outcomes and learning from these to refine the management hypothesis to be applied (Holling, 1978; Walters, 1986). There are numerous applications of AM to coastal management (e.g. Walters, 1997; Marchand *et al.*, 2011, Mulder *et al.*, 2011), but there is *limited evidence* of its long-term effectiveness. Limitations of AM are also notable, such as the potential high cost of experimentation and a range of institutional barriers hindering the delivery of flexible management approaches (e.g. McLain and Lee, 1996).

Community-based adaptation (CBA) refers to the generation and implementation of locally-driven adaptation strategies that address both climate change impacts and development deficits for the climate vulnerable poor and aim to strengthen the adaptive capacity of local people to climate and non-climate risk factors (Reid *et al.*, 2009; Nicholls *et al.*, 2007; Ayers and Dodman, 2010; Ayers and Huq, 2013; 14.2.1; 15.4.3.1, 24.4.6.5). CBA is a bottom-up approach to adaptation involving all relevant stakeholders especially local communities (Ayers and Huq, 2009; UNDP, 2010; Riadh et al., 2012) (Table 5-4). As such, CBA approaches have been developed through active participatory processes with local stakeholders (Ayers and Forsyth, 2009), and operated on a learning-by-doing, bottom up, empowerment paradigm (Huq and Reid, 2007; Kates, 2000).

CBA experiences emphasize that it is important to understand a community's unique perceptions of their adaptive capacities in order to identify useful solutions (Parvin *et al.*, 2008; Paul and Routray, 2010; Badjeck *et al.*, 2010) and that scientific and technical information on anticipated coastal climate impacts needs to be translated into a suitable language and format that allows people to be able to participate in adaptation planning (Saroar and Routray, 2010). Furthermore, effective CBA needs to consider measures that cut across sectors and technological, social and institutional processes, as technology by itself is only one component of successful adaptation (Sovacool *et al.*, 2011; Rawlani and Sovacool, 2011; Pelling, 2011).

Efforts are also being made to integrate climate change adaptation into Disaster Risk Reduction (DRR) frameworks (Romieu *et al.*, 2010; Mercer, 2010; Polack, 2010; Gero *et al.*, 2011) and adaptation practice is likely to move forward as climate change adaptation (CCA) converges with disaster risk reduction (ISDR, 2009; Setiadi *et al*., 2010; Tran and Nitivattananon, 2011; Hay, 2012). In Japan, for example, coastal climate change adaptation has been mainstreamed into the framework of Coastal Disaster Management in the aftermath of the 2011 Tohoku Earthquake Tsunami. The priority of upgrading coastal defenses in the face of sea level rise is thereby judged from the potential damage on the assets in predicted inundation areas on the one hand as well as from the age and earthquake resistance of the coastal structures on the other hand (Central Disaster Management Council. 2011; Committee on Adaptation Strategy for Global Warming in the Coastal Zone, 2011). Other important policy and practice frameworks in place in the coastal zone include poverty reduction and development (Mitchell *et al.*, 2010).

[INSERT TABLE 5-4
Table 5-4: Community-based adaptation measures.]

5.5.4.2. Principles, Guidance, and Experiences

Much of the observed adaptation practice deals with the coastal hazards of erosion and flooding (Hanak and Moreno, 2012). In many parts of the world, small island indigenous communities address climate change consequences based on their own traditional knowledge (Percival, 2008; Langton *et al*., 2012; Nakashima *et al*., 2012). Long-term adaptation to sea level rise has been confined to a few major projects such as the Venice Lagoon project, the Thames Estuary 2100 project (Box 5-1) and the Delta Programme, Netherlands (Norman, 2009).

Through the Delta Programme, the Dutch Government has set out far-reaching recommendations on how to keep the country flood-proof over the 21st century taking into account a sea level rise as high as 0.65-1.3 by 2100. These recommendations constitute a paradigm shift from 'fighting' the forces of nature with engineered structures to 'working with nature' and providing 'room for river' instead (Kabat *et al.*, 2009). The recommendations include soft and environmentally friendly solutions such as preserving land from development to accommodate increased river inundation; maintaining coastal protection by beach nourishment; improving the standards of flood protection and putting in place the necessary political-administrative, legal and financial resources (Stive et al., 2011).

From adaptation experiences, good practices (practices that have shown consistently better results and could be used as benchmark) have been derived. For some European cases, for example, McInnes (2006) has collected good practices for coastlines facing coastal erosion, flooding and landslide events. In the California adaptation study that includes coasts, the lessons learnt include using best available science, decision on goals and early actions, locating relevant partners, identification and elimination of regulatory barriers and encouragement of introduction of new state mandates and guidelines (Bedsworth and Hanak, 2010). Boateng (2010) presented 15 case studies from 12 countries of best practice in coastal adaptation to help coastal managers and policy makers.. Bangladesh provides good examples on awareness raising, disaster warning and control, and protective building measures (Martinez *et al.*, 2011). In general, documentation on good adaptation practices for coasts is improving.

In addition, numerous principles have been set forward. In a broad-scale assessment of climate change threats to Australia's coastal ecosystems, seven principles in adaptation were suggested: clearly defined goals by location, thorough understanding of connectivity within and between ecosystems, consideration of non-climatic drivers, involvement of all relevant stakeholders, easily available and shared data, re-thinking of existing policy and planning constraints and adaptation at local/regional scales (Hadwen *et al*., 2011). Based on Oxfam's adaptation programms in South Asia that include coastal communities, additional principles presented include a focus on the poor, vulnerable and marginalized, community or local ownership, flexible and responsive implementation, preparation for future and capacity building at multiple levels (Sterrett *et al*., 2011). An assessment of worldwide case studies indicates the importance of knowledge transfer of good practice methods for scaling up adaptation strategies in and between regions and beyond the national scale (Martinez *et al*., 2011).

Further principles reported include: Information on efficient adaptation options alone (as assessed through DA approaches) may not fully serve the needs of managers and must to be supplemented by financial and technical assistance as well as boundary organizations which serve as an interface between science and practice (Tribbia and Moser, 2008). The adaptation and decision-making processes should be participatory and inclusive, integrating all relevant stakeholders in a way that is culturally appropriate (Milligan *et al*., 2009; Nunn, 2009). The adaptation processes should be set up to foster mutual learning, experimentation and deliberation amongst stakeholder and researchers (Fazey *et al.*, 2010; Kenter *et al.*, 2011). For example, neither scientific climate knowledge alone nor indigenous knowledge alone are considered sufficient for coastal adaptation (Sales, 2009; Dodman and Mitland, 2011; Bormann *et al.*, 2012). Finally, as coastal systems are complex, diverse and dynamic, their governance needs experimentation and learning by doing (Jentoft, 2007).

In summary, a wealth of adaptation activities can now be observed in the coastal zone depending on technology, policy, financial and institutional support, and are supported by documentation on good practices (*very high confidence*). ICZM, with its emphasis on integration, is likely to remain a major framework for coastal adaptation. While there is *high agreement* on adaptation principles, there is to date little systematic review of and hence *limited evidence* on why a given principle or approach is effective in a given context (and not in another), which emphasizing the need for research to better understand this context (5.5.3.2). Some of the literature on adaptation practice needs to be treated with caution, because normative principles that have been established *ex-ante* are not systematically distinguished from *ex-post* evaluations of the experiences carried out. Despite the wealth of coastal adaptation activities, it must, however, be emphasized that meeting the multiple goals of coastal adaptation, improving governance, accounting for the most vulnerable populations and sectors and fully integrating consideration of natural ecosystems is still largely aspirational. Meanwhile, development continues in high-risk coastal areas, coastal ecosystems continue to degrade in many regions, coastal freshwater resources are being overexploited in many highly populated areas, and vulnerability to coastal disasters grows (e.g. Jentoft, 2009; McFadden, 2008; Mercer, 2010; Shipman and Stojanovic, 2007).

5.5.5. Global Adaptation Costs and Benefits

This section reports on studies that provide internally consistent estimates of the direct costs of sea level rise impacts and adaptation at global scales. These studies have used the models FUND and DIVA, which are described in Section 5.4.1. Studies that use computable general equilibrium models and growth models to estimate the indirect and dynamic costs of climate change, including sea level rise are reviewed in Chapter 10.

Generally, cost estimates are difficult to compare across studies due to differences in scenarios used, impacts and adaptation options considered, methodologies applied and baseline conditions assumed. Global adaptation costs have only been assessed for protection via dikes and nourishment. Nicholls et al. (2011) estimate annual adaptation cost in terms of dike construction, dike maintenance and nourishment to be US$ 25-270 billion/year in 2100 under a 0.5-2.0 m GMSL rise for 2005-2100. Anthoff et al. (2010) estimate the net present value of dike construction costs for 2005-2100 to be US$ 80-120 billion for 0.5 m SLR and US$ 900-1,100 billion for a 2m GMSL, respectively

The available global studies show that it is economically rational to protect large parts of the world's coastline during the 21st century against sea level rise impacts of increased coastal flood damage and land loss (Nicholls and Tol, 2006; Anthoff *et al.*, 2010; Hinkel *et al.*, 2013; *high agreement, limited evidence*). For dry land and wet land loss, the FUND model shows that cost-benefit analysis would justify protecting 80% of the exposed coast in all but 15 countries under a GMSL rise of 20-40 cm per century (Nicholls and Tol, 2006). Using the same method, Nicholls *et al.* (2008) show that under extreme GMSL rise of up to 4 m in 2100, this fraction would drop to 30% to 50%. For coastal flooding, an application of DIVA shows that for 21st century GMSL rise scenarios of 60-126 cm, the global costs of protection through dikes (levees) are much lower than the costs of damages avoided through adaptation (Hinkel *et al.*, 2013).

At the same time, costs and benefits of sea level rise impacts and adaptation vary strongly between regions and countries with some developing countries and Small Island States reaching limits of adaption or not being able to bear the costs of impacts and adaptation (*high agreement, limited evidence)* (29.6.2.1). The cost of 1 m of GMSL rise in 2100 (considering land loss due to submergence and protection costs) is projected to be above 1% of national GDP for Micronesia, Palau, the Bahamas and Mozambique (Anthoff *et al.*, 2010). For coastal flooding, annual damage and protection costs are projected to amount to several percentages of the national GDP for small island states such as Kiribati, the Solomon Islands, Vanuatu and Tuvalu under GMSL projections of 0.6-1.3 m by 2100 (Hinkel *et al.*, 2013). Further substantial costs arise, particularly for developing countries due to their current adaptation deficit (i.e. coastal defenses are not adapted to the current climate variability), which is not well understood and requires further analysis (Parry *et al.*, 2009). For example, the adaption deficit of Africa with regards to coastal flooding is estimated at US$ 300 billion (Hinkel *et al.*, 2011) and that of Bangladesh with respect to cyclones at US$ 25 billion (World Bank, 2011).

Several methodological gaps remain. As there are so few studies on the costs and benefits of sea level rise at a global level, uncertainties are largely unknown and the need for further research is great. The socioeconomic drivers, sea level rise scenarios and impacts considered as well as damages and losses valued are incomplete. For example, costs of salinity intrusion, land loss due to increased coastal erosion, cost of forced migration due to permanent inundation, the backwater effect and the impact of sea level rise in combination with other drivers on ecosystems have not been assessed at global scales (5.5.5). Generally for sea level rise impacts, it is difficult to establish a “no adaptation” baseline and the choice of the baseline the associated changes damage costs (Yohe *et al.*, 2011).

Another gap is realted to the fact that global studies have focused on protection via hard structures while many more, potentially cheaper or socially preferable measures are available including “soft” protection, retreat and accommodation measures (5.1). Future work needs to consider trade-offs between all available measures. Hard protection measures, for example, may incur additional costs on adjacent unprotected coasts (Brown *et al.*, 2013) or destroy coastal wetlands through coastal squeeze (5.4.2.3). While the costs of “soft” protection measures such as ecosystem-based adaptation (EBA) are largely unknown (Linham and Nicholls, 2010), these may provide additional benefits in the form of a variety of ecosystem services (Espinosa-Romero *et al.*, 2011; McGinnis and McGinnis, 2011; Pérez *et al.*, 2010; Anthony *et al.*, 2009; Alongi, 2008; Zeitlin *et al.*, 2012; Vignola *et al.*, 2009; IUCN, 2008). Finally, it must be noted that protection also further attracts people and development to the floodplain, which in turn increases the risk of potential catastrophic consequence in the case of defense failure. This is particularly true for many coastal cities such as London, Tokyo, Shanghai, Hamburg and Rotterdam that already rely heavily on coastal defenses (Nicholls *et al.*, 2007).

5.5.6. Adaptation Opportunities, Constraints, and Limits

There is a growing recognition of the potential co-benefits and new opportunities that can be achieved by mainstreaming adaptation with existing local to national goals and priorities (14.3.4). Disaster Risk Reduction (DRR) and adaptation share the common goals of reducing vulnerability against impacts of extreme events while creating strategies that limit risk from hazards (IPCC, 2012). This is especially true in coastal areas where extreme flooding events due to severe storm surges are one of the main sources of hazard. Besides, integrating adaptation with national and local planning can also contribute to build resilience in coastal areas.

Ecosystems-Based Adaptation (EBA) is considered to be an emerging adaptation opportunity (Munroe *et al.* 2011) (16.6, 16 CC-EA). In coastal areas, the conservation or restoration of habitats (e.g. mangroves, wetlands and deltas) can provide effective measures against storm surge, saline intrusion and coastal erosion by using their physical characteristics, biodiversity and the ecosystem services they provide as a means for adaptation (Borsje *et al*., 2011; Cheong *et al*., 2013; Duarte *et al*., 2013b; Jones *et al*., 2012; Cheong et al., 2013; 5.5.7).

Since AR4, a variety of studies have been published prodviding a better understanding of the nature of the constraints and limits to adaptation, both generally [16.3, 16.4] and more specifically in the coastal sector (e.g. Lata and Nunn, 2012; Mozumber *et al.*, 2011; Storbjörk and Hedrén, 2011; Bedsworth and Hannak, 2010; Frazier *et al.*, 2010; Saroar and Routray 2010; Moser *et al.*, 2008; Tribbia and Moser, 2008; Ledoux *et al.*, 2005).

Constraints specific to coastal adaptation are: polarized views in the community regarding the risk of sea level rise and concerns regarding the fairness of retreat schemes in Australia (Ryan *et al.*, 2011); lack of awareness of sea level rise risks and spiritual beliefs in Fiji (Lata and Nunn, 2012); insufficient budget for the development of adaptation policies and other currently pressing issues in the US (Mozumber *et al.*, 2011; Tribbia and Moser, 2008); distinct preferences for retreat options depending on several social and exposure conditions in Bangladesh (Saroar and Routray, 2010); need to provide compensatory habitats under the Habitats Regulations and lack of local public support in the UK (Ledoux *et al.*, 2005). Other relevant constraints include the lack of locally, relevant information, resource tenure and political will, especially critical in developing countries (*high agreement*, *robust evidence*). Besides a gap exists between the useful climate information provided by scientists and the one demanded by decision makers.

Different constraints typically do not act in isolation, but come in interacting bundles (*high agreement, robust evidence*). Therefore it is difficult to predict which constraints matter most in any specific context but instead multiple constraints need to be addressed if adaptation is to move successfully through the different stages of the management process (Moser and Ekstrom, 2010; Storbjörk, 2010; Londsdale *et al.*, 2010; *high agreement, moderate evidence*). Besides, some factors can act as enablers and add to the adaptation capacity, while acting as constraints for others (Burch, 2010; Storbjörk, 2010; *high agreement, moderate evidence*).

Finally, a common concern emerging from the literature reviews (Biesbroek *et al.*, 2010; Ekstrom *et al.*, 2011) is that some critical constraints arise from the interactions across policy domains, existing laws and regulations, and long-term impacts of past decisions and policies (*high agreement, low evidence*).

A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to existing objectives and values and prevent the loss of key attributes, components or services of ecosystem (Box 16-1; 16.2, 16.5) and may arise due to most of the constraints described above.

Regarding coastal areas, it is widely recognized that biophysical limitations arise, for example, in small developing island states where adaptation through retreat to increasing impact of sea level rise in conjunction with storm surges and flooding is not an option due to limited high land availability, creating a temporary and eventually permanent human displacement from low-lying areas (Pelling and Uitto, 2001; *high agreement, moderate evidence*). Nicholls *et al.* 2011, show that only a limited number of adaptation options are available for specific coastal areas if sea level exceeds a certain threshold (1 m) at the end of the century.

Regarding natural (unassisted) adaptation, several researchers have examined biophysical limits, e.g., of coastal marshes (Kirwan *et al.*, 2010; Craft *et al.*, 2009; Langley *et al.*, 2009; Mudd *et al.*, 2009). Kirwan *et al.* (2010) found that under certain nonlinear feedbacks among inundation, plant growth, organic matter accretion and sediment deposition coastal wetlands can adapt to conservative rates of sea level rise (A1B) if suspended sediment surpasses a certain threshold. In contrast, even coastal marshes with high sediment supplies, will submerge near the end of the 21st century under scenarios of more rapid sea level rise (e.g., those that include ice sheet melting).

Increased ocean acidification is expected to limit adaptation of coral reefs to climate change (Boxes CC-OA and CC-CR).

5.5.7. Synergies and Tradeoffs between Mitigation and Adaptation

Klein *et al.* (2007, p. 749) defined trade-offs between mitigation and adaptation as the “balancing of adaptation and mitigation when it is not possible to carry out both activities fully at the same time (e.g., due to financial or other constraints)”. Successful adaptive coastal management of climate risks will involve assessing and minimizing potential trade-offs with other non-climate policy goals (e.g., economic development, enhancement of coastal tourism) and interactions between adaptation and mitigation (e.g. Bunce *et al.*, 2010; Barbier *et al.*, 2008; Tol, 2007; Brown *et al.*, 2002).

Adaptation will be the predominant approach to reducing climate risks to coastal communities, populations, resources and activities over the 21st century as large increases in sea level rise cannot be ruled out (WG1, Chapter 13, 13.5.2.) and because of the time lag between emission reductions, temperature changes and impacts on global sea levels (Nicholls *et al.*, 2011; Nicholls *et al.*, 2007, 5.5.7). Still, positive synergies and complementarities between mitigation and adaptation in the coastal sector exist.

Since AR4, a series of studies have pointed out that marine vegetated habitats (seagrasses, saltmarshes, macroalgae or mangroves) contribute to almost 50% of the total organic carbon burial in ocean sediments leading to the so-called Blue Carbon (coastal carbon stocks) strategies (Duarte *et al*. 2013b, McLeod *et al*., 2011, Nellemann *et al*. 2009). These strategies aim at exploring and implementing the necessary mechanisms allowing Blue Carbon to become part of emission and mitigation protocols along with other carbon-binding ecosystems such as rainforests (Nellemann *et al*. 2009).

Besides, marine vegetated habitats provide additional functions including the buffering of impacts against storm surges and waves, soil preservation, raising the seafloor and shelter for fish nursery or habitat protection (Duarte *et al.* 2013b, Alongi, 2002, Kennedy and Björk, 2009). Consequently, restoration or ecosystem engineering of marine vegetated areas can be considered as a good example of positive synergies between adaptation and mitigation in coastal areas (Duarte *et al.* 2013b, Jones, *et al.* 2012, Borsje *et al.* 2011) and should be further explored to be considered as a valid alternative in the portfolio of measures for climate change mitigation and adaptation. Only recently results have been presented on the role of a 1700 ha seagrass restoration in carbon storage in sediments of shallow coastal ecosystems in Virginia (USA). Restored seagrass meadows are expected to accumulate carbon at a rate comparable to ranges measured in natural seagrass meadows within 12 years of seeding, providing an estimated social cost of \$4.10 $ha^{-1}yr^{-1}$ (Greiner *et al.* 2013).

Many coastal zone-based activities and various coastal management strategies involve emissions of greenhouse gases. Reduction or cessation of some of them may have positive implications for both mitigation and adaptation. Limiting offshore oil production may imply a net reduction in GHG emissions depending on what form of energy replaces it, but also a reduced risk of oil spills, a reduction of stresses on the marine/coastal eco-systems and variable socio-economic impacts on human communities and public health (O'Rourke and Connolly, 2003). This may result in reduced vulnerability or increased resilience and consequently could prove positive for adaptation. However, this measure would increase the vulnerability of countries whose economies are highly dependent on oil extraction.

Some coastal adaptation options may have potentially negative implications on mitigation. Relocation of infrastructure and development out of the coastal floodplains (retreat) will imply increase in one-time GHG emissions due to rebuilding of structures and possible increase in low-density urban development and ongoing transportation-related emissions (Biesbroek *et al.* 2010). The building or upgrading of coastal protection structures or ports will also imply an increased energy use and GHG emissions related to construction (e.g. cement production) (Boden *et al.* 2011).

Similarly, actions beneficial for mitigation may result in potential negative impacts for adaptation. A more compact coastal urban design, increasing development in floodplains (Giridharan *et al.* 2007) or the development of marine renewable energy (Boehlert and Gill, 2010), may introduce additional drivers on coastal systems reducing coastal resilience and adaptive capacity.

5.5.8. Long-Term Commitment to Sea Level Rise and Adaptation

In AR4 both WG1 and WG2 highlighted the long-term commitment to sea level rise (Meehl *et al*., 2007; Nicholls *et al*., 2007), which means that sea levels will continue to rise for centuries due to global warming until reaching equilibrium conditions even if climate forcing is stabilized, because there is a delay in the response of sea level rise to global warming [WG1, 13.4.1]. In AR5 WG1 has now assessed GMSL rise until 2500 and this shows that even with aggressive mitigation measures (RCP2.6), sea level continues to rise after 2100 [Table 5-1, WGI, 13.5.1, 13.5.4]. With more moderate (RCP4.5.) and little (RCP8.5) mitigation, larger ongoing increases in sea level are expected lasting for several centuries. Note that the ranges given after 2100 are only model spread and not *likely* ranges. Looking beyond 2500, Levermann *et al*. (2013) project that GMSL will rise on average by about 2.3 m per degree Centigrade of global warming within the next 2000 years. Under present levels of global warming, this means that we have already committed to a long term sea level rise of 1.3 m above current levels (Strauss, 2013). For other climate-related drivers, responses to global warming levels are more immediate. For ocean acidification, for example, pH rise would cease several decades after strict CO_2 emission reductions begin (Bernie *et al.* 2010) [19.7.1].

This long term commitment to sea level rise means that there is also a long-term commitment to sea level rise impacts and adaptation. Few studies have considered this and, from a methodological point of view, it is difficult to look at socio-economic conditions and human responses on such large temporal scales. A limited number of studies have estimated the effects of mitigation on coastal impacts on human settlements and adaptation for the 21st century [5.4.3.1]. These studies show that despite the delayed response of sea level rise to global warming, mitigation can reduce impacts significantly already during the 21st century. These studies also show that for most urban areas, coastal protection is cost-efficient in reducing impacts during the 21st century [5.5.5]. Past and current adaptation practice also confirms this: cities such as Tokyo and Shanghai have protected themselves against local sea level rise of several meters during the 20th century and the Dutch and UK Governments have decided that they can protect urban Netherlands and London against 21st century sea level rise above 1 m [5.5.4]. Not protecting cities such as Amsterdam, Rotterdam and London during the 21st century is not an option. On the other hand, there are coastal areas such as small island states where protecting against several meters of sea level rise in the long-term is not a viable option. Failing to mitigate, thus increasingly commits us to a world where densely populated areas lock into a trajectory of increasingly costly hard defenses and rising residual risks on the one hand and less densely populated areas being abandoned on the other hand. Mitigation thus plays, in the long-term, a very important role in avoiding climate change impacts in coastal areas by reducing the rate of sea level rise and providing more time for long-term strategic adaptation measures to be adopted. However, even if anthropogenic CO_2 emissions were reduced to zero, sea levels would continue to rise for centuries, making adaptation in coastal areas inevitable.

5.6. Information Gaps, Data Gaps, and Research Needs

This chapter has updated knowledge on the impacts of climate change on the coastal systems not in isolation but also from the perspective of overexploitation and degradation that have been responsible for most of the historical changes. There is a better understanding of the varying impacts of weather and climate extremes and long-term sea level rise on human systems.

That sea levels will rise is a confident projection of climate science but uncertainties around the magnitude of future sea level rise remain large. The rates and magnitude of sea level rise are summarized in Table 5-1 but under present levels of global warming, we are already committed to 1.3 m future sea level rise above current levels (5.5.8). However, many sea level rise assessments are not provided at spatial or temporal scales most relevant for decision makers who require information on baseline conditions and projections of change (Kettle, 2012) of relative sea level rise (i.e. including local subsidence) for vulnerability assessment and adaptation planning.

Generally, quantitative predictions of future coastal change remain difficult despite the application of improvements in technology, e.g., aerial photographs, satellite imagery, LiDAR (Sesil *et al.*, 2009; Revell *et al.*, 2011; Pe'eri and Long, 2012) to investigate and characterize large-scale shoreline changes. There is incomplete understanding of coastal changes over the decade and century timescales (Woodroffe and Murray-Wallace, 2012). Shoreline response is more complex than simple submergence because of factors such as sediment supply, mobilization and storage, offshore geology, engineering structures, and wave forcing (Ashton *et al.*, 2011).

The projection of the future impacts of climate change on natural systems is often hampered by the lack of sufficiently detailed data at the required levels of space and time. Although observations have been made on impacts on beaches, rocky coasts, wetlands, coastal aquifers, delta areas or river mouths by multi-drivers of climate and human-induced origin, there is still an incomplete understanding of the relative role played by each of these drivers and, especially of their combined effect. Uncertainties are even higher when it comes to the evaluation of projected impacts.

For coastal ecosystems, more work needs to be done to develop predictive models based on findings from multi-stressor experiments, both in the field and laboratory. Reliable predictions require information on multifactorial experiments performed on communities (preferably in the field), and on time scales of months to years in order to take into consideration the processes of biological acclimation and adaptation.

Although sea level is projected to rise in the future, there are significant gaps in vulnerability assessment of other specific coastal impacts. For example, the modeling of diseases that could affect coastal areas is based mainly on the mean values of climate. Also, despite tourism being one of the most important industries in the coastal areas, not enough is known about tourists' reactions to projected climatic change (Moreno and Amelung, 2009b) or required adaptation measures for port facilities (UNCTAD, 2009).

A wide range of coastal management frameworks and measures is available and used in coastal adaptation to climate change, and the scope for their integration has increased by combining scenarios of climate change and socio-economic conditions and risk assessment (Kirshen *et al.*, 2012). While various adaptation measures are available, at the local level, there remains insufficient information on assessment of adaptation options, particularly in developing countries.

Data and knowledge gaps exist or their reliability is insufficient. Despite the availability of potentially useful climate information, a gap exists between what is useful information for scientists and for decision makers. For example, at the project level engineers may have difficulties to "plug in" climate projections presented by scientists. The proposed actions to improve usability include varying levels of interaction, customization, value-adding, retailing and wholesaling (Lemos *et al.*, 2012) so that data and methods can be more openly-accessible to fellow scientists, users and public (Kleiner, 2011).

Coastal systems are affected by human and climate drivers and there are also complex interactions between the two. In general, certain components of coastal systems are sensitive and attributable to climate drivers while others are not clearly discernible. For example, data is available on the range shift in coastal plant and animal species and the role of higher temperatures on coral bleaching (see CC-CR). However, in many cases in the human systems, the detectable changes can be largely attributed to human drivers (5.3.4). Reducing our knowledge gaps on the understanding of the processes inducing changes would help to respond to them more efficiently.

The economics of coastal adaptation are under researched. More comprehensive assessments of valuation of coastal ecosystem services, adaptation costs and benefits that simultaneously consider both the gradual impact of land loss due to sea level rise and the stochastic impacts of extreme water levels (storm surges, cyclones) are needed, as well as other impacts such as salt water intrusion, wetland loss and change and backwater effects. Assessments should also consider a more comprehensive range of adaptation options and strategies, including "soft" protection, accommodation and retreat options as well as the trade-offs between these.

Governance of coastal adaptation and the role of institutions in the transition towards sustainable coasts are under-researched. While institutional factors are recognized to be decisive in constraining and enabling coastal adaptation, most work remains descriptive. There is a great need for dedicated social science research aimed at understanding institutional change and which institutional arrangements are effective in which socio-economic and biophysical contexts (5.5.3; 5.5.4; Kay, 2012).

Developing a coastal adaptation knowledge network between scientists, policy makers, stakeholders and the general public could be considered a priority area for large coastal areas or regional areas affected by climate change and sea level rise. This is well developed in the USA, European Union, the Mediterranean and Australia but less so in the developing countries, except in certain regions, e.g. Caribbean islands, Pacific Islands.

Future research needs for coastal adaptation are identified by several developments in climate science. Based on Li *et al.* (2011) survey of the foci of climate research in the 21st century, the implications for coasts would be on biodiversity and flooding. Future technological advances may be significant, e.g., new forms of energy and food production, information and communication technology (ICT) for risk monitoring (Zevenhagen *et al*., 2013; Campbell *et al*., 2009; Delta Commission, 2008) and these would be useful for flood risks and food production in deltas and coastal systems (aquaculture).

With recent adverse climatic and environmental events on coasts, adaptation demands different decision regimes (Kiker *et al.*, 2010) but adaptation, mitigation and avoidance measures still require integrating research that includes natural and social sciences (CCSP, 2009). Although many gaps still remain, there is nevertheless a greater foundation of climate change research on coasts across a wide range of fields (Grieneisen and Zhang, 2011) upon which scientists, policymakers and public may find improved solutions for coastal adaptation.

Frequently Asked Questions

FAQ 5.1: How does climate change affect coastal marine ecosystems? *[to be placed in Section 5.4.1]*
The major climate-related drivers on marine coastal ecosystems are sea level rise, ocean warming, and ocean acidification.

Rising sea level impacts marine ecosystems by drowning some plants and animals as well as by inducing changes of parameters such as available light, salinity, and temperature. The impact of sea level is mostly related to the capacity of animals (e.g. corals) and plants (e.g. mangroves) to keep up with the vertical rise of the sea. Mangroves and coastal wetlands can be sensitive to these shifts and could leak some of their stored compounds, adding to the atmospheric supply of these greenhouse gases.

Warmer temperatures have direct impacts on species adjusted to specific and sometimes narrow temperature ranges. They raise the metabolism of species exposed to the higher temperatures and can be fatal to those already living at the upper end of their temperature range. Warmer temperatures cause coral bleaching, which weakens those animals and makes them vulnerable to mortality. The geographical distribution of many species of marine plants and animals shifts towards the poles in response to warmer temperatures.

When atmospheric carbon dioxide is absorbed into the ocean, it reacts to produce carbonic acid, increasing the acidity of seawater and diminishing the amount of a key building block (carbonate) used by marine species like shellfish and corals to make their shells and skeletons. The decreased amount of carbonate makes it harder for many of these 'calcifiers' to make their shells and skeletons, weakening or dissolving them. Ocean acidification has a number of other impacts, many of which are still poorly understood.

FAQ 5.2: How is climate change influencing coastal erosion? *[to be placed in Section 5.4.2]*
Coastal erosion is influenced by many factors; sea level, currents, winds and waves (especially during storms, which add energy to these effects). Erosion of river deltas is also influenced by precipitation patterns inland which change patterns of freshwater input, run-off and sediment delivery from upstream. All of these components of coastal erosion are impacted by climate change.

Based on the simplest model, a rise in mean sea level usually causes the shoreline to recede inland due to coastal erosion. Increasing wave heights can cause coastal sand bars to move away from the shore and out to sea. High storm surges (sea levels raised by storm winds and atmospheric pressure) also tend to move coastal sand offshore. Higher waves and surges increase the probability that coastal sand barriers and dunes will be over-washed or breached. More energetic and/or frequent storms exacerbate all these effects.

Changes in wave direction caused by shifting climate may produce movement of sand and sediment to different places on the shore, changing subsequent patterns of erosion.

FAQ 5.3: How can coastal communities plan for and adapt to the impacts of climate change, in particular sea level rise? *[to be placed in Section 5.5]*
Planning by coastal communities that considers the impacts of climate change reduces the risk of harm from those impacts. In particular, proactive planning reduces the need for reactive response to the damage caused by extreme events. Handling things after the fact can be more expensive and less effective.

An increasing focus of coastal use planning is on precautionary measures, i.e. measures taken even if the cause and effect of climate change is not established scientifically. These measures can include things like enhancing coastal vegetation, protecting coral reefs. For many regions, an important focus of coastal use planning is to use the coast as a natural system to buffer coastal communities from inundation, working with nature rather than against it, as in the Netherlands.

While the details and implementation of such planning take place at local and regional levels, coastal land management is normally supported by legislation at the national level. For many developing countries, planning at the grass roots level does not exist or is not yet feasible.

The approaches available to help coastal communities adapt to the impacts of climate change fall into three general categories:

1) Protection of people, property and infrastructure is a typical first response. This includes 'hard' measures such as building seawalls and other barriers, along with various measures to protect critical infrastructure. 'Soft' protection measures are increasingly favored. These include enhancing coastal vegetation and other coastal management programs to reduce erosion and enhance the coast as a barrier to storm surges.
2) Accommodation is a more adaptive approach involving changes to human activities and infrastructure. These include retrofitting buildings to make them more resistant to the consequences of sea level rise, raising low-lying bridges, or increasing physical shelter capacity to handle needs caused by severe weather. Soft accommodation measures include adjustments to land use planning and insurance programs.
3) Managed retreat involves moving away from the coast and may be the only viable option when nothing else is possible.

Some combination of these three approaches may be appropriate, depending on the physical realities and societal values of a particular coastal community. The choices need to be reviewed and adjusted as circumstances change over time.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

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

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection and appealing environments for tourism (Wild *et al*., 2011). About 275 million people live within 30 km of a coral reef (Burke *et al*., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling) and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5) and more than half of the world's reefs are under medium or high risk of degradation (Burke *et al*., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show

that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see 6.3.1. for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs towards net dissolution (*medium confidence*; 5.4.2.4). Ocean warming and acidification have synergistic effects in several reef-builders (5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg *et al*., 2007). The abundance of reef building corals is in rapid decline in many Pacific and SE Asian regions (*very high confidence*, 1-2% per year for 1968-2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner *et al*., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski *et al*., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones *et al*., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the RCP3-PD scenario (Frieler *et al*., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan *et al*., 2013). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

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

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton *et al*. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the SRES A2 emissions scenario (Bell *et al*., 2013).

- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard *et al*., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke *et al*., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the Global Domestic Product but their economic importance can be high at the country and regional scales (Pratchett *et al*., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001-2011; Laurans *et al*., 2013). At the local scale, these two services provided in 2009-2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans *et al*., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour *et al*., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod *et al*., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig *et al*., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau *et al*., 2012; Billé *et al*., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm *et al*. 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod *et al*., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann *et al*., 2012) and coastal pollutants enriched with fertilizers can increase acidification (Kelly *et al.*, 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; 5.2.4.4, 30.5).

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Box CC-OA. Ocean Acidification

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

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Fig. CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30.8, 30.9). Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several metaanalyses (6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea-floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves and gastropods reducing the competitiveness with non-calcifiers (5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; 6.1.2).

Projections of ocean acidification effects at ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (5.4.2.2).

Due to an incomplete understanding of species-specific responses and trophic interactions the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, 5.4.2.4) and the goods and services that they provide such as fisheries, tourism and coastal protection (*limited evidence, high agreement*; Box CC-CR, 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially-exploited shelled mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global GDP, it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e. reduce anthropogenic emissions of CO_2), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (6.4.2.1).

CC-OA References

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Box CC-TC. Building Long-Term Resilience from Tropical Cyclone Disasters

[Yoshiki Saito (Japan), Kathleen McInnes (Australia)]

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

About 90 tropical cyclones occur globally each year (Seneviratne et al., 2012) although interannual variability is large. Changes in observing techniques particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities. Therefore, IPCC (2012) "Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)" concluded that there is *low confidence* that any observed long-term (i.e. 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne et al., 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is *likely* to increase (AR5 WG1 Ch 14.6). Regionally specific projections have *lower confidence* (see AR5 WG1 Box 14.2).

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

Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray et al., 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga et al., 2003; Brakenridge et al., 2013). The flooded areas were captured by a NASA MODIS image on 5 May 2008 (see Figure TC-1).

[INSERT FIGURE TC-1 HERE
Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. Source: Brakenridge et al., 2013.]

Murray et al. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargis in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation. Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3,400 compared to over 138000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multistoried cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. The strategies of disaster risk management for tropical cyclones in coastal areas, that create protective measures, anticipate and plan for extreme events, increase the resilience of potentially exposed communities. The integration of activities relating to education, training, and awareness-raising into relevant ongoing processes and practices is important for the long-term success of disaster risk reduction and management (Murray et al., 2012). Birkmann and Teichman (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

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Table 5-1: Main climate-related drivers for coastal systems, their trends due to climate change, and their main physical and ecosystem effects.

Climate-related Driver	Physical/chemical effects	Trends	Projections	Progress since AR4
Sea Level	Submergence, flood damage, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change).	GMSL very likely increase (5.3.2.2, AR5 WG1 Ch 3.7.2, 3.7.3;)	GMSL very likely increase (see Table 5.1, WG1 Ch. 13.5.1) Regional variability (5.3.2.2, WG1 Ch. 13)	Improved confidence in contributions to observed sea level. More information on regional and local SLR.
Storms (Tropical cyclones (TC's), extratropical cyclones (ETC's)	Storm surges and storm waves, coastal flooding, erosion; saltwater intrusion; rising water tables/impeded drainage; wetland loss (and change). Coastal infrastructure damage and flood defense failure.	TC's (Box 5.1, WG1 2.6.3) Low confidence in trends in frequency and intensity due to limitations in observations and regional variability ETC's (5.3.3.1 AR5 WG1 2.6.4) Likely poleward movement of circulation features but low confidence in intensity changes.	TC's (Box 5.1) Likely decrease to no change in frequency; Likely increase in the most intense TC's ETC's (5.3.3.1) High confidence that reduction of ETC's will be small globally. Low confidence in changes in intensity.	Lowering of confidence of observed trends in TC's and ETC's since AR4. More basin-specific information on storm track changes.
Winds	Wind waves, storm surges, coastal currents, land coastal infrastructure damage.	Low confidence in trends in mean and extreme wind speeds (5.3.3.2, SREX, WG1 Ch 3.4.5).	Low confidence in projected mean wind speeds. Likely increase in TC extreme wind speeds (5.3.3.2, SREX).	Winds not specifically addressed in AR4.
Waves	Coastal erosion, overtopping and coastal flooding.	Likely positive trends in Hs in high latitudes (5.3.3.2, WG1, Ch 3.4.5).	Low confidence for projections overall but medium confidence for southern ocean increases in Hs (5.3.3.2).	Large increase in number of wave projection studies since AR4.
Extreme Sea Levels	Coastal flooding erosion, saltwater intrusion	High confidence of increase due to GMSL rise (5.3.3.3, WG1 Chapter 13).	High confidence of increase due to GMSL rise, low confidence of changes due to storm changes (5.3.3.3, AR5 WG1 Ch13.5)	Local subsidence is an important contribution to RSL rise in many locations.

Sea Surface Temperature	Changes to stratification and circulation; reduced incidence of sea ice at higher latitudes; increased coral bleaching and mortality, poleward species migration; increased algal blooms.	High confidence that coastal SST increase is higher than global SST increase. (5.3.3.4,).	High confidence that coastal SSTs will increase with projected temperature increase (5.3.3.4).	Emerging information on coastal changes in SSTs.
Freshwater Input	Altered flood risk in coastal lowlands; altered water quality/salinity; altered fluvial sediment supply; altered circulation and nutrient supply.	Medium confidence (*limited evidence*) in a net declining trend in annual volume of freshwater input (5.3.3.6).	Medium confidence for general increase in high latitudes and wet tropics and decrease in other tropical regions (5.3.3.6).	Emerging information on freshwater input.
Ocean Acidity	Increased CO2 fertilisation; decreased seawater pH and carbonate ion concentration (or ‘ocean acidification’)	High confidence of overall increase, with high local and regional variability (5.3.3.5).	High confidence of increase at unprecedented rates but with local and regional variability (Box CC-OA).	Coastal ocean acidification not specifically addressed in AR4. Considerable progress made in chemical projections and biological impacts.

Table 5-2: Projections of global mean sea level rise in meters relative to 1986–2005 are based on ocean thermal expansion calculated from climate models, the contributions from glaciers, Greenland and Antarctica from surface mass balance calculations using climate model temperature projections, the range of the contribution from Greenland and Antarctica due to dynamical processes, and the terrestrial contribution to sea levels, estimated from available studies. For sea levels up to and including 2100, the central values and the 5-95% range are given whereas for projections from 2200 onwards, the range represents the model spread due to the small number of model projections available. Source: WGI AR5 SPM and Sections 12.4.1, 13.5.1, and 13.5.4.

	RCP	**2100 CO_2 Concentration (ppm)**	**Temperature increase (C)**	**Mean Sea Level Rise (m)**				
			2081-2100	2046–2065	2100	2200	2300	2500
Low	2.6	421	1.0 [0.3 to1.7]	0.24 [0.17 to 0.31]	0.43 [0.28 to .60]	0.35–0.72	0.41–0.85	0.50–1.02
Medium	4.5	538	1.8 [1.1 to 2.6]	0.26 [0.19 to 0.33]	0.52 [0.35 to .70]	0.26–1.09	0.27–1.51	0.18–2.32
High	6.0	670	2.2 [1.4 to 3.1]	0.25 [0.18 to 0.32]	0.54 [0.37 to .72]			
	8.5	936	3.7 [2.6 to 4.8]	0.29 [0.22 to 0.37]	0.73 [0.53 to .97]	0.67–1.92	0.92–3.59	1.51–6.63

Table 5-3: Main impacts of relative sea level rise. Source: Adapted from Nicholls et al., 2010.

Biophysical impacts of relative sea level rise	**Other climate-related drivers**	**Other human drivers**
Dryland loss due to erosion	Sediment supply, wave and storm climate	Activities altering sediment supply (e.g., sand mining)
Dryland loss due to submergence	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Wetland loss and change	Sediment supply, CO_2 fertilization,	Sediment supply, migration space, direct destruction
Increased flood damage through extreme sea level events (storm surges, tropical cyclones, etc.)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
Saltwater intrusion into surface waters (backwater effect)	Runoff	Catchment management and land use (e.g., sand mining and dretching)
Saltwater intrusion into ground waters leading to rising water tables and impeded drainage	Precipitation	Land use, aquifer use

Table 5-4: Community-based adaptation measures.

Impact	Type of option	Measures	Brief description	References
Salinity	New and diversified livelihoods	Saline-tolerant crop cultivation	Farmer production of saline-tolerant multi-vegetable varieties and non-rice crops.	Rabbani *et al.* 2013; Ahmed 2010
	New and diversified livelihoods	Keora nursery	Mangrove fruit production to develop local female entrepreneurship.	Ahmed 2010
	New and diversified livelihoods	Crab fattening	Collection, rearing and feeding of crabs for 15 days to increase local market value.	Pouliotte *et al.* 2009
	Structural	Homestead protection	Houses constructed on raised foundations to mitigate salinity ingress.	Ayers and Forsyth 2009
Flooding/ Waterlog ging	Socio-technical	Disaster management committees	Multi-community stakeholder committees established to discuss disaster preparedness and response on a monthly basis.	Ahammad 2011
	Socio-technical	Early flood warning systems	Established systems converted into a language and format understood by local communities; warning dissemination through community radio services.	Ahmed 2005; Saroar and Routray 2010
	New and diversified livelihoods	Aquaculture: cage and integrated approaches	Small-scale fish culture in cages on submerged agriculture land; aquaculture integrated with other livelihood practices.	Pouliotte *et al.* 2009; Khan *et al.* 2012; Pomeroy *et al.* 2006
	New and diversified livelihoods	Embankment cropping	Growing different vegetable varieties around heightened shrimp enclosures/coastal polders for productive use of fallow land.	Ahmed 2010
	New and diversified livelihoods	Hydroponics	Cultivating vegetables and other crops on floating gardens.	Dev 2013; Ahmed 2010; Ayers and Forsyth 2009
Cyclones / storm surges	Structural/hard	Homestead reinforcement	Low-cost retrofitting to strengthen existing household structures especially roofs; strict implementation of building codes.	Ahmed 2010; Sales 2009
	Structural/soft	Homestead ecosystem protection	Plantation of specific fruit trees around homestead area.	Haq *et al.* 2012
	Structural/hard	Underground bunker construction	Underground bunker established providing protected storage space for valuable community assets.	Raihan *et al.* 2010
sea level rise (SLR)	Institutional	Risk insurance mechanisms	Farmers educated on comprehensive risk insurance focusing on sea level rise and coastal agriculture.	Khan *et al.* 2012
Multi-coastal impacts	Institutional	Integrating climate change into education	Formal and informal teacher training and curriculum development on climate change, vulnerability and risk management.	Ahmed 2010
	Institutional	Integrated coastal zone management plan (ICZM)	ICZM plan development at local institutional level including land and sea use zoning for ecosystem conservation.	Sales 2009
	Structural / soft	Restoration, regeneration and management of coastal habitats	Community-led reforestation and afforestation of mangrove plantations including integration of aquaculture and farming to increase household income levels.	Sovacool *et al.* 2012; *Rawlani and Sovacool, 2011*
	Institutional	Community participation in local government decision-making	Active female participation in local government planning and budgeting processes to facilitate delivery of priority coastal adaptation needs.	Faulkner and Ali 2012
	Institutional /socio-technical	Improved research and knowledge management	Establishment of research centres; community-based monitoring of changes in coastal areas.	Rawlani and Sovacool, 2011; Sales 2009

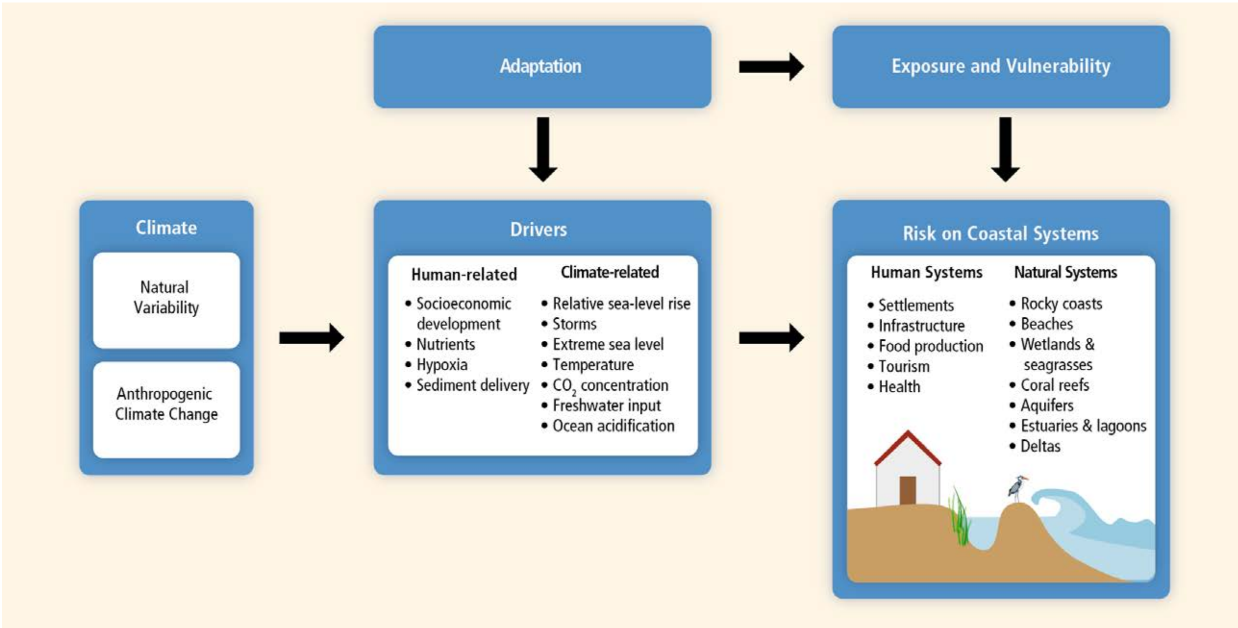

Figure 5-1: Climate, just as anthropogenic or natural changes, affects both climate and human related drivers. Risk on coastal systems is the outcome of integrating drivers and exposure and vulnerability. Adaptation options can be implemented either to modify the drivers or exposure and vulnerability or both.

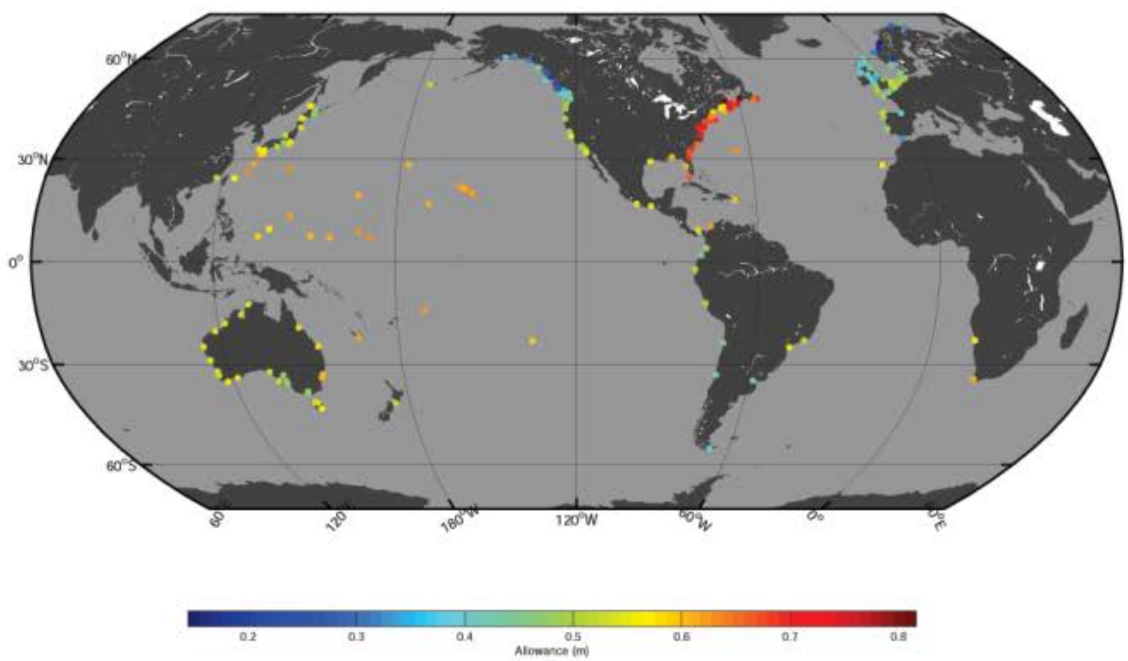

Figure 5-2: The estimated increase in height (m) that flood protection structures would need to be raised in the 2081-2100 period to preserve the same frequency of exceedences that was experienced for the 1986-2005 period, shown for 182 tide gauge locations and assuming regionally-varying relative sea level rise projections under an RCP4.5 scenario (adapted from Hunter *et al*., 2013).

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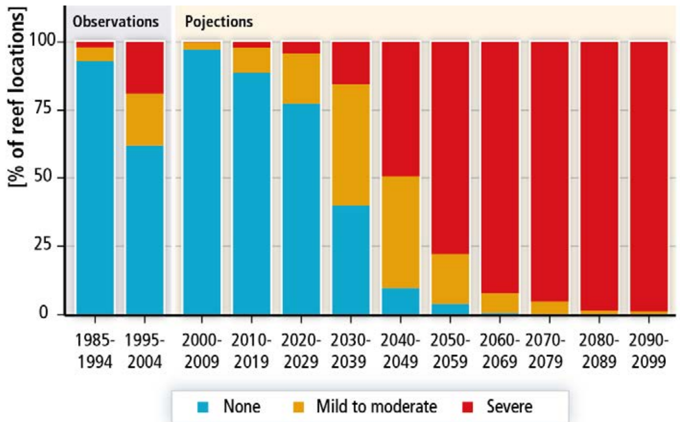

Figure 5-3: Percent of reef locations (1°x1° grid cells which have at least one reef) that experience no bleaching, at least one mild bleaching event, or at least one severe bleaching event for each decade. Observed bleaching events are summarized from the ReefBase dataset (Kleypas *et al.*, 2008). In the observations, some of the "no bleaching" cells may have experienced bleaching but it was either not observed or not reported. Modeled bleaching events are averages of data from four ensemble runs of the Community Climate System Model version 3 using the SRES A1B CO_2 scenario and the standard degree heating month formula (Teneva *et al.*, 2011). The labels of values ≤ 1% are not shown.

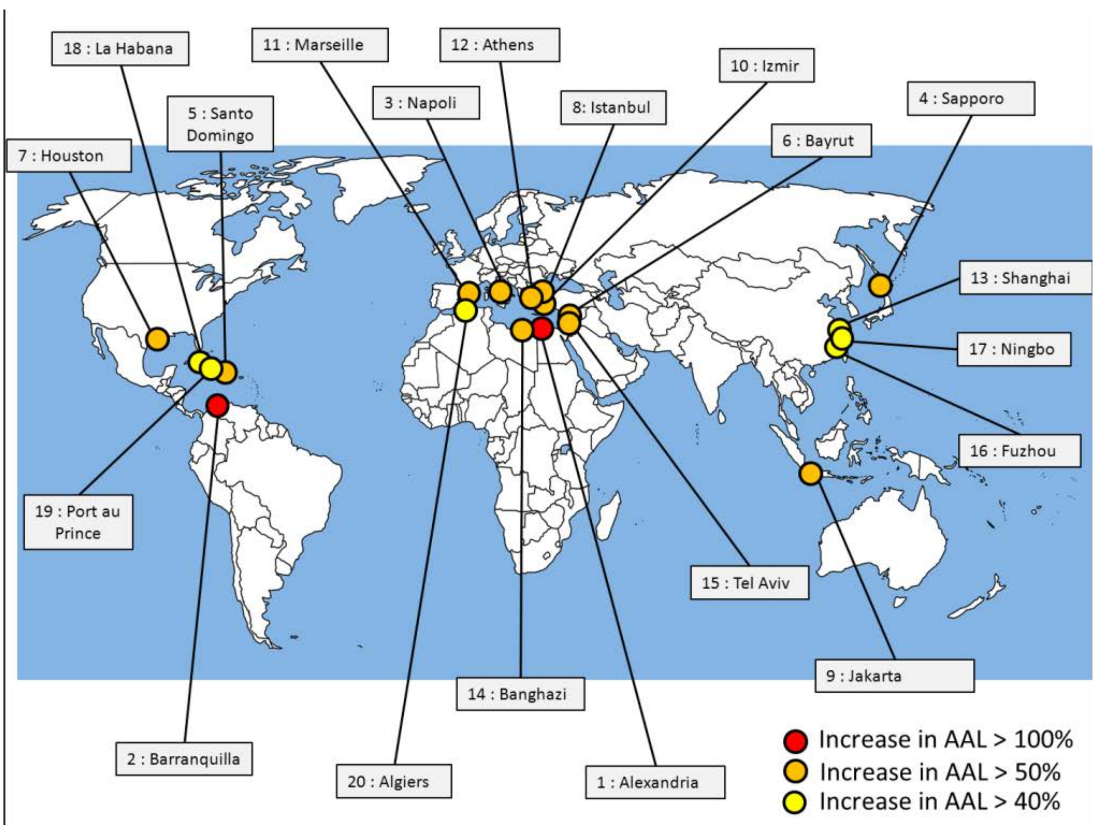

Figure 5-4: The 20 cities where average annual losses (AAL) increase most (in relative terms in 2050 compared with 2005) in the case of optimistic sea level rise, if adaptation maintains only current defense standards or flood probability (PD). Source: Hallegatte *et al*., 2013.
[Illustration to be redrawn to conform to IPCC publication specifications.]

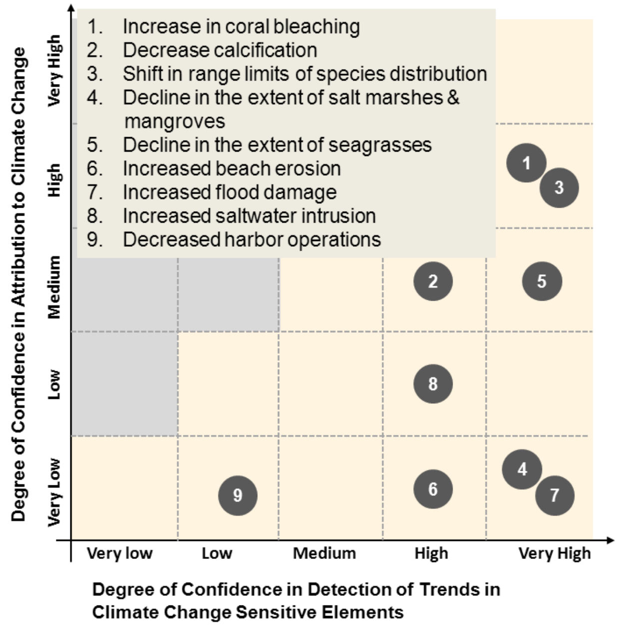

Figure 5-5: Summary on detection and attribution in coastal areas.
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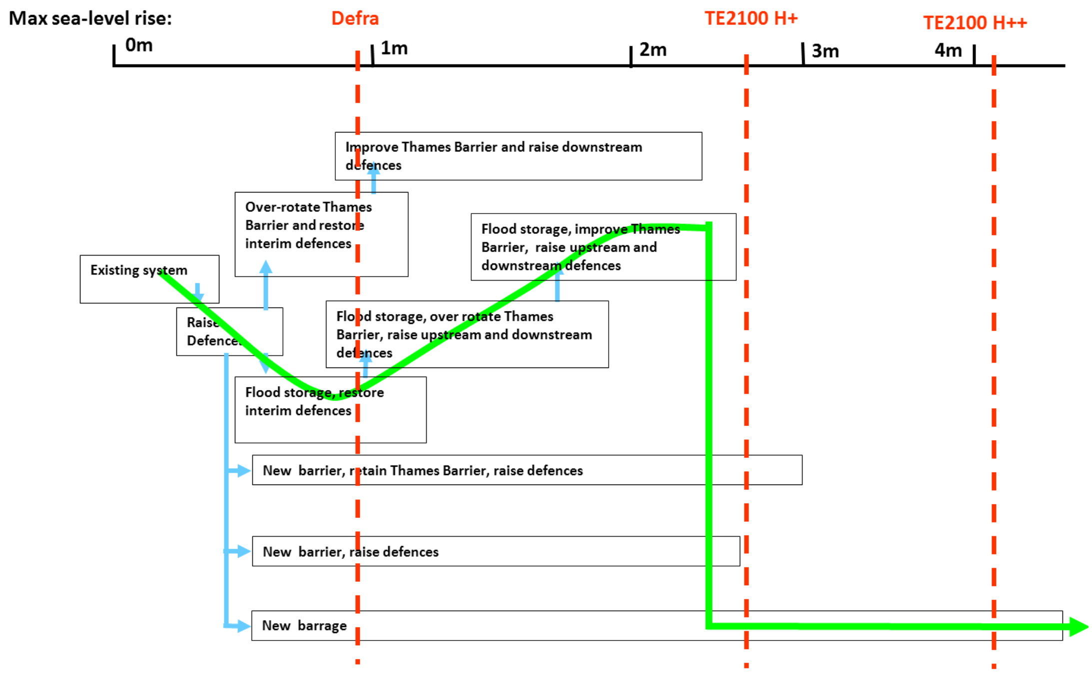

Figure 5-6: Adaptation measures and pathways considered in the TE2100 project. The boxes show the measures and the range of sea level rise over which the measures are effective. The blue arrows link to alternative measures that may be applied once a measure is no longer effective. The red lines show the various 21st century sea level rise scenarios used in the analysis including a conservative estimate of about 0.9 m by the UK Department for Environment Food and Rural Affairs (Defra), a high-level scenario of 2.6 m (H+) and an extreme scenario of over 4 meters (H++). The fat green line shows a possible future adaptation pathway that allows for lower-end sea level rises but also for the unlikely event of extreme change.
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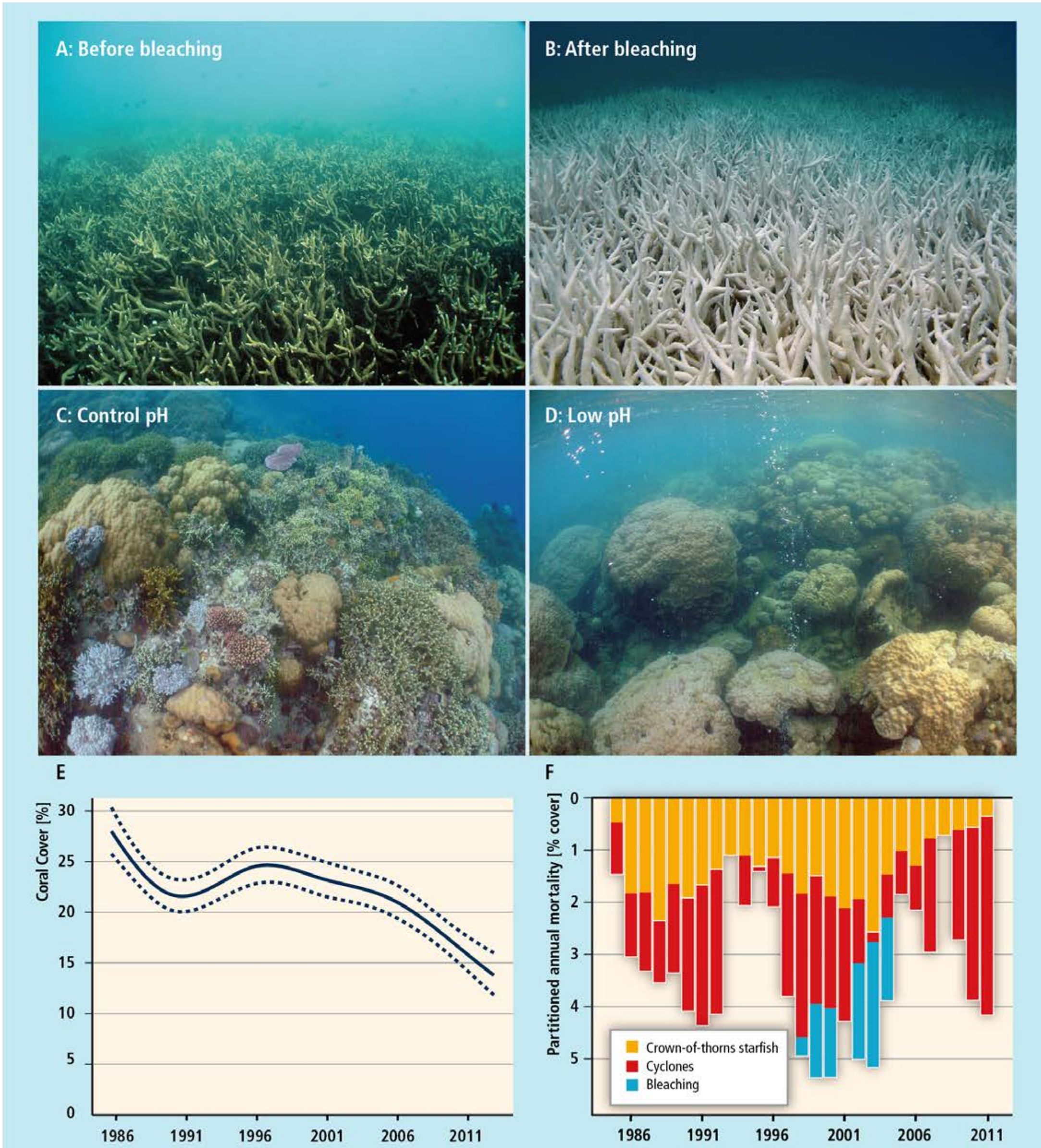

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

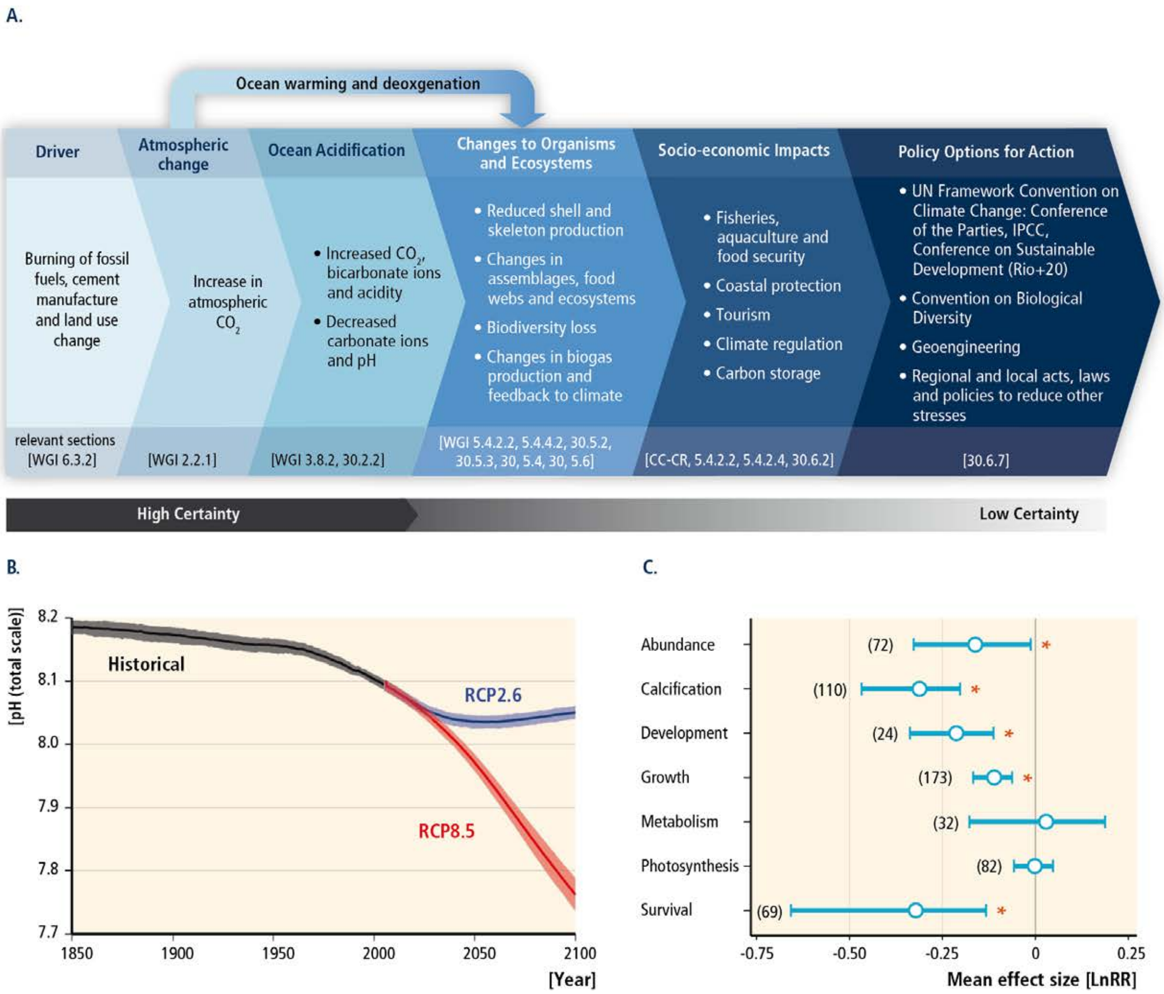

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.

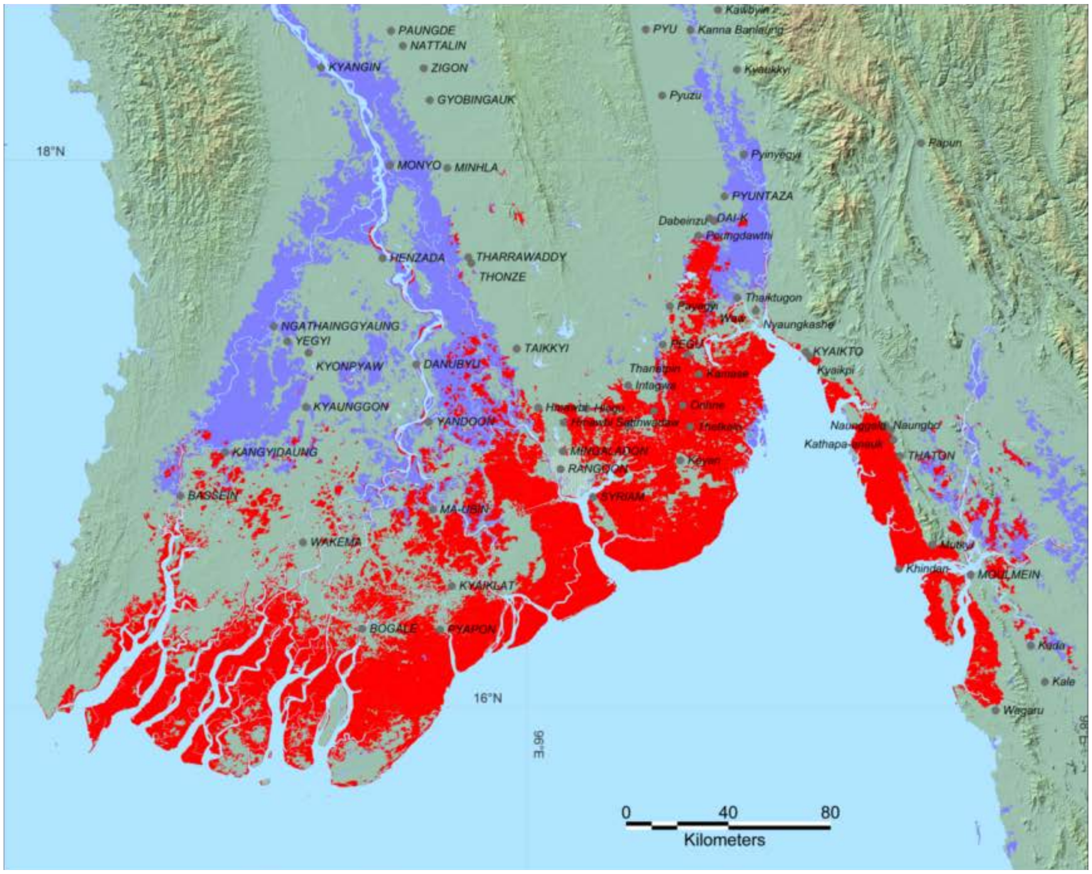

Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. Source: Brakenridge et al., 2013.

Chapter 6. Ocean Systems

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Contents

6.4: What changes in marine ecosystems are likely because of climate change?

Executive Summary

Ocean ecosystems have responded and will continue to respond to climate changes of different rates, magnitudes, and durations (*virtually certain*). Human societies depend on marine ecosystem services, which are sensitive to climate change (*high confidence*), in particular the provisioning of food (fisheries and aquaculture) and other natural resources, nutrient recycling, regulation of global climate (including production of oxygen and removal of atmospheric CO_2), protection from extreme weather and climate events, aesthetic, cultural, and supporting services. [6.3, 6.4, 6.5]

Climate change alters physical, chemical, and biological properties of the ocean (*very high confidence*). Oceanic drivers include salinity, circulation, temperature, carbon dioxide (CO_2), oxygen (O_2), nutrients, and light. These drivers shape the physiological performance of individual cells and organisms and ultimately determine ecosystem composition, spatial structure and functioning. [6.1.1, 6.3]

The fossil record and present field and laboratory observations confirm links between key environmental drivers and responses of ocean ecosystems to climate change (*high confidence*). For millions of years in Earth history, natural climate change at rates slower than today's anthropogenic change has led to significant ecosystem shifts (*high confidence*), including species emergences and extinctions (*high confidence*). Contemporary multidecadal natural climate variations associated with regional transient warming periods by 1°C have led to fundamental restructuring of ecosystems and large socioeconomic implications (*high confidence*). [6.1.2, 6.3.1, 6.4]

Vulnerability of most organisms to warming is set by their physiology which defines their limited temperature ranges and hence their thermal sensitivity (*high confidence*). Temperature defines the geographic distribution of many species and their responses to climate change. Shifting temperature means and extremes alter habitat (e.g., sea ice and coastal), and cause changes in abundance through local extinctions and latitudinal expansions or shifts (*very high confidence*). Vulnerability is greatest in polar animals due to their narrow temperature ranges (*medium confidence*) and in tropical species living close to upper thermal limits (*medium confidence*). Although genetic adaptation occurs (*medium confidence*), the capacity of present-day fauna and flora to compensate for or keep up with the rate of ongoing thermal change is limited (*low confidence*). [6.3.1, 6.3.5, 6.5.2]

The warming-induced shifts in the abundance, geographic distribution, migration patterns, and timing of seasonal activities of species (*very high confidence*) have been and will be paralleled by a reduction in their maximum body size (*medium confidence*). This has resulted and will further result in changing interactions between species, including competition and predator-prey dynamics (*high confidence*). Numerous observations over the last decades in all ocean basins show global-scale changes including large-scale distribution shifts of species (*very high confidence*) and altered ecosystem composition (*high confidence*) on multidecadal time scales, tracking climate trends. The distribution and abundance of many fishes and invertebrates have shifted poleward and/or to deeper, cooler waters (*high confidence*). Poleward displacements of phyto- and zooplankton have occurred by hundreds of km's per decade (*high confidence*). Some warm-water corals and their reefs have responded with species replacement, bleaching and a decreased coral cover causing habitat loss (*high confidence*). While marine reptiles such as turtles encounter direct effects of warming, impacts to seabirds and marine mammals are mostly indirect through effects of warming on their prey (*high confidence*) [6.3.1, 6.3.7, 6.5, CC-CR, CC-MB].

In response to further warming by 1°C or more by the mid 21st century and beyond, ocean-wide changes in ecosystem properties are projected to continue (*high confidence*). Large irreversible shifts in the spatial distribution of species and seasonal timing of their activities (feeding, growth, development, behaviors, and productivity) will have implications for species composition, and ecosystem goods and services. [6.3.1, 6.4, 6.5, 6.6]

By the mid 21st century, the spatial shifts of marine species will cause species richness to increase at mid and high latitudes (*high confidence*) and to decrease at tropical latitudes (*medium confidence*), resulting in global redistribution of catch potential for fishes and invertebrates, with implications for food security (*medium*

***confidence*).** Animal displacements are projected to lead to high-latitude invasions and high local-extinction rates in the tropics and semi-enclosed seas. This will cause a 30–70% increase in the fisheries yield of some high-latitude regions by 2055 (relative to 2005), a redistribution at mid latitudes, but a drop of 40%- 60% in the tropics and the Antarctic, based on 2°C warming above pre-industrial values (*medium confidence* in the direction of trends in fisheries yields, *low confidence* in the magnitude of change). If a decrease in global net primary production (NPP) or a shift towards smaller primary producers occurs, the overall fisheries catch potential may also decrease. [6.3.1-4, 6.4.1, 6.5.1-4]

Open ocean NPP is projected to fall globally depending on RCP scenario (*medium confidence*). The estimated decrease will occur by up to 9% by 2100 under the RCP 8.5 business-as-usual climate scenario (relative to 1990, *low confidence*). The oceans currently provide about half of global net primary production (NPP). Environmental controls on NPP include temperature, CO_2, nutrient supply and light (through cloud cover, mixed layer depth), all of which will be altered (WGI, Ch. 6.3). Present observations indicate increasing NPP at high (Arctic) latitudes (*medium confidence*), projected to continue beyond 2100 (*medium confidence*). This increase is offset by a decrease at temperate and tropical latitudes (*medium confidence*). Poor representation of shelf and coastal regions hamper projections in global NPP models for near-shore waters, reducing confidence in global projections. [6.3.4, 6.5.1, CC-PP]

Large-scale processes and climatic feedbacks sustained by microbes (bacteria, archaea, unicellular algae and protozoans) play key roles in marine ecosystems (e.g., carbon and nitrogen fixation, nutrient recycling) and will be altered by climate change (*medium confidence*). Identifying which microbial species, groups and processes are being affected and how these will be altered is difficult as these organisms and their responses to environmental change are extremely diverse and often modulated by biological interactions or changes in circulation and nutrient supply (*limited evidence* and *low agreement*). Warming will cause species-specific responses, such as enhancing metabolic rates and exceeding thermal tolerances, which will affect abundance, distribution, and community structure. Warmer, CO_2- and nutrient-enriched coastal oceans may stimulate harmful algal blooms (*medium confidence*), and the redistribution of certain microbes causing diseases like cholera (*medium confidence*). [6.3, 6.4.2]

Rising atmospheric CO_2 over the last century and into the future not only causes ocean warming but also changes carbonate chemistry in a process termed ocean acidification (WGI, Chs. 3.8.2, 6.4.4). Impacts of ocean acidification range from changes in organismal physiology and behavior to population dynamics (*medium* to *high confidence*) and will affect marine ecosystems for centuries if emissions continue (*high confidence*). Laboratory and field experiments as well as field observations show a wide range of sensitivities and responses within and across organism phyla (*high confidence*). Most plants and microalgae respond positively to elevated CO_2 levels by increasing photosynthesis and growth (*high confidence*). Within other organism groups, vulnerability decreases with increasing capacity to compensate for elevated internal CO_2 concentration and falling pH (*low* to *medium confidence*). Among vulnerable groups sustaining fisheries, highly calcified corals, mollusks and echinoderms, are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*). Trans-generational or evolutionary adaptation has been shown in some species, reducing impacts of projected scenarios (*low* to *medium confidence*). Limits to adaptive capacity exist but remain largely unexplored. [6.3.2, CC-OA]

Few field observations conducted in the last decade demonstrate biotic responses attributable to anthropogenic ocean acidification, as in many places these responses are not yet outside their natural variability and may be influenced by confounding local or regional factors. Shell thinning in planktonic foraminifera and in Southern Ocean pteropoda has been attributed fully or in part to acidification trends (*medium* to *high confidence*). Coastward shifts in upwelling CO_2-rich waters of the Northeast-Pacific cause larval oyster fatalities in aquacultures (*high confidence*) or shifts from mussels to fleshy algae and barnacles (*medium confidence*), providing an early perspective on future effects of ocean acidification. This supports insight from volcanic CO_2 seeps as natural analogues that macrophytes (seaweeds and seagrasses) will outcompete calcifying organisms. During the next decades ecosystems, including cold- and warm-water coral communities, are at increasing risk of being negatively affected by ocean acidification (OA), especially as OA will be combined with rising temperature extremes (*medium* to *high confidence*, respectively). [6.1.2, 6.3.2, 6.3.5]

The expansion of hypoxic regions termed Oxygen Minimum Zones (OMZs) and anoxic "dead" zones, observed over the last 50 years and projected into the future under climate change, especially if combined with nutrient enrichment (eutrophication), will constrain the habitat of O_2-dependent organisms and benefit anaerobic microbes (*medium confidence*). Hypoxia tolerance varies among species and is influenced by temperature, elevated CO_2, food consumption, and O_2-demand (*high confidence*). Warming-induced stratification limits the exchange of gases between water layers. Enhanced oxygen consumption by heterotrophic organisms depletes the oxygen further, causing a community shift toward lower species richness and hypoxia-tolerant specialists. Under extreme hypoxia ecosystems are dominated by microbes. These OMZs are also characterized by microbial removal of fixed nitrogen (denitrification), which can significantly reduce the low latitude nutrient inventories with implications for regional productivity. [6.3.3, 6.3.5]

The climate-change-induced intensification of ocean upwelling in some eastern boundary systems, as observed in the last decades, may lead to regional cooling rather than warming of surface waters and cause enhanced productivity (*medium confidence*), but also enhanced hypoxia, acidification, and associated biomass reduction in fish and invertebrate stocks. Due to contradictory observations there is currently uncertainty about the future trends of major upwelling systems and how their drivers (enhanced productivity, acidification, and hypoxia) will shape ecosystem characteristics (*low confidence*). [6.1.1, 6.3.2, 6.3.3, 6.3.5-6, CC-UP]

Environmental drivers acting simultaneously on ocean biota* often lead to interactive effects and complex responses (*high confidence*). Interactions of temperature, ocean acidification, and hypoxia narrow thermal ranges and enhance sensitivity to temperature extremes in organisms like corals, coralline algae, mollusks, crustaceans, and fishes (*high confidence*). In primary producers light and individual nutrients can also interact with temperature and acidification. Combined warming and ocean acidification reduce calcification in warm-water corals (*high confidence*). Ocean acidification will alter availability of trace metals (*low confidence*). (*The term biota encompasses the organisms of a region, habitat, or geological period.) [6.3.2.2, 6.3.5, 6.5.2]

The combination and often amplification of global and regional climate change and local anthropogenic drivers result in enhanced vulnerability of natural and human systems (*high confidence*). Major regional and local drivers include fishing, pollution, and eutrophication. [6.3.5, 6.4, 6.5]

The progressive redistribution of species and the reduction in marine biodiversity in sensitive regions and habitats puts the sustained provision of fisheries productivity and other ecosystem services at risk, which will increase due to warming by 1°C or more by 2100 compared to the present (*high confidence*). Human societies respond with limited adaptive capacity. Socio-economic vulnerability is highest in developing tropical countries involving a risk of reduced supplies, income, and employment from marine fisheries (*high confidence*). This emphasizes disparities in food security between developed and underdeveloped nations. [6.4.1, 6.5]

With continuing climate change, local adaptation measures (such as conservation) or a reduction in human activities (such as fishing), may not sufficiently offset global-scale effects on marine ecosystems (*high confidence*). Effects of climate change will thus complicate management regimes such as of marine protected areas once species undergo distributional shifts. This increases the vulnerabilities of marine ecosystems and fisheries. [6.4.2.1]

Geoengineering approaches involving manipulation of the ocean to ameliorate climate change (such as nutrient fertilization, binding of CO_2 by enhanced alkalinity, or direct CO_2 injection into the deep ocean) have very large environmental and associated socioeconomic consequences (*high confidence*). Some actually require purposeful alteration of ocean ecosystems for implementation. Alternative methods focusing on solar radiation management (SRM) leave ocean acidification largely unabated as they cannot mitigate CO_2 emissions. [6.4.2]

6.1. Introduction: Point of Departure, Observations, and Projections

The oceans cover about 71% of Earth's surface to an average depth of 3,700 m. Their importance for life on Earth, including humans, is vast (FAQ 6.1). Marine habitats display natural variability on various spatial and temporal scales but a dearth of long-term observational data from the vast open oceans limits our understanding of the causes and ecological consequences of this variability. The available information indicates that climate controls ocean temperatures, chemistry, circulation, upper ocean stratification, nutrient supply, and sunlight exposure. These drivers affect marine ecosystems through direct effects on organisms, amplified by their changing interactions with other species. Food webs are modified by changes in phytoplankton growth and the availability of live organisms or their decomposing bodies, i.e. debris or dissolved organic matter, as food to (chemo-) heterotrophs (organisms gaining energy by feeding on organic matter). Organismal responses lead to changes in biogeochemical processes, such as the carbon cycle, and in biological diversity and the services the oceans provide.

Some impacts of climate change on marine ecosystems and their services were addressed in the 4th IPCC assessment report (AR4), WGII, chapters 4-6 (ecosystems, food, coastal areas), and regional chapters, e.g., 15 (polar regions) and 16 (small islands). The ecosystem assessment in chapter 4 focused on terrestrial, coastal, and marine systems, their properties, goods, and services. It emphasized the difficulty in assessing future ecosystem responses as a result of ecosystem complexity, different vulnerabilities of species, and ecosystem-specific, critical thresholds associated with non-linear responses to environmental change. Focusing on terrestrial ecosystems, Ch. 4 concluded that more than 2-3°C warming above pre-industrial levels causes high extinction risks to 20 to 30% of present-day species (*medium confidence*), paralleled by substantial changes in ecosystem structure and functioning (*high confidence*). Authors projected that a wide range of planktonic and benthic calcifiers will be impacted by ocean warming (*very high confidence*) and acidification (*medium confidence*), particularly in the Southern Ocean. They characterized sea ice and coral reef biomes as highly vulnerable. Key uncertainties identified in AR4 were the incomplete knowledge of ocean acidification (addressed in present chapter 6.3.2), synergistic effects and their mechanisms (6.3.5), biotic feedbacks to the climate system (6.4), and the impacts of interactions between climate change, human uses, and ecosystem management (6.4.2).

Much more than in previous IPCC reports (Figure 1-2), impacts on the oceans are a focus in AR5. This allows for a more comprehensive discussion of phenomena and impacts, as well as the associated uncertainties and the levels of confidence in observed and projected changes. The present chapter focuses on the general principles and processes characterizing climate change impacts on ocean systems and on the uses of these systems by human societies. For projections of responses to climate change, the chapter also assesses our understanding of underlying functional mechanisms causing change across all levels of biological organization, from molecules to organisms to ecosystems. As the ocean is a heterogeneous environment, the comparison of major ocean regions is required to understand variability and differences in key processes and carbon inventories (Box CC-PP, Figure 1). We discuss the changes and variability in the ocean's principal physical and chemical properties and assess knowledge drawn from paleo- and historical to present observations. We develop a conceptual framework for analyzing effects on organisms and ecosystems and assess present knowledge derived from experiments, field studies, and numerical model projections mostly using Representative Concentration Pathways (RCP) of climate change scenarios to provide trajectories of climate change drivers (Moss *et al*., 2010). Finally, we assess the implications of such changes for ecosystem services, and identify plausible socioeconomic consequences.

Assessing climate change impacts on coastal systems is the topic of chapter 5. An integrative treatment of regional climate changes and impacts in seven key ocean regions is the focus of regional chapter 30. Marine issues are also included in regional chapters 22 to 29, with a focus on polar oceans (Ch. 28) and small island nations (Ch. 29). Topics important to several chapters, such as ocean acidification, upwelling systems, primary productivity, changes in biogeography, and coral reefs, are discussed in joint assessments presented in the respective cross chapter boxes.

6.1.1. Changes in Physical and Chemical Variables

Trends in ocean conditions over the last 60 years reflect significant human impacts beyond natural variability on temperature, salinity, dissolved inorganic carbon and oxygen content, pH, and other properties of the upper ocean (e.g., Pierce *et al*., 2012; Sen Gupta and McNeil, 2012; WGI, Ch. 3.8., WGI, Table 10.1). With climate change, marine ecosystems are and will be exposed to rising temperature, ocean acidification, expansion of hypoxic zones, and other environmental drivers changing concomitantly.

6.1.1.1. Temperature and Salinity

Over the last 39 years, oceans have warmed at average rates of >0.1 °C per decade in the upper 75 m and 0.015 °C/ decade at 700 m depth (WGI, Ch. 3.2.2, Figure 3.1). Trends differ regionally, seasonally, and interannually (WGI, Ch. 2.7, for ocean regions see 30.5). Temperature changes are particularly large at ENSO (El Nino-Southern Oscillation) with high (3 to 4 year) and low (5 to 7 year) frequencies, and on multidecadal scales (>25 years, Figure 6-1). The strongest warming trends are found at high latitudes where most of the interdecadal variability occurs, while tropical oceans are dominated by interannual frequencies. Global climate models have explored changes in different frequency domains, but their spatial resolution is poor (WGI, Ch. 11.3.3, WGI, Ch. 12.4.7).

Temperature variations are often accompanied by changes in salinity. Increased salinity results from reduced precipitation relative to evaporation, e.g., above the thermoclines (layer separating the upper mixed layer from deeper water where temperature and density change rapidly with depth) of subtropical gyres at mid to low latitudes since 1950 (WGI, Ch. 3). Decreased salinity due to enhanced precipitation relative to evaporation has occurred at some tropical and higher latitudes, exacerbated by sea-ice melt (Durack *et al*., 2012). Both warming and freshening cause enhanced density stratification, a trend projected to continue into the 21^{st} century (WGI, Figure 12.34; Helm *et al*., 2010; WGI, Ch. 3, Ch. 11.3.3). Mean sea surface temperature in 2090 will be by 2.7°C warmer than in 1990 (RCP8.5, WGI, Ch.12, Bopp *et al*., 2013).

[INSERT FIGURE 6-1 HERE
Figure 6-1: Sea surface temperature variability between 1911 and 2011. The top left map shows the sea surface temperature average for the period. The top right map illustrates the temperature range calculated as the difference between the maximum and minimum values for each grid component during the century. The spatial distribution of variability by time scales (left hand map series, based on the Extended Reynolds Sea Surface Temperature, NOAA, 2012) corresponds to the multidecadal (25 to 40 years), bidecadal (15 to 25 years), decadal (8 to 15 years), low ENSO (El Niño Southern Oscillation) frequency (5 to 8 years), high ENSO frequency (3 to 5 years), and very high frequency (2 to 3 years) scales. The summed variabilities from the same 2°x2° box in all six maps corresponds to 100% of the time series variability. The areas of the right hand bubbles show the spectral density of some of the most widely used climate indices, accumulated in the same frequency windows: the Global Average Temperature and SST (sea surface temperature) Anomalies (GSST), the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO), the Multidecadal Atlantic Oscillation (AMO), and the Pacific Decadal Oscillation (PDO). The sum of bubble surface areas for each vertical column (each climate index) corresponds to 100% of the time series variability between the 2 and 40 year periods. Climate indices where obtained from the NOAA ESRL Physical Sciences Division website.]

6.1.1.2. CO_2-Induced Acidification

Rising carbon dioxide (CO_2) concentrations in air (given as partial pressures, pCO_2, in µatm) cause increasing upper ocean CO_2 levels (Watson *et al*., 2009). Starting from a pre-industrial value of 280 µatm atmospheric pCO_2 levels will have reached around 500 µatm by 2050 under SRES scenarios (IPCC, 2000) and all RCPs (Moss *et al.*, 2010; Meinshausen *et al*., 2011). By 2100 values are projected to reach between 420 µatm and 940 µatm depending on the RCP. The rise in pCO_2 causes ocean acidification (OA), measured as a decline in water pH (negative log of proton concentration), accompanied by a fall in both carbonate ion (CO_3^{2-}) concentration and the saturation states (Ω) of various calcium carbonates ($CaCO_3$; Zeebe and Westbroek, 2003; WGI Ch. 3.8.2, Box 3.2, Ch. 6, Figure 6.29). Hence, the seawater solubilities of three forms of calcium carbonate, namely calcite, Magnesium-calcite, and aragonite, increase. These minerals are important components of shells and skeletons of many marine organisms (6.3.2).

Ocean acidification occurs on a background of natural temporal and spatial variability of pH, pCO_2, and Ω. In the open ocean, the mean pH (total scale, pH_T) of surface waters presently ranges between 7.8 and 8.4 (WGI Ch. 3.8.2). In stratified mid-water layers, largely isolated from gas exchange between surface waters and air, decomposition of organic material leads to lowered oxygen (O_2) and elevated CO_2 levels (Paulmier *et al*., 2011) associated with lower pH values. The few existing field data of sufficient duration, resolution, and accuracy (WGI Figure 3.18) show that trends in anthropogenic OA clearly deviate from the envelope of natural variability (Friedrich *et al*., 2012). OA presently ranges between -0.0013 and -0.0024 pH_T units per year (WGI, Ch. 3.8.2, Table 3.2, Box 3.2; Dore *et al.*, 2009). Average surface ocean pH has decreased by more than 0.1 units below the pre-industrial average of 8.17. By 2100 pH is expected to change by -0.13, -0.22, -0.28, -0.42 pH_T units, at CO_2 levels of 421, 538, 670, and 936 ppm under RCP 2.6, 4.5, 6.0 and 8.5 climate scenarios, respectively (WGI, Figure 6.28). The rate of acidification in surface waters varies regionally and is 50% higher in the northern North Atlantic than in the subtropical Atlantic (Olafsson, 2009). Salinity reduction caused by ice melt or excess precipitation (Jacobs and Giulivi, 2010; Vélez-Belchí *et al*., 2010) exacerbates OA by diluting the concentrations of substances acting as buffers (Steinacher *et al*., 2009; Denman *et al*., 2011). At high sustained CO_2 concentrations the changes in ocean chemistry will take thousands of years to be buffered by the natural dissolution of calcium carbonate from sediments and tens to hundreds of thousands of years to be eliminated completely by the weathering of rocks on land (Archer *et al.*, 2009).

6.1.1.3. Hypoxia

The average dissolved oxygen concentration in the ocean is presently 162 µmol kg^{-1} (Sarmiento and Gruber, 2006). Concentrations range from over 500 µmoles kg^{-1} in productive Antarctic waters super-saturated with oxygen (Carrillo *et al.*, 2004) to zero in coastal sediments and in permanently anoxic deep layers of isolated water bodies, such as the Black Sea and the Cariaco Basin. Hypoxia results from oxygen depletion in excess of supply as in stratified water bodies (6.1.1.2). Vast oxygen minimum zones (OMZ) exist between less than 100 and more than 900 m depths in Eastern Atlantic and Pacific tropical oceans. The ecological literature applies the term hypoxia (see 6.3.3) to O_2 concentrations below 60 µmoles kg^{-1} (estimated at ~5 % of global ocean volume; Deutsch *et al*., 2011). Pacific OMZs regularly reach oxygen levels below 20 µmoles kg^{-1} (about 0.8% of global ocean volume; Paulmier and Ruiz-Pino, 2009), lower than Atlantic ones. Suboxic waters at < 4.5 µmoles O_2 kg^{-1} occupy about 0.03 % of the ocean volume, mainly in the northeastern tropical Pacific (Karstensen *et al*., 2008).

OMZs are naturally present in many habitats including marine sediments, but are also expanding due to anthropogenic influences. Over the past 50 years, open ocean O_2 concentrations have decreased by a mean rate of 0.1 to over 0.3 µmoles kg^{-1} $year^{-1}$ (WGI, Ch. 3.8.3, Stramma *et al*., 2008). In some OMZs the rate has been much higher due to warming, increased stratification, and rising biological O_2 demand (WGI, Box 6.5, Figure 1). Long-term declines in O_2 by about 7 µmoles kg^{-1} $decade^{-1}$ have been documented at mid-water depths over much of the subarctic North Pacific (Keeling *et al*., 2010). In coastal regions, extremely hypoxic 'dead zones' that exclude animal life, have increased from 42 reported in the 1960s to over 400 in 2008 and been attributed to high oxygen demand from eutrophication, the local enrichment of nutrients, resulting in organic matter loading and its decay as well as nitrous oxide formation and release (Naqvi *et al*., 2000; Díaz and Rosenberg, 2008; Zhang *et al*., 2010).

Future warming will *likely* accelerate the spread of hypoxic zones, especially in temperate to subpolar regions. Most models project decreasing global ocean oxygen contents by 1 to 7 % from present-day concentrations in 2100 (Keeling *et al.*, 2010; WGI Figure 6.30 under RCP 8.5), with a mean decline by 3.4 % in 2090 compared to the 1990s (Bopp *et al*., 2013). Warming and freshening of the surface layer will increase stratification and reduce the depth of winter mixing. The evolution of low O_2 zones will be linked to changes in fluvial runoffs (e.g. Milly *et al.*, 2008; 5.3.4.3), the wind regime (e.g., Vecchi and Soden, 2007), as well as the intensity, duration and seasonal timing of upwelling events (Snyder *et al.*, 2003, 30.5.2). The potential contributions of destabilized methane hydrates and bacterial methane oxidation to exacerbate hypoxia and acidification at high latitudes remain to be explored (Westbrook *et al*., 2009). Currently, there is no consensus on the future volumes of hypoxic and suboxic waters because of large uncertainties in potential biogeochemical effects and in the evolution of tropical ocean dynamics due to both natural and anthropogenic causes (WGI, Ch. 6). While volumes with O_2 concentrations below 80 µmoles kg^{-1} are projected to increase by several %, suboxic waters <5 µmoles O_2 kg^{-1} may undergo a 30 % increase by 2100 compared to 2005 (*low confidence*, Bopp *et al*., 2013).

6.1.1.4. Light and Nutrients

Most models project that the mixed layer at the ocean surface (see Figure 6-2) will become shallower in the coming decades through a strengthening of the vertical density gradient (e.g. Sarmiento *et al.*, 1998; Sallée *et al*., 2013). Mean light levels encountered by phytoplankton are set by incoming light from solar radiation, the depth of the mixed layer, and the degree to which underwater light is attenuated by living and non-living particles (Kirk, 1994). A shallower mixed layer will *likely* result in the resident phytoplankton receiving higher mean underwater light levels if the organisms are physically mixed through this stratum (Figure 6-2).

Enhanced, seasonally prolonged stratification (Holt *et al*., 2010), especially in the tropics, the North Atlantic, the Northeast Pacific, and the Arctic (Capotondi *et al*., 2012), will lead to decreased vertical transport of nutrients to surface waters (Doney, 2010; Figure 6-2). River plumes (Signorini *et al*., 1999), nutrient accumulation in the pycnocline as reported for North Pacific waters (Whitney, 2011), human-induced eutrophication, enhanced upwelling (Box CC-UP), and tidal mixing and estuarine circulation in coastal oceans could partly compensate for the projected reduction in nutrient supply in the oceans (*limited evidence, medium agreement*).

[INSERT FIGURE 6-2 HERE
Figure 6-2: Projected alteration (magnitude and frequency) of oceanic fluxes and atmospheric events due to a changing climate in the coming decades. Ocean properties will be altered from the sunlit surface layer to the mid-water stratum. In the surface ocean, the depth of the mixed layer (solid horizontal line) will shallow resulting in higher mean light levels. Increased density stratification (i.e., a strengthening sea water density gradient represented by the increasing thickness of the solid horizontal line) will reduce the vertical supply of nutrients for photosynthesizing organisms residing in the mixed layer. Anthropogenic CO_2 will acidify, i.e., lower the pH of the surface ocean (note this happens in a pH range higher than 7 such that oceans will remain alkaline but less so due to acidification). The penetration of acidified waters to depth will result in a shallower depth (dashed horizontal line) at which calcium carbonate structures, such as shells, dissolve. At depth, the location of low oxygen waters will progressively become shallower. In addition, changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean biota and hence ecosystems (courtesy of Reusch and Boyd, 2013).]

6.1.2. Historical and Paleo-Records

6.1.2.1. Historical Observations

Ocean ecosystems are variable in time and space, and in a non-steady-state, reflected in indices such as the North Atlantic Oscillation Index (NAO), the Atlantic Multidecadal Oscillation (AMO), the Arctic Climate Regime Index (ACRI), Pacific Decadal Oscillation (PDO), or the El Niño-Southern Oscillation (ENSO) (WGI, Box 2.5; Figure 6-1, 30.5). The combination of large, global data sets such as Reynolds, NCAR (National Center for Atmospheric Research), ICOADS (International Comprehensive Ocean-Atmosphere Data Set), with multidecadal time-series, for example near Hawaii (HOT), Bermuda (BATS), the Ligurian Sea (DYFAMED), the Canaries (ESTOC), Kerguelen Island (KERFIX), Hokkaido Island (KNOT), and Taiwan (SEATS) has provided data on the physical and biogeochemical state of the oceans (Karl *et al*., 2003). These have been augmented by the limited-term, high resolution programs World Ocean Circulation Experiment (WOCE) and Joint Global Ocean Flux Study (JGOFS).

Historical data sets provide baseline information on ecosystem states and document the responses of biota to both, natural variability in the ocean system and surface ocean warming since the 1970s (Figure 6-3; 6.3.1). Such datasets are rare and regionally biased. Examples include changes in geographic ranges of plankton and seasonal timing (phenology) of different components of the ecosystem detected by the Continuous Plankton Recorder (CPR: e.g., Edwards *et al.*, 2001; Richardson *et al.*, 2006; Box 6-1) or multidecadal shifts in pelagic ecosystems (CalCOFI) including higher parts of the food chain such as sardines and anchovies (Brinton and Townsend, 2003; Lavaniegos and Ohman, 2003; Chavez *et al.*, 2003, 6.3.1) and the skeletal archives of long-lived organisms such as coralline algae (Halfar *et al*., 2011), bivalves (Schöne *et al*., 2003), and corals (De'ath *et al*., 2009).

Systematic, long-term interdisciplinary observations using repeated, highly calibrated measurements at a given field site are required to capture high- and low-frequency events, e.g., regime shifts (abrupt changes between contrasting, persistent states of any complex system, deYoung *et al*., 2008). Direct observations are complemented by satellite remotely-sensed datasets. Ocean color data (e.g. Coastal Zone Color Scanner [1978-1986], SeaWiFS [1997-2010], and MODIS-AQUA [2002-present], McClain, 2009) provide estimates of chlorophyll concentrations (a proxy for phytoplankton stocks and Net Primary Production, NPP, 6.2.1, 6.3.4; Saba *et al*., 2011). Total chlorophyll cannot be measured from space; therefore, the near-surface value (approximately one optical depth) is extrapolated to whole water-column chlorophyll based on vertical distribution using region-specific algorithms. Large uncertainties persist, as these estimates reflect both phytoplankton stocks and their physiological status (Dierssen, 2010; Behrenfeld, 2011). The ~15 year archived time series of SeaWiFS is too short to reveal trends over time and there causes. It is an example for the general issue that undersampling of ocean phenomena in time and space limits our current ability to assess present states, to distinguish effects of anthropogenic change from natural variability and to project future changes (Henson *et al*., 2010; Beaulieu *et al*., 2013; Box CC-PP).

6.1.2.2. Paleontological Records

Paleontological records in marine sediments provide long-term, low-resolution data on the spatial distributions of organisms and their abundances from all ages and latitudes. This information can be readily related to the concurrent shifts in multiple environmental properties that are also recorded in these sediments. The records provide insights into shifts, expansions and contractions of biogeographic ranges, species extinctions and emergences, and changes in species abundance, as well as the environmental forcings to which organisms respond. Temporal trends reveal influences of temperature, hypoxia, CO_2, and food availability on organisms and ecosystems (6.1.1, Figure 6-3).

Due to insufficient resolution the geological record often does not allow the direct attribution of a biological change to a single driver or the identification of various drivers and their relative importance. Support for projections of future changes in present-day ecosystems and their services is thus limited (6.4, 6.5, *low confidence*). Nonetheless, information gained from the geological record is invaluable as both paleo and present climatic shifts share the same combination and sign of environmental changes: increasing atmospheric CO_2 causing warming and CO_2 enrichment in the surface ocean, leading to enhanced stratification of the upper ocean and a decrease in dissolved O_2 (WGI, Chs 3, 5.3). A combination of models (WGI, Chs 3, 6, 12) and geological data can be used to forecast future impacts on ocean biota (*medium confidence)*.

[INSERT FIGURE 6-3 HERE
Figure 6-3: Environmental changes (bottom) and associated biological responses (top) for the Paleocene Eocene Thermal Maximum (PETM, left) and the industrial era (right). The PETM represents the best geological analogue for the future ocean in terms of biological responses. Episodes of largest environmental change are indicated with yellow bars. Note the different time scale between the two columns. Both time intervals are characterized by rapid warming both on land and in the ocean and increases in CO_2. Atmospheric CO_2 and temperature are described with direct measurements (black), proxy reconstructions (grey) and model results (light grey). For the recent anthropocenic record, the AMO is shown to highlight high frequency natural temperature fluctuations (Enfield *et al.*, 2001) and their influence on marine biota. Biological responses to the environmental forcing are divided into calcification, extinction and migration. Note the highly group-specific responses to the environmental change, especially with regards to calcification with decreases, increases and high variability. While there was extinction during the PETM, there is currently no evidence for climate-related extinction in the marine record. The warming led to migration of warm water species into previous cold water habitats indicating range expansion due to warming (modern: planktic foraminifera, *G. ruber* Field *et al.*, 2006; PETM: coccolithophores, *Discoaster* spp. Bralower, 2002). CO_2 data: Mauna Loa (Keeling *et al.*, 2005), ice core records (Etheridge et al. 1996) and model output for the PETM (Zeebe *et al*., 2009; Ridgwell and Schmidt, 2010). Sea surface temperatures modern: Wilson *et al.*, 2006 and PETM: Kennett and Stott, 1991. Biotic responses: growth changes in coralline algae (Halfar *et al.*, 2011, bottom)

and corals (Vásquez-Bedoya *et al.*, 2012, middle, De'ath *et al.*, 2009 [corrigendum], top); calcification changes (Foster *et al*., 2013) and extinction in benthic foraminifers (Thomas, 2003) for the PETM.]

The last glacial-interglacial transition is associated with an average increase in atmospheric CO_2 of ~1 µatm/century between 18 and 10 thousand years before present (kyr BP) (WGI Ch. 5), a significantly slower increase than the ~90 µatm in the last century (WGI Chs. 5, 6). Consequently, the average pH change of 0.002 pH units per century during the glacial-interglacial transition is small relative to the ongoing anthropogenic perturbation of >0.1 pH unit per century (WGI, Ch. 3.8.2). Overall the upper glacial ocean was more O_2 rich than today's ocean (Jaccard and Galbraith, 2012) and between 0.7 and 2.7°C colder, with strong regional differences of up to 10°C cooling in the North Atlantic and 2-6°C in the Southern Ocean (WGI Ch. 5, Table 5.2). During warming from the glacial into the interglacial marine plankton such as foraminifera, coccolithophores, diatoms, dinoflagellates, and radiolarians showed marked poleward range expansion (*high confidence*, see WGI, Ch. 5.7; CLIMAP Project Members, 1976; MARGO Project Members, 2009). Under the lower glacial CO_2 concentrations, calcification in planktonic foraminifera was higher (*limited evidence, medium agreement)*.

The most prominent abrupt climate change periods in the recent geological record, developing within 10-100 years, are associated with Dansgaard-Oeschger (DO) and Heinrich events (WGI, Ch. 5.7), which occurred repetitively during the last 120 kyrs. While the atmospheric changes happened within a few decades, the sea surface temperature in the North Atlantic changed by up to 5°C within decades to centuries (WGI, Ch. 5.7). Southern Ocean temperature changes were slower (hundreds to thousands of years, Barker *et al*., 2009). The cold phase of a DO event led to the migration of polar foraminiferal species towards the equator, in the North Atlantic as far south as the Iberian Peninsula (Martrat *et al*., 2004). Abrupt (~100 year) abundance changes in the Southern Ocean were associated with latitudinal shifts in the Antarctic Circumpolar Current and associated species (Barker *et al*., 2009) akin to modern changes in plankton range due to warming (Box CC-MB, Box 6-1). During the DO warm phases the Monsoon-driven Arabian Sea upwelling records show enhanced primary and export production, reduced oxygenation, and denitrification, all within ~200 years (Higginson *et al*., 2004).

The last time the atmospheric CO_2 content approached that of today was during the Pliocene warm period (3.3 to 3.0 Ma, i.e., million years ago), with long periods of atmospheric CO_2 levels between 330-400 µatm (Pagani *et al.*, 2010; Seki *et al.*, 2010) and equlibrated temperatures ~2°C warmer than today (Haywood *et al.*, 2009, WGI Ch. 5) (*medium confidence*). The Mid-Pliocene Warm Period saw a poleward expansion of tropical planktonic foraminifera (Dowsett, 2007) (*high confidence*). Coccolithophores (Bown *et al.*, 2004), corals (Jackson and Johnson, 2000) or mollusks (Vermeij and Petuch, 1986) remained unaffected with respect to rates of species extinction or emergences compared to background rates.

Perhaps the best analogue for the future ocean is the Paleocene-Eocene Thermal Maximum (PETM, 55.3 Ma). The PETM was an event of warming (Dunkley Jones *et al*., 2013), and ocean acidification (Zachos *et al*., 2005) over millennia (Stassen *et al*., 2012; Cui *et al*., 2011) with increased runoff and nutrients into the shelf ecosystems. Model simulations for the PETM show 10 times lower rates of CO_2 input and hence ocean acidification compared to today (Ridgwell and Schmidt, 2010) (*medium confidence*). Depending on the assumed rate and magnitude of the CO_2 release, models project pH declined by 0.25 to 0.45 units in PETM surface waters and a reduction in surface ocean aragonite saturation from Ω=3 to Ω=2 or even as low as 1.5 (Ridgwell and Schmidt, 2010). Warming caused range expansions of warm-water taxa towards higher latitudes (*high confidence)*. The composition of plankton assemblages changed both within and between phytoplankton groups (Gibbs *et al.*, 2006; Sluijs and Brinkhuis, 2009), possibly reflecting the warming trend and/or changes in nutrient availability (6.2.2.-3). There was no bias in extinction towards more heavily calcifying species, possibly as slow CO_2 input led to minor surface water acidification. By contrast, benthic foraminifera, the dominant deep water eukaryote, recorded up to 50% extinction (Thomas, 2007). In contrast to sediment dwellers, more mobile pelagic crustaceans (ostracods) did not show any significant change in species composition (Webb *et al.*, 2009). In shallow coastal waters, calcareous algae and corals were replaced by symbiont-bearing benthic foraminifera (Scheibner and Speijer, 2008) (*medium confidence*).

The warm climates of the Mesozoic (251 to 65 Ma) led to a number of anoxic events in the oceans (Jenkyns, 2010). In some cases, OMZs expanded vertically leading to anoxia in upper water layers (Pancost *et al.*, 2004). Some of the Cretaceous oceanic anoxic events were associated with extinctions or increased species turnover (normalized sum of originations and extinctions) of planktonic foraminifera and radiolarians (30%). Such turnover was very small in other groups of organisms, (e.g., a maximum of 7% of coccolithophores, Leckie *et al.*, 2002). The attribution of these evolutionary changes to reduced O_2 is tenuous as warming, changes in nutrient supply and, possibly, ocean acidification occurred concomitantly (Hönisch *et al*., 2012).

Global-scale collapse of marine ecosystems is rare, even in the geological record. Some mass extinctions, in particular the Permian Period extinction 251 Ma ago, have been associated with large-scale inputs of carbon into the atmosphere and ocean, with associated warming and deep-sea O_2 decline (Knoll *et al.*, 2007; Kiessling and Simpson, 2011). The end-Permian mass extinction preferentially affected reef organisms such as corals and sponges resulting in a 4 Myr period without reef builders (Kiessling and Simpson, 2011), and underscores that vulnerabilities differ among organisms depending on anatomy, physiology, and ecology (Knoll and Fischer, 2011). The rates of environmental change and any potential acidification have not yet been accurately constrained for these events.

Of the last 100 Myr, only the last 2 Myr had CO_2 levels of ~190 to 280 ppm, comparable to preindustrial values. Values like those predicted by the mid and end of this century can solely be found in the geological record older than 33 Ma, with large uncertainties in the absolute numbers (WGI, Ch. 5.3; Hönisch *et al*., 2012). That marine biota thrived throughout high CO_2 times cannot imply that marine organisms will remain unaffected in a future warm, high-CO_2 world. The key environmental issue of the 21st century is one of an unprecedented rate of change, not simply magnitude, of CO_2 levels (Hönisch *et al*., 2012). The current rate and magnitude of ocean acidification are at least 10 times faster than any event within the last 65 Ma (*high confidence*, Ridgwell and Schmidt, 2010) or even 300 Ma of Earth history (*medium confidence*, Hönisch *et al*., 2012). The slower events in geological history provide *robust evidence* (*high agreement*) for environmentally-mediated changes in biogeographic ranges of fauna and flora, their compositional changes, extinctions, and, to much lesser degree, emergences (*very high confidence*). No past climate change event perfectly parallels future projections of anthropogenic climate change, which is unprecedented in evolutionary history. Existing similarities indicate, however, that future challenges (6.1.1, 6.3.1-8) may be outside the adaptive capacity of many organisms living in today's oceans (*low to medium confidence*).

6.2. Diversity of Ocean Ecosystems and their Sensitivities to Climate Change

Global-scale observation and modeling studies provide *robust evidence* of present and future climate-mediated alterations of the ocean environment (*high agreement*, 6.1.1, WGI, Chs. 3, 6; Bopp *et al*., 2013), which in turn impact ocean ecosystems (*high confidence*; Boyd and Doney, 2002; Hoegh-Guldberg and Bruno, 2010; Drinkwater *et al*., 2010). An assessment of present findings and projections requires knowledge of the characteristics of ocean biota and ecosystems and their climate sensitivity.

Life on Earth is diverse as a result of nearly 4 billion years of evolutionary history. Marine microorganisms are the oldest forms of life and the most functionally diverse; multicellular organisms are constrained to limited functional abilities. Knowledge of overarching similarities across the organism domains Archaea, Bacteria, and Eukarya (Woese *et al*., 1990) or kingdoms Bacteria, Protozoa, Fungi, Plantae, Animalia, and Chromista (Cavalier-Smith, 2004) would facilitate projections of climate impacts. The phylogenetic and metabolic diversity of microbes (i.e., viruses, archaea, bacteria, protists and microalgae) sustains key ecosystem processes such as primary production, CO_2 fixation and O_2 production, the conversion of nitrogen into ammonia (N_2 fixation), and the use of nitrate, sulphate, CO_2, and metals (Fe and Mn) in metabolism instead of O_2 when it is absent. Microbes enhance the horizontal transfer of genetic information between unrelated individuals, thereby enhancing biodiversity (McDaniel *et al*., 2010). Microbes may respond to climate change by exploiting their large diversity, undergoing species replacements (Karl *et al*., 2001), and thereby sustain their biogeochemical roles. Species replacements also occur among plants and animals, but in most cases research has focused on their resilience, well-being, abundance, survival, and conservation under climate change (FAQ 6.2).

6.2.1. Pelagic Biomes and Ecosystems

Pelagic organisms are key to biogeochemical processes in the ocean. The base of the marine food web is the photosynthetic fixation of CO_2 by phytoplankton, a process termed (net) primary production (NPP, Box CC-PP). Photosynthesis is controlled by light, temperature, inorganic nutrients (CO_2, nitrate, phosphate, silicate, and trace elements including iron), and the density-dependent stability of the surface mixed-layer depth (MLD) (6.1.1; Figure 6-2; Sverdrup, 1953; González-Taboada and Anadón, 2012). Environmental variability and the displacement of organisms by ocean currents cause variability in phytoplankton productivity, competitiveness, and natural selection (Margalef, 1978) and result in changes in carbon sequestration (Box CC-PP, Figure 6-4). Nutrient limitation leads to a decrease in NPP or chlorophyll levels and a reduction in the amount of energy supplied to higher trophic levels, including fish and invertebrates (*high confidence*, Ware and Thomson, 2005; Brander, 2007), affecting fishery yields (Cheung *et al*., 2008; Friedland *et al*., 2012). The wide range of trophic structures in marine food webs and the potentially non-linear changes in energy transfer under different NPP and temperature scenarios (Stock and Dunne, 2010) hamper accurate projections of changes in higher trophic levels.

[INSERT FIGURE 6-4 HERE
Figure 6-4: A schematic representation of the ocean's biological pump, which will be influenced by climate change and is a conduit for carbon sequestration. It is difficult to project how the pump might be altered (Table 6-1) and whether it would represent a positive or negative feedback to climate change through the cumulative effects of affected processes, surface to depth (Table 6-1): shifts in Net Primary Production, floristic and faunistic community composition in the pelagic realm, and in grazing rates; alterations to the ballasting of settling particles and the proportion of NPP released as DOM (Dissolved Organic Matter); modified bacterial enzymatic rates and particle solubilization; faunistic shifts at depth. Modified from Buesseler *et al.* (2008) by J. Cook (WHOI).]

[INSERT TABLE 6-1 HERE
Table 6-1: To assess how a changing climate will alter the ocean's biological pump (Figure 6-4) and determine the resulting biogeochemical feedbacks on global climate, changes in a wide range of processes from cellular to ocean basin scale, and from epipelagic to mesopelagic, must be quantified. This table illustrates the complexity of the integrated knowledge platform needed to provide evidence of these biogeochemical ramifications and thus the present limits to clear conclusions about climate-induced effects on the biological pump (C, Carbon; TEP, Transparent Exopolymer Particle; DOM, Dissolved Organic Matter; POM, Particulate Organic Matter).]

6.2.2. Benthic Habitats and Ecosystems

The ocean's primary production is inextricably linked with benthic (sea floor) communities via the biological pump (Figure 6-4), the chemical exchange of nutrients and gases, and the existence of organisms with both pelagic and benthic life history stages. Even in abyssal habitats, a continuous rain of organic detritus serves as the primary source of carbon and energy. Therefore climate impacts on surface marine ecosystems will impact even the deepest benthic communities, even if direct changes to their physical habitat do not occur (Smith *et al.*, 2009).

Benthic organisms living in shallow waters or the intertidal zone (where they encounter temporary exposure to air) are exposed to widely fluctuating and progressively changing means and extremes of environmental variables, such as temperature, oxygen, CO_2, salinity, and sea level (WGI, Chs. 3, 13; 6.3.1-3, 6.3.5). Sessile or slow moving plants and animals may be unable to escape from unfavorable changes except by means of advection of fertilized eggs or planktonic larvae. If climate change harms those species engineering benthic habitats, the entire ecosystem may be impacted. This concerns those ecosystem engineers, which form habitat from the structures they produce (e.g., corals forming skeletons, 6.3.1) and those forming habitat through their behaviour (e.g., worms reworking and irrigating sediment in a process termed bioturbation). Effects on both types of ecosystem engineers (6.3.1 to 8) influence the regeneration of nutrients and affect benthic-pelagic coupling.

6.3. Climate Change Impacts from Organism to Ecosystem

Understanding climate-induced alterations in the functioning of individual organisms, species populations, communities (assemblages of various species) and ecosystems builds on studies in the laboratory, in micro- and mesocosms (closed small- to medium-sized experimental systems approximating natural conditions, holding selected biological communities), and of biota or communities in the field as well as modeling. These data inform us which taxonomic groups in what regions are more susceptible to climate change (Boyd *et al.*, 2011). Empirical studies of marine organism and ecosystem sensitivities have begun identifying the mechanisms and processes linking climate to ecosystem changes (Drinkwater *et al.*, 2010; Ottersen *et al.*, 2010). Changes in ecological community composition, species interactions, and food web dynamics often build on organismal effects elicited by climate forcing (e.g., 6.3.1.5; Boyd *et al*., 2010; Ottersen *et al.*, 2010). The underlying mechanisms respond to climate-related factors in a hierarchy from organism (highest), tissue, cell to molecular (lowest) levels of biological organization (Pörtner, 2002a; Pörtner and Knust, 2007; Raven *et al*., 2012). Such knowledge aids the interpretation and attribution to climate change of observed effects and is a major asset for projections of future impacts.

The genetic and physiological underpinning of climate sensitivity of organisms sets the boundaries for ecosystem response and provides crucial information on sensitivities, resilience, and the direction and scope of future change. As anthropogenic climate change accelerates, a key issue is whether and how quickly organisms can compensate for effects of individual or multiple drivers, by short-term acclimatization or long-term evolutionary adaptation across generations. Evolutionary adaptation depends on the genetic variation within a population, from which the environment selects the fittest genotypes (Rando and Verstrepen, 2007; Reusch and Wood, 2007). Genetic variation depends on mutation rates, generation time, and population size (Bowler *et al*., 2010). However, epigenetic mechanisms, such as modifications of the genome by DNA methylation, can also influence fitness and adaptation (Richards, 2006) and can be remarkably rapid as seen in terrestrial ecosystems (Bossdorf *et al*., 2008). In plants and animals the rate of evolutionary adaptation is constrained by long generation times, but enhanced by high phenotypic variability and high mortality rates among early life stages as a selection pool (e.g., Sunday *et al*., 2011). The limits to acclimatization or adaptation capacity are presently unknown. However, mass extinctions occurring during much slower rates of climate change in Earth history (6.1.2) suggest that evolutionary rates in some organisms may not be fast enough to cope.

Comprehensive understanding of climate change effects on ecosystems requires addressing the effects of individual drivers across organism taxa (6.3.1 – 6.3.4), the integrated action of multiple drivers (6.3.5), the consequences for food webs (6.3.6), and the specific effects on animals breathing in air (6.3.7) and operating at the highest trophic levels.

6.3.1. Temperature Effects

The effects of temperature on ecosystems largely result from organismal responses. This requires that information on organisms' thermal sensitivities, limits, and functional properties is used to assess how temperature changes have affected and will continue to affect species distributions, abundances, diversity, trophic interactions, community assemblages, risks of species extinctions, and ecosystem functioning. Organisms also respond to temperature-driven changes in the physical environment such as stratification, reduced sea-ice cover and freshening. Ambient temperature interacts with other drivers such as ocean acidification and hypoxia (6.3.5). Ambient temperature plays a more limited role for marine mammals and seabirds (6.3.7).

6.3.1.1. Principles

All organisms including marine ones have limited temperature ranges within which they live and function. Organismal performance is related to temperature by curves called thermal reaction norms (Figure 6-5) which *likely* apply across all organisms (Chevin *et al.*, 2010), from viruses (Knies *et al*., 2006), bacteria (Ratkowsky *et al*., 1983), and phytoplankton (Eppley, 1972; Thomas *et al*., 2012) to macroalgae and plants (Bolton and Lüning, 1982; Müller *et al.*, 2009; Vitasse *et al*., 2010), and animals (Huey and Kingsolver, 1989; Angilletta, 2009). Heat tolerance thresholds differ greatly between organisms and are hypothesized to be lowered by rising organizational complexity and body size (Pörtner, 2002a,b). Maximum heat limits of animals and plants are close to the maximum temperature found in the warmest oceans (Figure 6-6). Knowledge of reaction norms, thermal limits, and underlying mechanisms is most advanced in animals (Pörtner *et al*., 2012; 6.3.1.4). Their role in underpinning biogeography has not been explored systematically in other organisms (e.g., Green *et al*., 2008), reducing the confidence level in assessments of thermal impacts. In animals, changes in physiological performances influence growth, body size, behavior, immune defense, feeding, reproductive success, biogeography, phenology and therefore, ecosystem structure and functioning. Shape and width of the curves can shift through acclimatization and evolutionary adaptation (Figure 6-5A) and during life history (Figure 6-5B) with implications for the distribution boundaries of species or populations (6.3.1.5).

For any species, tracking the climate-induced displacement of tolerated ambient temperatures by undergoing shifts in biogeographical ranges to, e.g., higher latitudes during warming (6.3.1.5: Figure 6-7), can be understood as a simple mode of adaptation, implemented through dispersal (e.g., of pelagic life stages), active movements (e.g., of migrating adult fishes) or passive displacement (e.g., of early lifestages or plankton with drifting water masses). Conversely, fully completed acclimatization or evolutionary adaptation (Figure 6-5) would involve shifting thermal tolerance ranges and allow species to resist the temperature trend (e.g., warming) and to sustain fitness in their previous habitat.

[INSERT FIGURE 6-5 HERE
Figure 6-5: Thermal specialization of an organism explains the why, how, when, and where of climate sensitivity. (A) The thermal tolerance range and performance levels of an organism are described by its performance curve (exemplified for an animal). Each Performance (e.g., exercise, growth, reproduction) is maximal at its optimum temperature (T_{opt}), and becomes progressively constrained during cooling or warming. Surpassing the first low and high temperature thresholds (T_p, p, pejus: getting worse) means going into time-limited tolerance. Once further cooling or warming surpasses the next low or high thresholds (T_c, c, critical), oxygen availability becomes insufficient and an anaerobic metabolism begins. Denaturation temperatures (T_d) are even more extreme and characterized by the onset of damage to cells and proteins. Horizontal arrows indicate that T_p, T_c, and T_d-thresholds of an individual can shift, within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) and in hypoxic waters performance levels can decrease and thermal windows narrow (dashed grey curves). (B) The width of the thermal range (horizontal arrows) also changes over time when an individual develops from egg to larva to adult and gains weight and size. Blue to red colour gradients illustrate the range between cold to warm temperatures (after Pörtner, 2002a, 2012; Pörtner and Farrell, 2008).]

[INSERT FIGURE 6-6 HERE
Figure 6-6: Maximal values of temperature covered by various domains and groups of free-living marine organisms (bacteria to animals, domains, and groups modified after Woese *et al*.,1990). High organizational complexity is hypothesized to be associated with decreasing tolerance to heat and to enable an increase in body size which in turn, decreases heat tolerance further (Alker *et al*., 2001; Baumgartner *et al*., 2002; Campbell *et al*., 2006; Chevaldonné *et al*., 2000; De Jonckheere *et al*., 2009, 2011; Pörtner, 2002a,b; Sorokin and Kraus, 1962). In the domain Bacteria, the Thermotogales are less complex and most tolerant to high temperatures (Abed *et al*., 2002; Huber *et al*., 1986; Takai *et al*., 1999; Tenreio *et al*., 1997; Ventura *et al*., 2000). The highest temperature, at which growth can occur is 122°C for hydrothermal vent archaea, seen under elevated hydrostatic pressure in laboratory experiments (Kashefi and Lovley, 2003; Takai *et al*., 2008.)]

6.3.1.2. Microbes

Temperature effects on growth, abundance, distribution, phenology, and community structure of highly diverse microbes might have large implications for ecosystem functioning (6.3, Box CC-PP). A warming ocean may initially enhance the metabolic rates of microbes (Banse, 1991) and stimulate their overall growth (Bissinger *et al*., 2008). Data from the Continuous Plankton Recorder (6.1.2) in the Northeast Atlantic confirm that warming from 1960 to 1995 enhanced phytoplankton growth (Edwards *et al*., 2001). Eventually, with warming, the thermal tolerance of some groups will be challenged (Chevin *et al*., 2010), leading to the replacement of species. This is reflected in increasing fractions of smaller phytoplankton in warmer relative to colder waters (Morán *et al*., 2010; Flombaum *et al*., 2013).

In response to transient warming, phytoplankton distribution in the North Atlantic shifted poleward by hundreds of km per decade since the 1950s. Phenology of plankton in the North Atlantic was also affected, with differences in sensitivity between groups (6.3.1.5; Box 6-1, *high confidence*). Coccolithophore blooms (*E. huxleyi*) in the Bering Sea were reported for the first time during the period 1997-2000, probably in response to a 4°C warming, combined with a shallower mixed layer depth, higher light levels and low zooplankton grazing (Merico *et al*., 2004). Loss of multi-year Arctic sea ice has had a profound effect on the diversity, structure, and function of the epipelagic microbial assemblage (i.e., found in the layer into which enough light penetrates for photosynthesis) (Comeau *et al*., 2011), and further warming is likely to have even greater impacts on the food web and on ecosystem services (*medium confidence*). Warming may also have caused the southward range extension of coccolithophores in the Southern Ocean in the 2000s (Cubillos *et al*., 2007). However, further experimental and field observations (Giovannoni and Vergin, 2012) are required to validate model projections (Taucher and Oschlies, 2011) of differential responses to warming by different microorganisms.

6.3.1.3. Macroalgae and Seagrasses

Macrophytes in coastal waters (WGII, Ch. 5) cover 0.6 % of the world's marine areas and supply about 2-5 % of total oceanic production (Smith, 1981; Charpy-Roubaud and Sournia, 1990; Field *et al*., 1998). They have limited temperature ranges and are sensitive to temperature extremes (*high confidence)* resulting in changes of photosynthesis, growth, reproduction and survival (following the principles of Figures 6-5, 6-6, Harley *et al*., 2012), with consequences for their abundance, distribution, and productivity. Ice retreat in polar areas leads to an expansion of macroalgal distribution, e.g. in the Antarctic (Quartino *et al*., 2013).

Warm- *versus* cold- water adapted species may have different sensitivities to warming and show a range of responses in distribution shifts (Lima *et al*., 2007). Temperate macroalgae with wide windows of thermal tolerance acclimatize by shifting these windows following seasonal temperature changes (Kübler and Davison, 1995). Antarctic and tropical macroalgae are exposed to permanently low or high temperatures, respectively, and have consequently specialized in a limited temperature range, paralleled by a low acclimatization potential (Pakker *et al*., 1995; Eggert *et al*., 2006; Gómez *et al*., 2011). Thus, Antarctic and tropical macroalgae appear to be most vulnerable to warming (*high confidence*, Short and Neckles, 1999). While observations in the tropics indicate that seagrasses tolerate higher temperatures than seaweeds (Campbell *et al*., 2006), an increase in maximum temperature by over 1°C from 1988-1999 to 2002-2006 (30.5.3.1.5) led to increased seagrass shoot mortality in the Mediterranean Sea (Marbà and Duarte, 2010). The molecular basis of acclimatization and evolutionary adaptation, as well as their limitation in relation to the climate regime require further study in the macrophytes.

6.3.1.4. Animals

The mechanisms shaping the thermal performance curve and, thereby, an animal's thermal niche have been explained by the concept of "oxygen and capacity limited thermal tolerance" (OCLTT), applicable to marine invertebrates and fishes (Pörtner *et al*., 2010; Figure 6-5A; FAQ 6.2). The temperature range at which animals can function best, results from optimal oxygen supply at minimal oxygen usage. At temperature extremes, oxygen supply capacity becomes constrained in relation to demand, and metabolism becomes thermally limited. Beyond upper and lower temperature thresholds (T_p, Figure 6-5A), growth, reproduction, and other key functions decrease. These thresholds change during the individual life cycle, and with body size. At large body size, limitations in oxygen supply are exacerbated and heat tolerance limits shift to lower temperatures.

Surpassing species-specific heat tolerance limits (Figure 6-5, T_p) during warming causes a reduction of abundance (Pörtner and Knust, 2007; Katsikatsou *et al*., 2012), coral losses (Donner *et al*., 2005), shifts in the seasonal timing of (zooplankton) biomass formation (Mackas *et al*., 1998; Schlüter *et al*., 2010), and changes in growth (Lloret and Rätz, 2000; Brunel and Dickey-Collas, 2010). During early life, due to incomplete development, or as adult spawners, due to large body size, animals may become more sensitive to warming because of narrower thermal windows (Pörtner *et al*., 2008). This may cause high vulnerability of winter-spawning Atlantic cod to warming winter to spring temperatures (Table 6-2). In contrast, adult bigeye, bluefin, and skipjack tuna spawn at high temperature. They need to prevent overheating by moving to cooler (deeper) waters (Lehodey *et al*., 2011).

Although temperature means are still most commonly used when attributing responses of marine organisms to climate effects, temperature extremes rather than means are most often mediators of effects (e.g., Easterling *et al.*, 2000; Wethey *et al.*, 2011; Wernberg *et al*., 2013; Figure 6-5). During heat exposure near the borders of the distribution range (including the high intertidal or warming surface waters), reductions in growth, activity, and abundance accompany even small (<0.5°C) shifts in ambient temperature extremes (e.g., Takasuka and Aoki, 2006; Pörtner and Knust, 2007; Nilsson *et al.*, 2009; Neuheimer *et al.*, 2011). Local extinction events follow due to mortality or behavioral avoidance of unfavorable thermal environments (Breau *et al.*, 2011). Shifted species distribution ranges follow temperature clines from high to low, usually along latitudes, a lateral gradient at basin scale (Perry *et al*., 2005; Poloczanska *et al*. 2013), or a vertical temperature gradient to deeper waters (Dulvy *et al*., 2008; Figure 6-5B, Box CC-MB, *high confidence*).

Adopting OCLTT principles has enabled modeling studies to project climate effects (6.5), and paleo-studies to explain climate-induced mass extinction events and evolutionary patterns in Earth history (Pörtner *et al.*, 2005; Knoll *et al.*, 2007). For example, long-term observations show that warming affects the body size of marine fishes (*medium confidence*). Assessing effects of warming on body size may be complicated by effects on the animal's energy budget, the changing availability and body size of prey species, community structure, species interactions, or effects of fishing (Genner *et al*., 2010; Cheung *et al*., 2013a). Below the thermal optimum, warming causes growth and weight-at-age of some juvenile or younger fish populations to increase (e.g., Brunel and Dickey-Collas, 2010; Neuheimer and Grønkjær, 2012). However, OCLTT predicts that small individuals are more heat tolerant than large ones, in line with observations of falling animal body sizes in warming oceans ((Box 6-1, e.g., Daufresne *et al.*, 2009). This trend is projected to continue into the 21st century (*medium to high confidence*; Cheung *et al*., 2013a).

Thermal windows of fishes and invertebrates roughly match ambient temperature variability (Figure 6-1) according to climate regime and seasonality (Pörtner and Peck, 2010; Sunday *et al*., 2012). Sub-Arctic, small or highly mobile species are eurytherms. They function across a wide temperature range, i.e., they have wide thermal windows and distribution ranges, at the expense of higher energetic costs and associated lifestyles (Pörtner, 2002a, 2006). Conversely, high polar species are stenotherms, i.e., they have narrow thermal windows and low energy demand lifestyles, making them sensitive to temperature change. In a warming world, polar stenotherms will be marginalized, with no possibility to escape to colder regions (*high confidence*). However, extinction of polar species has not yet been reported. As marine fishes and invertebrates in the Southern hemisphere are adapted to less variable ocean temperatures than those in the Northern hemisphere (Jones *et al*., 1999; Figure 6-1), they may generally be more vulnerable to warming extremes than northern ones. Tropical species (with thermal windows of intermediate width) live close to the highest temperatures tolerated by marine animals (Figure 6-6). Vulnerability is, therefore, highest for polar stenotherms, similar or lower for tropical and lowest for temperate species (*high confidence*).

Short-term shifts in thermal thresholds of an individual organism may happen over days and weeks, such as during seasonal acclimatization. Long-term shifts occur over many generations during evolutionary adaptation of a population to cooler or warmer climates (Figure 6-5A, Pörtner, 2006; Pörtner *et al.*, 2008; Eliason *et al.*, 2011). Both acclimatization and adaptation involve adjustments in biochemical characters (membranes, enzymes); however, the capacity to shift those boundaries is limited and depends on the species and the prevailing climate regime (Pörtner *et al.*, 2008, 2012). Ocean acidification, hypoxia, food availability, and stress affect those limits (6.3.5, Figure 6-5A).

Local adaptation may reduce climate vulnerability at the species level, by causing functional and genetic differentiation between populations, thereby enabling the species to cover wider temperature ranges and live in heterogeneous environments. Local adaptation on small spatial scales is particularly strong in intertidal organisms (Kelly *et al*., 2012). On larger scales, the widening biogeographic and roaming ranges of Northern hemisphere eurytherms into Arctic waters (Pörtner *et al*., 2008) are supported by the differentiation into populations with diverse thermal ranges, combined with high acclimatization capacity. By contrast, such capacity is small in high polar, e.g. Antarctic species (Peck *et al*., 2010). Tropical reef fishes undergo rapid warm acclimation across generations

(Donelson *et al.*, 2012) but some may approach animal heat limits. The rates, mechanisms and limits of thermal acclimatization and evolutionary adaptation are poorly understood (*low confidence*).

[INSERT TABLE 6-2 HERE
Table 6-2: Selected examples of species responses and underlying mechanisms to changing temperature, oxygen level and ocean acidification (OA). References are indicated by superscript numbers and in the footnote.]

Warm- and cold-water coral communities

Tropical corals live in shallow water and differ from most other animals by hosting dinoflagellates (*Symbiodinium sp.*) in their tissues, which provide the host with organic carbon from photosynthesis and with nitrogen and enable the corals to build and sustain carbonate reefs (Box CC-CR). High light, rapid salinity changes and small increases in temperature can trigger 'coral bleaching', the loss of symbionts and tissue color. In case of warming, early steps involve shifts in the photosynthetic processing of light, generating Reactive O_2 Species (ROS) that may in turn damage the symbionts (Glynn and D'Croz, 1990; Hoegh-Guldberg and Smith, 1989; Hoegh-Guldberg, 1999; Jones *et al*., 1998). Mass bleaching is correlated with small temperature anomalies (+1-2 °C of the long-term summer maximum, satellite observations), causing mortalities (Goreau and Hayes, 1994; Strong *et al*., 2011) and decreasing coral abundance, on average by 1-2 % per year (Bruno and Selig, 2007; Box CC-CR, 30.5.6, *high confidence*).

The degree of impact will depend on the coral reefs' adaptability to thermal stress and the interaction of multiple drivers (Meissner *et al*., 2012; Teneva *et al*., 2012; Box CC-CR). Such capacity is suggested by different heat tolerances among coral genera (Hoegh-Guldberg and Salvat, 1995; Loya *et al*., 2001), the exchange of genetic clades of *Symbiodinium* with more tolerant varieties (Baker, 2001; Jones *et al*., 2008), as well as acclimatization phenomena (Howells *et al*., 2012).

Studies of the thermal sensitivity of deeper-living cold-water corals (without endosymbionts) are scarce. One species, *Lophelia pertusa* responds to about 3°C warming with a three-fold increase in metabolic rate (Dodds *et al.*, 2007), indicating a narrow thermal window in the cold (cf. Pörtner, 2006).

6.3.1.5. Ecosystems

Heat exposure of ecosystem engineers may threaten the existence of a whole ecosystem. During the last warm interglacial period equatorial coral reefs deteriorated and retreated (Kiessling *et al*., 2012), a finding emphasizing their thermal sensitivity (Veron *et al*., 2009) and showing that warming oceans can reach temperatures well beyond the upper heat limits of distinct animal groups and marine animals overall (Figure 6-6). In present-day Great Barrier Reef, a large-scale survey found diverse coral types along a climatic gradient, with no consistent response to climatic drivers (Hughes *et al*., 2012). However, warm-induced bleaching has contributed to the progressive decrease in live coral cover observed over the last decades (Box CC-CR, 30.5.6; De'ath *et al*., 2012).

Within ecosystems, shifting competitive or trophic interactions, differential risks for species extinctions and, thereby, scenarios of community-level responses to temperature change (Urban *et al*., 2012; Milazzo *et al*., 2013) can be traced back to changing differences in the performance of participating animal species (Figure 6-7, e.g., Cairns *et al*., 2008; Harley, 2011; Pörtner, 2012). Knowledge is insufficient to assess interactions of species from different domains, impeding a deeper understanding of shifting distributions, abundances, community assemblages, and food webs in space and time (Parmesan and Matthews, 2005, *low confidence* in current understanding).

For example, in a coastal microcosm (small-scale, simplified experimental ecosystem) resident heterotrophic bacteria were stimulated by warming more than a laboratory-reared phytoplankter (Wohlers-Zöllner *et al*., 2011). Also, high- to low-latitude transects in both the North and South Atlantic revealed a shift between cold and warm waters, from photoautotrophs (gaining energy from photosynthesis) to chemo-heterotrophs (Hoppe *et al*., 2002). Thermal stimulation of bacteria over phytoplankton has biogeochemical implications, for example, microbially-mediated carbon dioxide flow to the atmosphere might increase (Sarmento *et al*., 2010). The principles and wider applicability of these findings require further investigation (*limited evidence, low agreement*, Kirchman *et al*., 2009).

[INSERT FIGURE 6-7 HERE
Figure 6-7: Role of thermal tolerance and performance of organisms at ecosystem level. (A) Thermal tolerance ranges (Figure 6-5) differ between species across polar, temperate and tropical climate zones, then overlapping between coexisting species. Shifting temperatures and specific effects of additional drivers on the respective performance curves (dashed lines) change the fitness of coexisting species relative to each other as well as their temperature range of coexistence (after Pörtner and Farrell, 2008). Warming alters the timing of seasonal activities (e.g., elicited by spring warming cues) earlier, or can benefit only one of two interacting species (e.g., in predator-prey dynamics or competition) causing shifts in predominance. (B) During climate warming a largely unchanged thermal range of a species causes it to follow its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the Northern hemisphere, modified after Beaugrand, 2009). The polygon delineates the distribution range in space and seasonal time; the level of grey denotes abundance. The southern time window of tolerated temperatures shifts to earlier and contracts, while the northern one dilates (indicated by arrows). Species display maximum productivity in low latitude spring, wide seasonal coverage in the center, and a later productivity maximum in the North. The impact of photoperiod (length of daily exposure to light) increases with latitude (grey arrow). Water column characteristics or photoperiod may overrule temperature control in some organisms (e.g. diatoms), limiting northward displacement.]

Observations of shifting distributions and phenologies, reproduction, and range shifts of phytoplankton, zooplankton, other invertebrates, fishes, and seabirds in pelagic and coastal marine ecosystems have at least partly been attributed to temperature-mediated biological responses (*high confidence,* Figure 6-8; Box 6-1; Box CC-MB). In the North Atlantic as a key example, many biological events have been occurring earlier in the year (*robust evidence*, *high agreement,* Box 6-1, 30.5.1.1.1). Species richness has increased due to shifts in ranges and abundances. In the Norwegian and Barents Seas a time series (1959 to 2006) of four commercial fish species and their zooplankton prey showed that climate shapes population growth rates through complex influences early in life, including direct temperature effects on growth, indirect effects via the biomass of zooplankton prey, and delayed feedback effects through predators (Stige *et al.,* 2010). Differential species responses to temperature and trophic amplification were demonstrated to modify species interactions at five trophic levels, primary producers (phytoplankton), primary, secondary, and tertiary consumers (zooplankton, fishes and jellyfishes), and benthic detritivores (echinoderms and bivalves) (Kirby and Beaugrand, 2009). Also, the responses of various plankton functional groups, such as diatoms, dinoflagellates, and copepods, to warming are not synchronous, resulting in predator-prey mismatches that carry over to higher trophic levels (Figure 6-7A; Edwards and Richardson, 2004; Costello *et al.*, 2006; 6.3.6, *high confidence*). In the intertidal, warming-induced changes in relative species ranges lead to shifts in dominance through competitive interactions and to modifications in predator pressure (Poloczanska *et al*., 2008; Harley, 2011). Trans-Arctic interchange of species between Atlantic and Pacific has happened repeatedly in warm periods of the Pleistocene (Dodson *et al*., 2007) and may occur again, now facilitated by ballast transport by enhanced trans-Arctic shipping (*low* to *medium confidence*).

Warming may increase the risk of disease outbreaks or parasite infections, in marine organisms and ecosystems, and ultimately, humans (Burge *et al*., 2013; Altizer *et al*., 2013 *medium confidence*). Some marine pathogens and protist diseases are shifting their distribution poleward as oceans warm (e.g., Baker-Austin *et al*., 2013; Burge *et al*., 2013). Climate change may weaken the immune response of hosts, particularly fishes and invertebrates and increase their susceptibility to disease, as observed during warming in coral reefs of the Pacific and Caribbean (Harvell *et al*., 2009). Global outbreak frequencies of jellyfish aggregations may follow rising sea surface temperatures (SSTs) (*low confidence,* Mills, 2001; Purcell and Decker, 2005), but evidence is inconclusive. Some studies report an increasing trend (Brotz *et al*., 2012) and others do not support this view (Condon *et al*., 2013).

In conclusion, organisms live in limited temperature ranges and are sensitive to temperature extremes (*very high confidence*). Temperature governs the biogeography, diversity, development, reproduction, behavior and phenology of marine species as well as the composition of communities in both pelagic and benthic systems and the seasonal timing of relevant processes (phenology) (*very high confidence*). Ecosystems functioning at the coldest temperatures and warm adapted ones existing at their upper thermal limits are more sensitive (*medium confidence*).

[INSERT FIGURE 6-8 HERE
Figure 6-8: Multi-decadal changes in ecosystem structure in the NE Atlantic driven by warming from both anthropogenic climate change and natural climate variability. **A.** Index of temperature change over the North Atlantic (31°N-65°N and 99°W-11°E) reflecting climate change. This index is the first principal component (i.e., explaining 30.5% of observed variability) based on a Principal Component Analysis (PCA) performed on sea surface temperature. **B.** Index of temperature change (17.5% of observed variability) reflecting the Atlantic Multidecadal Oscillation (AMO). The index is the second principal component. **C-D.** Observed mean annual sea surface temperature in the North Sea during 1960-1981 (**C**) and 1988-2005 (**D**). The location of the critical thermal boundary (9-10°C) is indicated by '+'. **E**. Long-term changes in the mean number of warm-temperate pseudo-oceanic species from 1958 to 2005. **F**. Long-term changes in the mean number of temperate pseudo-oceanic species from 1958 to 2005. The period 1958-1981 was a period of relative stability and the period 1982-1999 was a period of rapid northward shifts, indicating that the abrupt ecosystem shift observed in the North Sea was part of a large-scale response of the zooplankton biodiversity to warming temperatures (see **A**-**D**). Average values are below 1 because they are annual averages. Note that the color bar is 10-fold smaller for warm-temperate pseudo-oceanic species because these species are less frequently observed than their temperate counterparts. Panels A. and B. from Edwards *et al*. (2013), and C. to F. from Beaugrand *et al*. (2008), and Beaugrand *et al*. (2009).]

_____ START BOX 6-1 HERE _____

Box 6-1. An Atlantic Ocean Example:
Long-Term Responses of Pelagic Organisms and Communities to Temperature

Long-term observations (6.1.2, 30.5.1.1.1) encompassing the pelagic Northeast Atlantic over a 50-year period and longer (Figures 6-8, 6-9) show changes in the seasonal abundance of phytoplankton, rapid northerly displacements of temperate and subtropical zooplankton (e.g. calanoid copepods), and phytoplankton (e.g. dinoflagellates and diatoms), and the resulting changes in the ecosystem functioning and productivity (Edwards *et al.*, 2001; Beaugrand *et al.*, 2002; Edwards and Richardson, 2004, *high confidence*). The range limit of warm water copepods shifted by 10° north since 1960 (Beaugrand *et al.*, 2009), with attendant mismatch in the seasonal timing of trophic levels (predators and prey) and functional groups (Edwards and Richardson, 2004). Modes of climate variability reflected in climate indices like the Northern Hemisphere Temperature (NHT) and the North Atlantic Oscillation (NAO) over multidecadal periods accompanied these changes (Figure 6-1). In cooler regions, increased phytoplankton activity caused by warming favored growth resulting in the observed increase in phytoplankton biomass, whereas a decrease in nutrient supply would have prevented growth in warmer regions and caused a decrease in biomass (6.3.4; Richardson and Schoeman, 2004). Hinder *et al*. (2012) attributed a recent decline in North Sea dinoflagellates relative to diatoms to warming, increased summer windiness and thus, water column turbulence. The ecosystem response to natural climate variability in the past provides a glimpse into the climate-induced changes of the near future (Figure 6-9).

In regions of high vulnerability to climate, mild warming can trigger rapid and substantial ecosystem shifts, offering a way to anticipate future changes (Figure 6-9). In line with the increased understanding of physiology (6.3.1.1), warming in the temperate to polar North Atlantic was paralleled by a reduction in the average body lengths of about 100 copepod species, from 3-4 mm to 2-3 mm (Beaugrand *et al.*, 2010). Warming was also correlated with an increase in species richness among copepods and within the dinoflagellate genus *Ceratium*. In diatoms, which are major contributors to carbon export (Armbrust, 2009), warming and decreasing annual variability in SST resulted in lower diversity, smaller size and reduced abundance (Beaugrand *et al*., 2010). Morán *et al.* (2010) found that temperature alone explained 73% of the variance in the contribution of small cells (picophytoplankton) to total phytoplankton biomass in the eastern and western temperate North Atlantic from -0.6 to 22°C. More recently, Marañón *et al*. (2012) analysed data from polar, sub-polar and tropical regions and suggested that nutrient availability may influence cell size more than temperature.

The ecosystem regime shift observed in North Sea plankton in the late 1980s involved an increase in phytoplankton and changes in species composition and abundance among holozooplankton (animals that are planktonic for their entire lifecycle) (Reid *et al.*, 2001; Kirby and Beaugrand, 2009; Kirby *et al.*, 2009; Lindley *et al.*, 2010). This shift was paralleled by the northward propagation of a critical thermal boundary (CTB, i.e., the boundary of the subpolar gyre) between the temperate and the polar biomes (Box CC-PP, Figure 1; Beaugrand *et al*., 2008). Warming to above the CTB coincided with pronounced and large-scale variations in phytoplankton productivity, an increase in calanoid copepod diversity (Beaugrand *et al*., 2008) and herring abundance (Schlüter *et al*., 2008), a reduction in the mean size of calanoids, and a decrease in the abundance of southern Atlantic cod populations in the North Atlantic Ocean (e.g., the North Sea, Pörtner *et al*., 2008; Beaugrand *et al*., 2010). These patterns also extend to the southern North Sea, where elevated salinities and average warming by 1.6°C, both in summer and winter between 1962 and 2007, expanded the time window for growth of microalgae and possibly supported the invasion and increase in numbers of warm-adapted silicified diatoms (Wiltshire *et al*., 2010). Recent findings indicate a regime shift in the Bay of Biscay, the Celtic and the North Seas, in the mid to end 1990s (Luczak *et al.*, 2011). Changing plankton composition and changing abundances of both sardine and anchovies (Raab *et al*., 2013) paralleled stepwise warming.

Northward range extensions or redistributions in fishes were largest along the European Continental shelf and attributed to regional warming, e.g. by 1.0°C from 1977 to 2001 in the North Sea, with winter warming being closely correlated with the shift of Atlantic cod (Perry *et al*., 2005; 6.3.1). Similar trends were observed due to warming by 1–2 °C in the waters south and west of Iceland during the past 15 years (Valdimarsson *et al*., 2012). In the Northwest Atlantic Arctic and sub-Arctic, winter and spring warming caused expansion of the area matching the thermal optimum of Atlantic salmon at 4–8°C and caused greater growth (Friedland and Todd, 2012). Pelagic sardines and anchovies entered the North Sea in the early to mid-1990s, after about 40 years of absence, in response to intensified NAO and AMO (Alheit *et al.*, 2012). Red mullet and bass extended into western Norway; Mediterranean and north-west African species extended to the south coast of Portugal (Brander *et al.*, 2003; Beare *et al.*, 2004; Genner *et al.*, 2004; 30.5.1.1.4).

In the Northwest Atlantic cooling and freshening occurred during the late 1980s-early 1990s and seemed to have the opposite effect, as capelin and their predator, Atlantic cod, shifted farther south (Rose and O'Driscoll, 2002). Between the early 1990s and mid-2000s in the Northwest Atlantic sub-polar gyre, phytoplankton biomass increased, due to warming. At the same time, Arctic copepod species became more abundant, due to increased influx of Arctic water (Head and Pepin, 2010). Although temperatures have risen on the Newfoundland Shelf (Colbourne *et al*., 2011), capelin and cod remain scarce for reasons probably unrelated to climate (DFO 2011a, b). Farther south, Arctic freshwater inflows caused freshening and increased stratification of the area around the Gulf of Maine throughout the 1990s, resulting in enhanced phytoplankton abundance, a larger and later fall bloom, increased abundance of small copepods, and a decrease in the large copepod *Calanus finmarchicus* (deYoung *et al*., 2004; Pershing *et al*., 2005, 2010). Various fish species showed poleward shifts in distribution (Table 6-2) which were associated with reduced survival of larval cod (Mountain and Kane, 2010) and fewer right whale calves (Greene *et al*., 2003), but increased herring abundance (Greene and Pershing, 2007).

[INSERT FIGURE 6-9 HERE
Figure 6-9: Schematic depiction of observed effects of ~1°C ocean warming in the northern North Atlantic driven by climate variability (A, C) versus effects expected from anthropogenic climate change (B, D). A) Transient warming and cooling associated with AMO variability (Drinkwater, 2006), based on the Kola Section temperatures (0-200 m; Stations 3-7, 71.5°-72.5°N, 33.5°E) in the Barents Sea obtained from http://www.pinro.ru and filtered using a 20-year running mean. Similar trends occurred across most of the northern North Atlantic although the amplitude and timing of the peaks and troughs varied spatially. B) Warming driven by climate change for the same region (RCP 8.5 simulations averaged from CMIP5 models, computed as the mean over the upper 200 m in the grid box (2.5x2.5 degrees) centered at 71.25N and 33.75E). C) Warming and subsequent cooling in the northern North Atlantic during the period shown in A resulted in complex multi-faceted changes (shown schematically) in NPP (green curve), zooplankton biomass (red curve) and fish stock abundances (blue curve). There was a general poleward shift and range expansion of many commercial (e.g., Atlantic herring, Atlantic cod, haddock) and non-commercial species, reversed during the subsequent cooling period (denoted by black dashed curve). Polewards shifts in spawning areas (e.g., Atlantic cod) were also reversed as the waters cooled. The purple and grey dashed curve represents shifts in seasonal timing (phenology) and community composition, respectively, that were influenced by earlier arrivals and later retreat of migratory fish (not shown). For more details see Drinkwater (2006). D) Projected effects of climate mediated warming on northern sub-polar and polar biota based on model projections of altered NPP (Bopp *et al*.,

2013), and of the range shift of exploited fishes and invertebrates (Cheung *et al*., 2009, 2013a). The projected trends in panel D will differ with latitude, e.g., decreased NPP at lower latitudes and no significant change to NPP in temperate waters (Bopp *et al*., 2013). Higher NPP supported and is projected to support higher trophic levels at high latitudes (C, D, 6.3.4). Note that climate variability will be superimposed on anthropogenic warming (B, see Figure 6-1, 6-8A,B). Dotted lines indicate projected changes to continue beyond the range of historical observations.]

_____ END BOX 6-1 HERE _____

6.3.2. CO_2 Effects

Evidence for biological effects of ocean acidification (OA) stems from paleo-observations (6.1.2), few observations in the field (6.3.2.5), studies at volcanic CO_2 seeps as natural analogues, and mostly from short- to medium-term (hours to months) experiments in the laboratory or field, exposing organisms to projected future CO_2 levels (6.3.2.1-4). A surging number of studies is providing evidence that rising CO_2 levels will increasingly affect marine biota and interfere with ecological and biogeochemical processes in the oceans (*high confidence*, FAQs 6.2, 6.3).

6.3.2.1. Principles

The absorption of rising atmospheric CO_2 by oceans and organisms changes carbonate system variables in the water and in organism internal fluids, i.e., the relative proportions of CO_2, carbonate, bicarbonate, and hydrogen ions (pH). Internal pH must be tightly controlled, as some processes, such as calcification, release protons thereby affecting pH and as other biochemical processes are pH-sensitive. Accumulation of CO_2 and the resulting acidification can also affect a wide range of organismal functions, such as membrane transport, calcification, photosynthesis in plants, neuronal processes in animals, growth, reproductive success, and survival. Effects translate from organism to ecosystem.

The capacity of organisms to resist and compensate for the CO_2 induced acidification of internal fluids depends on acid-base regulation, i.e., the capacity of ion exchange to accumulate bicarbonate internally, an aspect unexplored in many phyla (Figure 6-10A, *low* to *medium confidence*; e.g., animals: Heisler, 1986; Pörtner, 2008; Claiborne *et al*., 2002; phytoplankton: Taylor *et al*., 2011) (FAQ 6.3).

In unicellular microbes the regulation of intracellular pH may play a key role in modulating CO_2 responses (Taylor *et al*., 2011). Findings in invertebrates and fish indicate an additional role for extracellular pH (Figure 6-10A); effective pH values may vary between species. Organisms pre-adapted to elevated CO_2 may minimize the decrease in pH (acidosis). They may also modify their sensitivity such that they respond less or not at all to the acidosis. Recent evidence, however, emphasizes a role for acid-base regulation in a natural low-pH setting. Between two urchin species, only the one successful in maintaining its setpoints of extracellular pH is able to settle close to volcanic CO_2 seeps (Calosi *et al.*, 2013). Compensating for the acidosis may cause increased energy demand and respiration rates. In general, such capacity rises with metabolic energy turnover, e.g., it is higher in more active marine animals, such as fishes, cephalopods and pelagic copepods, and in mobile coastal crabs compared to sessile species (Table 6-3, Pörtner *et al*., 2005, 2011; Ishimatsu *et al.*, 2008; Melzner *et al.*, 2009; Ishimatsu and Dissanayake, 2010). This matches the sensitivity distribution seen among animals at the phylum level (Figure 6-9B, *medium confidence*).

Some species have lower metabolic rates in response to acidosis (Pörtner *et al*., 1998; Michaelidis *et al*., 2005; Pörtner, 2008; Liu and He, 2012; Navarro *et al*., 2013); others display increased energy turnover and food ingestion rates, possibly indicating a capacity to resist acidification effects (Parker *et al.*, 2011; Saba *et al*., 2012). The effects of the acidosis on various processes relevant to fitness may explain changes in whole-organism energy demand, probably paralleled by modified ion exchange, protein synthesis, growth and feeding rates. The magnitude of effect depends on the CO_2 concentrations reached (Figure 6-10B).

The internal formation of carbonate from bicarbonate is essential to calcification, which is the formation of solid $CaCO_3$ in internal or external calcified structures, used for defense and structural support. Calcification usually occurs in separate body or cell compartments, where pH and thus, CO_3^{2-} concentration and saturation Ω (6.1.1) are maintained at values higher than in other body fluids or ambient water (Trotter *et al*., 2011; Taylor *et al*., 2011; McCullough *et al*., 2012; Venn *et al*., 2013). CO_2 impedes the formation of carbonate such that calcification rate decreases. It may be maintained by enhanced transport of ions, incurring elevated energetic costs (Figure 6-10).

External carbonate structures like shells rely on ambient seawater being supersaturated with carbonates. Decreasing oceanic carbonate levels reduce the saturation levels (Ω) of calcite or aragonite in the water. Reduction to below unity may lead to the corrosion of carbonate shells (FAQ 6.3). However, many species protect their shells from direct contact with seawater by various types of organic coating (e.g., a periostracum in mollusks and brachiopods, an epicuticle covering the carapace of crustaceans; an epidermis covering the tests of urchins, epithelial tissue covering aragonite in corals, coralline algae precipitating calcium carbonate (mostly Mg-calcite) within their cell wall). A meta-analysis of the effects of ocean acidification on biological processes indicates that reductions in the rate of net calcification (calcification minus dissolution) and survival are the most uniform responses across organisms studied, relative to other, more variable impacts such as reduced growth, development, and abundance (Box CC-OA, Kroeker *et al*., 2013).

Some organisms benefit from elevated CO_2 partial pressures (pCO_2). Photosynthesis and/or nitrogen fixation in selected microorganisms are impacted by OA, but effects are species- or taxon-specific, possibly depending on how they acquire carbon (i.e., the presence and in particular the type, capacity, and energetic costs of carbon-concentrating mechanisms (CCM's, Giordano *et al.*, 2005; Kranz *et al.*, 2011).

A comprehensive picture of responses to CO_2 requires consideration of variable sensitivities between species and life stages and taxon-specific sensitivity distributions, as shown by a meta-analysis of animal data (Figure 6-10B, Wittmann and Pörtner, 2013). Echinoderms, bivalves, gastropods, and corals begin to respond negatively at lower CO_2 levels than crustaceans or cephalopods (Figure 6-10B). This sensitivity pattern resembles the one seen in the Permian mass extinction (Knoll *et al.*, 2007; Knoll and Fischer, 2011). The picture for fishes is less clear, as the present findings of high vulnerability are not met by similar observations in the fossil record. Evolutionary adaptation may thus eliminate or minimize reported effects.

The capacity for pH and ion regulation and other relevant processes can be upregulated by gene expression, as seen in acclimation studies in echinoderm larvae (O'Donnell *et al*., 2010; Martin *et al.*, 2011) and fishes (Deigweiher *et al*., 2008; Tseng *et al*., 2013), in warm-water coral branches (Kaniewska *et al*., 2012) but not in a study of warm-water coral larvae (Moya *et al*., 2012). Few studies address whether and to what extent species undergo evolutionary adaptation to high pCO_2, as seen in the coccolithophore *Emiliania huxleyi* over 500 asexual generations (Lohbeck *et al*., 2012). In organisms with longer generation times, perturbation studies in the laboratory measure tolerance and acclimation, but not adaptation or natural selection. Animal adaptation is accelerated by high functional variability among larvae, enabling selection of resistant genotypes (*low* to *medium confidence*, Parker *et al*., 2012; Sunday *et al*., 2011; Pespeni *et al*., 2013). This may explain the selective mortality seen in Atlantic cod larvae under elevated CO_2 (Frommel *et al*., 2012). Both acclimatization and adaptation will shift sensitivity thresholds but the capacity and limits of species to acclimatize or adapt remain largely unknown and hence impacts of acute exposures cannot easily be scaled up to effects on the longer, evolutionary timescales of ocean acidification (Wittmann and Pörtner, 2013). Observations in ecosystems characterized by permanently elevated or fluctuating CO_2 levels, like upwelling areas, OMZs (6.1.1), or seeps, reflect the existence of sensitivity thresholds (*high confidence*, 6.3.2.5) but organisms may have evolved a higher resistance to increased CO_2 levels than elsewhere (*low confidence*).

[INSERT FIGURE 6-10 HERE
Figure 6-10: A: Responses of a schematized marine animal (left) and a phytoplankter (right) to ocean acidification (OA). Effects are mediated via diffusive CO_2 entry (black arrows) into body and cell compartments, resulting in a rise in pCO_2 (highlighted in red), a drop in compartmental pH (highlighted in blue) and their effects (red arrows) on various processes (red text) in tissues and cellular compartments, as well as on calcium carbonate saturation state (Ω) at calcification sites (after Pörtner, 2008; Taylor *et al*., 2011). Variable sensitivity relates to the degree of pH decline and compensation, depending on the capacity of pH and ion regulation. B: Distribution of sensitivities across

species within animal phyla, under progressively rising water CO_2 levels, as percent of studied scleractinian coral, echinoderm, molluskan, crustacean and fish species affected negatively, positively or not at all (for effects considered see text). As not all life stages, variables and pCO_2 ranges were covered in all species two assumptions partially compensate for missing data: 1) Negative effects at low pCO_2 will remain negative at high pCO_2. 2) A positive or neutral outcome at both low and high pCO_2 will be the same at intermediate pCO_2. As responses reported for each species vary for each CO_2 range, variable species numbers result (on top of columns). The total number of species studied in a group is shown as the number above the control column. Horizontal lines above columns represent frequency distributions significantly different from controls (Wittmann and Pörtner, 2013). C: Areas with reported annual catches of marine calcifiers (crustaceans and mollusks) >0.001 t km^{-2}, depicted on a global map showing the distribution of ocean acidification in 2100 according to RCP8.5 (WGI AR5 SPM) as well as the distribution of warm-water (green dots) and cold-water coral communities (pink dots).]

Table 6-3 compiles effects of ocean acidification observed across taxa in laboratory and field experiments. The latter include studies in mesocosms and at natural analogues, submarine CO_2 venting areas at locales like Ischia, Italy (Hall-Spencer *et al*., 2008), Papua New Guinea (Fabricius *et al*., 2011), and Puerto Morelos, Mexico (Crook *et al*., 2012). It should be noted that anthropogenic CO_2 accumulation according to RCPs adds to the natural variability of CO_2 concentrations in marine environments. Many groups, especially sessile or non-photosynthetic calcifiers have sensitive species with vulnerability thresholds surpassed under RCP6.0 by 2100 (*low* to *medium confidence*).

Recent meta-analyses also summarize OA effects, two for biogeochemical processes and relative effect sizes (Kroeker *et al*., 2013; Harvey *et al*., 2013), one for the distribution of sensitivity between species within major animal phyla and its change depending on ambient pCO_2 (Figure 6-10, Wittmann and Pörtner, 2013). All of these analyses consider the interaction of warming and CO_2 accumulation (6.3.5). Present limitations in understanding the mechanisms of effect and their long-term persistence compounds accurate projections of the long-term effects of OA (*medium confidence*, Wittmann and Pörtner, 2013).

[INSERT TABLE 6-3 HERE
Table 6-3: Tolerances to ocean acidification in marine taxa, assessed from laboratory and field studies of species in the pCO_2 range from <650 to >10 000 µatm, compared to present day atmospheric levels of 400 µatm. (It should be noted that anthropogenic CO_2 emissions add to the natural variability of CO_2 concentrations in marine environments, which can reach much higher than atmospheric levels). Variables studied include growth, survival, calcification, metabolic rate, immune response, development, abundance, behavior and others. Neither all life stages, nor all variables, including the entire range of CO_2 concentrations, were studied in all species. *Confidence* is based on the number of studies, the number of species studied and the agreement of results within one group. +: denotes that possibly more species or strains (genetically distinct populations of the same species) were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: more than 5% of species in a group will be negatively affected by 2100; tolerant: more than 95% of species will not be affected by 2100. RCP 6.0: representative concentration pathway with projected atmospheric pCO_2 = 670 µatm; RCP 8.5: pCO_2 = 936 µatm in 2100 (Meinshausen *et al.*, 2011). *Confidence* is limited by the short- to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary timescales, i.e., across generations (see separate reference list, online supplementary material). Note that the assessment of variability between species from the same animal phylum has revealed an increase in the fraction of sensitive species with rising CO_2 levels, see Figure 6-10. *Rather than a sensitivity threshold the entire range of investigated pCO_2 values is given for groups of photosynthetic organisms. In all studies photosynthetic rates are stimulated to different, species-specific degrees by elevated pCO_2, indicating low vulnerability. Coccolithophores and calcifying algae are assessed as being more sensitive than other photosynthetic organisms due to reduced calcification and shell dissolution. NA, not availaible, +confidence levels for fishes were converted from medium to low, in light of uncertainty on the long-term implications of behavioral disturbances.]

6.3.2.2. Microbes

The physiology of both calcifying (coccolithophores) and non-califying phytoplankton can be influenced by changes in carbonate system variables caused by ocean acidification (Figure 6-10A). Growth and photosynthetic rates of diatoms in laboratory cultures are considered relatively insensitive to elevated CO_2 (Rost *et al.*, 2003; Trimborn *et al.*, 2008). Dinoflagellate sensitivity to elevated CO_2 is poorly studied (Hansen *et al.*, 2007), but in one species carbon fixation rates were enhanced at 750 µatm CO_2 while growth remained unaffected (Fu *et al.*, 2008). Indirect effects of ocean acidification on phytoplankton physiology include altered availability of trace metals needed for many biochemical cycles (Hoffmann *et al*., 2012).

Harmful algal blooms are a growing problem in coastal waters worldwide (6.4.2.3), and many of the various phytoplankton species that produce bio-accumulated toxins are sensitive to changes in the seawater carbonate buffer system (Hallegraeff, 2010, Fu *et al*., 2012). For example, the dominance and community structure of harmful bloom dinoflagellates can be profoundly altered by changing pCO_2 (Tatters *et al*., 2013), and both toxic dinoflagellates and diatoms have been shown to produce higher toxin levels under near-future levels of ocean acidification (Fu *et al*., 2010, Sun *et al*., 2011).

Some planktonic N_2-fixing cyanobacteria (diazotrophs), e.g., strains (genetically distinct populations of the same species) of offshore cyanobacteria of the genera *Trichodesmium* and *Crocosphaera*, respond to rising CO_2 with increased rates of both carbon and N_2 fixation (Fu *et al*., 2008; Lomas *et al*., 2012). In contrast, laboratory studies using the bloom-forming cyanobacteria *Nodularia* (an organism largely found in coastal stratified, eutrophic waters) revealed decreased growth and N_2 fixation under elevated CO_2 conditions (Czerny *et al.,* 2009). The wide range of responses in N_2 fixation (e.g., Hutchins *et al.*, 2007; Levitan *et al*., 2007; Kranz *et al.*, 2010) may be explained by different CO_2 affinities (i.e., dependences of growth rates on CO_2 concentration) of a range of N_2-fixing cyanobacteria (*Trichodesmium* and *Crocosphaera*) from different oceanic biomes. Some species/strains operate at close to maximum growth rates at present-day oceanic CO_2 levels, whereas others had sub-optimal growth rates under these conditions (Hutchins *et al*., 2013). To date, the physiological mechanisms underlying these responses remain unknown, especially in open-ocean nitrogen fixers. Cyanobacteria may reallocate energy from their energetically expensive CCMs toward N_2 fixation and the acquisition of growth limiting nutrients (Kranz *et al.*, 2010; Levitan *et al*., 2010), but evidence for such diversion of energy is lacking. Whether nitrogen fixation will increase with progressive ocean acidification remains to be explored (*low confidence*, *limited in situ evidence*, *medium agreement*).

The responses of coccolithophore calcification to OA are species-specific and highly variable. The function(s) of calcification are not well understood, making it difficult to evaluate the consequences of lowered calcification (e.g., Rost *et al*., 2008). Reductions, increases, and unchanged calcification rates (and shell structure) have all been found in different coccolithophore species for RCP 8.5 CO_2 conditions projected around 2100 (Riebesell *et al.*, 2000; Zondervan *et al.*, 2001; Langer *et al.*, 2006; Iglesias-Rodriguez *et al.*, 2008). Calcification in coccolithophores is species- (Langer *et al.*, 2006) and in *Emiliana huxleyi* even strain-specific (Langer *et al.*, 2009, 2011; Hoppe et al., 2011). It thus remains unclear whether OA will result in exoskeletons that are insufficiently calcified for sustained structural support and protection in coccolithophores (*medium evidence, low agreement*).

Foraminifera display decreasing calcification and shell weight under elevated CO_2 (Lombard *et al.*, 2010). Changes in historical specimens (Moy *et al*., 2009, see below) and during glacial-interglacial cycles (Barker and Elderfield, 2002) support projections of future reductions in net calcification by foraminifera (*medium* to *high confidence*).

6.3.2.3. Macroalgae and Seagrasses

Primary production, shoot density, reproductive output, and below-ground biomass of seagrasses generally respond positively to elevated pCO_2, indicating CO_2 limitation of their productivity. Such effects were identified in both laboratory and field above 720 to 1800 µatm (*high confidence,* e.g., Palacios and Zimmerman, 2007; Hall-Spencer *et al.*, 2008; Andersson *et al.*, 2011, cf. 5.4.2.3). Production, growth, and recruitment of most but not all non-calcifying seaweeds also increased at CO_2 levels from 700 to 900 µatm (RCP8.5; Porzio *et al.*, 2011; Kroeker *et al.*, 2013). Some non-calcifying seaweeds and seagrasses will thus benefit from future ocean acidification (*high confidence*) but OA exposes them to higher than usual grazing as a consequence of losing deterrent phenolic substances (*low confidence,* Arnold *et al*., 2012).

Calcifying algae (corallines) show complex and species-specific responses of photosynthesis to elevated CO_2, but calcification is impacted once species-specific pCO_2 thresholds are surpassed (*medium confidence*, Anthony *et al.*, 2008; Martin and Gattuso, 2009). At habitat temperature calcification by temperate coralline red and calcareous green algae increased at CO_2 levels up to 900 µatm and only decreased at the highest concentration applied (2850 µatm), but did not fall below rates found at present-day pCO_2 (Ries *et al.*, 2009). During 3 months of exposure, growth of *Lithothamnion glaciale*, a cold-water calcareous red alga, decreased progressively with rising CO_2 levels, and its structural integrity was weakened beyond 590 µatm (Ragazzola *et al*., 2012), potentially influencing ecosystem function. Some calcifying algae may thus be impacted by future ocean acidification (*medium confidence*).

6.3.2.4. Animals

Studies of marine animals and their life stages show a high diversity and variability of processes affected by ocean acidification. Many variables studied reflect physiological performance (O_2 consumption, exercise, behavior, calcification, growth, immune response, acid-base balance, gene expression, fertilization, sperm motility, developmental time, production of viable offspring, and morphology; Table 6-3, Figure 6-10). In some species growth may be stimulated by OA, in others depressed, or unaffected (cf. Gooding *et al.*, 2009; Munday *et al.*, 2009a, 2011a; Dupont *et al.*, 2010). The degree of CO_2-induced acidosis and its compensation by ion exchange may shape sensitivity (6.3.2.1). Full exploitation of the ability to resist pCO_2 increases depends on the availability and high quality of food and the strengthening of fitness (Gooding *et al.*, 2009; Melzner *et al*., 2011). However, food quality of prey organisms may decrease under elevated pCO_2. For example, slower reproduction and growth of the copepod *Acartia tonsa* under 760 µatm pCO_2 was related to the decreasing quality of its diatom food (Rossoll *et al*., 2012).

Changes in calcification rates reported from CO_2 manipulation experiments vary widely. Reduced calcification and weakened calcified structures were seen under elevated pCO_2 in corals (see below), echinoderms (Kurihara and Shirayama, 2004), mollusks (Gazeau *et al*., 2013), and larval crustaceans (Arnold *et al.*, 2009; Walther *et al*., 2011). Some adult limpets and urchins increased calcification rates at pCO_2 from 600 to 900 µatm, before it fell at even higher pCO_2. In some adult crabs, lobsters, and shrimps calcification rates increased further with rising pCO_2 (Ries *et al.*, 2009). Stronger internal structures such as cuttlebones and otoliths resulted from enhanced calcification under elevated pCO_2 in juvenile cuttlefish (cephalopods, Gutowska *et al.*, 2008) and fishes (Checkley Jr *et al.*, 2009; Munday *et al.*, 2011b), with unclear impacts on fitness. Energy costs in epithelia or calcification compartments may be enhanced by elevated pCO_2 causing a stimulation of metabolism (6.3.2.1). In some cases, this may indicate imbalances in energy budget rather than increased CO_2 resistance, for example, if costs are down-regulated in muscle or liver. Enhanced calcification can then occur at the expense of growth (*medium confidence*, Wood *et al.*, 2008; Beniash *et al.*, 2010; Thomsen and Melzner, 2010; Parker *et al.*, 2011).

Studies on calcifying zooplankton focused on pteropods (planktonic mollusks with aragonite shells). These form an integral part of the food web, both as grazers and prey, e.g., for pink salmon (Armstrong *et al*., 2005; Hunt *et al.*, 2008). In the Subarctic, the Arctic, and the Southern Ocean, pteropods will reduce calcification in response to OA until at least the end of the century (*medium confidence*, Orr *et al.*, 2005; Comeau *et al.*, 2009; Lischka *et al*., 2011).

Elevated CO_2 causes behavioral disturbances in fishes (studied mostly in larvae and juveniles, Munday *et al.*, 2010; Ferrari *et al*., 2011; Domenici *et al*., 2012; Jutfeld *et al*., 2013) through neural mechanisms (Nilsson *et al*., 2012). The long-term persistence and evolutionary relevance of these behavioral effects need further study before general conclusions can be drawn (*low confidence*, Wittmann and Pörtner, 2013, Table 6-3).

6.3.2.4.1. Animal life cycles

It is generally held that early lifestages are always more sensitive to environmental stress than adults. In the context of ocean acidification this statement is supported by findings like larval oyster fatalities in aquaculture caused by upwelled CO_2-rich waters (*high confidence*; Barton *et al*., 2012). A key aspect may also be that larvae growing or developing more slowly under elevated CO_2 as in various groups including fishes (Baumann *et al*., 2012, 6.3.2.1) may encounter enhanced mortalities due to prolonged predator exposure. Comparative studies of animal sensitivities to OA over a complete life cycle or during critical transition phases (e.g. fertilization, egg development and hatching, metamorphosis, moulting) are scarce and do not support generalized conclusions (*low confidence*).

Effects of elevated CO_2 on one life stage or transition phase may affect or carry over to the next one. Moulting success into the final larval stage was reduced in a crab species (Walther *et al.*, 2010). In a sea urchin species, negative impact was found to accumulate during 4 months acclimation of adults reducing reproductive success. This impact was, however, compensated for during extended acclimation of female urchins for 16 months (Dupont *et al*., 2012). Negative impact was still transferred from urchin larvae to juveniles under elevated pCO_2. Conversely, adult oysters acclimated to high CO_2 acquired resistance which was carried over to their offspring (Parker *et al.*, 2012). More long-term acclimation studies to realistic emission scenarios are needed for generalized conclusions. Furthermore, the preposition that juvenile lifestages are always more sensitive than adults needs thorough re-investigation in the context of ocean acidification, especially in the context of the notion that larvae may provide a selection pool for survival of the most suitable phenotypes (6.3.2.1, *low confidence*).

6.3.2.4.2. Warm- and cold-water coral communities

In warm-water reef-building corals, OA causes genus-specific reductions in calcification (Leclercq *et al*., 2002; Langdon and Atkinson, 2005; Kleypas and Langdon, 2006). Nutrient availability to symbionts may sustain calcification. Heterotrophic feeding by the corals also supports energy-dependent calcification and acid-base regulation and thus, resilience (Edmunds, 2011; Figure 6-10). Females may sacrifice calcification more than males due to energetic tradeoffs with reproduction (Holcomb *et al.,* 2012). Warm-water corals are sensitive to future OA (*high confidence*, Table 6-3)

The cold-water coral, *L. pertusa* shows resilience to ocean acidification. In short-term ship-board incubations pH reductions between 0.15 and 0.3 units (540 and 790 µatm) led to calcification rates reduced by 30-56 % (Maier *et al.,* 2009), especially in young, fast growing polyps. However, net calcification was maintained at seawater aragonite saturation <1. Exposure to a pCO_2-induced pH reduction by 0.1 units or even to the projected end of century pCO_2 of 930 µatm led to calcification rates being maintained over six to nine months (Form and Riebesell, 2012; Maier *et al*., 2013). This ability is probably due to a regulated upward shift of pH and carbonate saturation at organismal calcification sites (Figure 6-10; McCulloch *et al*., 2012). Natural distribution of other cold-water species covers wide natural pH gradients in Chilean fjords (*Desmophyllum dianthus*; Jantzen *et al*., 2013) and ranges into waters with undersaturated carbonates as in Australian waters (4 scleractinian corals, Thresher *et al*., 2011). Pre-adaption to elevated pCO_2 apparently exists, however species vulnerabilities to further increases in pCO_2 have not been investigated. Again, vulnerability is species specific, colonial scleractinians may be limited to water saturated or near-saturated with aragonite, whereas others are not (Thresher *et al*., 2011). Conclusions on the relative vulnerability of the group appear premature (Table 6-3). To what extent a further lowering of carbonate saturation values will influence the future distribution of various calcite or aragonite forming cold-water corals is not clear (*low confidence*, Guinotte *et al*., 2006).

6.3.2.5. Ecosystems

For insight into ecosystem level processes, laboratory studies have been supplemented with experimental studies in large volume mesocosms (i.e., > 1000 L) and in the field, and with long- term field observations. Together they inform the debate over the attribution of field observations to ocean acidification.

6.3.2.5.1. Evidence from field observations

Contributions of anthropogenic ocean acidification to climate-induced alterations in the field have rarely been established and are limited to observations in individual species (see also 30.5.1.1.3). Shell thinning in modern planktonic foraminifera (collected 1997 to 2004) in the Southern Ocean compared to those from the Holocene and before was attributed to anthropogenic ocean acidification (Moy *et al*., 2009). Both anthropogenic OA and the upwelling of CO_2-rich deep waters (30.5.4.1.4) were held responsible for shell thinning in planktonic foraminifera in the Arabian Sea over the last century (de Moel *et al.*, 2009) or in live pteropods collected in 2008 in the Southern ocean (Bednaršek *et al.*, 2012; *medium evidence*, *medium agreement*). However, no changes were observed in a 57-year record of the composition and abundance of calcifying zooplankton in the increasingly acidified California Current System (Ohman *et al.*, 2009). Possible explanations for the absence of significant responses in some studies include insufficient lengths of time series (6.1.2), organisms being preadapted to naturally high CO_2 in upwelling or other systems, linked to a low signal-to-noise ratio, or the difficulty of detecting small OA effects in comparison with larger ecosystem effects of other drivers such as temperature, e.g., in calcifying plankton, Beaugrand *et al*. (2013). Similarly, declines in coral calcification and performance in the field (De'ath *et al.*, 2009) were attributed to thermal extremes, but may also include an as-yet unclear contribution from OA.

6.3.2.5.2. Microbial communities and nutrient cycles

Laboratory experiments, coastal mesocosm studies (Weinbauer *et al*., 2011) and field experiments (Beman *et al.*, 2011; Law *et al*., 2012) have yielded various, sometimes conflicting results on the effects of CO_2 on microbial processes. From a meta-analysis of available data, Liu *et al.* (2010) conclude that the rates of several microbial processes will be affected by OA, some positively, others negatively. The potential of the microbial community to adapt to ocean acidification and maintain functionality, either by genetic change at the species level or through the replacement of sensitive species or groups at the community level, remains to be explored further. At the present time there is insufficient field-based evidence to conclude that elevated CO_2 will affect natural assemblages of microorganisms (*limited evidence, low agreement*) with the possible exception of the negative impact on calcification (Joint *et al*. 2011).

Experimental studies on OA effects (through reduced pH or increased CO_2) on autotrophic and heterotrophic microbial production have provided inconsistent results. Microbes are characterized by large diversity and broad environmental adaptation, and hence may respond to environmental challenges by exploiting such diversity via species replacements (Krause *et al*., 2012). This makes it difficult to project the findings of laboratory experiments investigating the response of microbes to OA to the ecosystem level. Relevant variables include cellular elemental stoichiometry (C-N-P ratios, Riebesell, 2004; Fu *et al*., 2007), rates of CO_2 and N_2 fixation (Riebesell, 2004; Hutchins *et al*., 2007; Hutchins *et al*., 2009), rates of nitrification (Beman *et al*., 2011), changes in the proportion of dissolved (i.e., DOC) to particulate photosynthate produced during carbon fixation (Kim *et al*., 2011), and the response of viruses (Danovaro *et al.,* 2011).

Field experiments led to the projection that nitrification rates (ammonia oxidation to nitrite and nitrite oxidation to nitrate) of bacteria and archaea will be reduced by 3–44% when pH is reduced by 0.05–0.14 (Beman *et al.*, 2011), corresponding to a mean rise in CO_2 by ~100 µatm. The reported decrease in nitrification occurred regardless of natural pH variability, providing no evidence for acclimation of the nitrifiers to reduced pH, e.g., in upwelling areas. Potential changes in microbial cell abundance, possibly as a result of lower cellular nitrification rates, could further decrease the total rate of nitrification.

It remains unclear whether OA has contributed to the systematic changes in phytoplankton abundance and community structure observed over recent decades, which have largely been attributed to warming (Chavez *et al.*, 2011). In natural assemblages from coastal and polar waters, NPP is stimulated by increased CO_2 (*medium confidence*; Riebesell *et al.*, 2008; Tortell *et al.*, 2008). Small differences in CO_2 sensitivity may lead to pronounced shifts in the dominance of species (Tortell *et al.*, 2008; Beaufort *et al*., 2011). Quantification of the calcite mass of the coccolithophore community in the present ocean and over the last 40,000 years were in large part attributed to shifts between differently calcified species and morphotypes according to carbonate chemistry (Beaufort *et al.*, 2011). The same study, however, also observed heavily calcified *E. huxleyi* morphotypes in upwelling systems characterised by low pH, a finding which highlights the complexity of assemblage-level responses and may indicate pre-adaptation to elevated pCO_2. Due to the complex response patterns, it is not possible to project ecosystem-level effects from effects on coccolithophore calcification in monospecific culture experiments (*low confidence*). Projections of OA impacts on phytoplankton become even more complicated by synergistic interactions with other drivers (Boyd, 2011; 6.3.5).

6.3.2.5.3. Macrophytes and macrofauna

Macrofauna and macrophyte communities have been studied in mesocosms and in ecosystems exposed to shifted upwelling regimes or at natural volcanic CO_2 vents (Kroeker *et al*., 2011; Fabricius *et al*., 2011). The latter are considered as natural analogues of future ocean acidification. An eight-year trend of (variable) pH decline in upwelled waters along the Northeast Pacific coast was paralleled by shifts in community composition, where shelled species like mussels were replaced by fleshy algae and barnacles (Wootton *et al*., 2008). Macrofaunal calcifiers at CO_2 vents (Hall-Spencer *et al.*, 2008; Fabricius *et al.*, 2011) and in mesocoms (Christen *et al.*, 2013) display a lowering of species richness. These findings suggest that non-calcifiers increasingly outcompete calcifiers once pH_T decreases to a mean of 7.8 to 7.7 (*medium confidence*). Finally, a loss of calcifiers from mesocosms occurred around 0.5 units below the pH values expected from OA under RCP 8.5 by 2100 (*medium confidence*, Christen *et al.*, 2013). At CO_2 seeps, calcitic bryozoans replace coralline algae, which have more soluble high-calcite skeletons (Martin *et al.*, 2008). Seagrasses and non-calcifying algae gain a competitive advantage (Fabricius *et al.*, 2011). Coral communities exposed to high pCO_2 waters (from upwelling or seeps) have lower growth, calcification and biodiversity (Manzello *et al*., 2008; Fabricius *et al*., 2011), resulting in a shift from net accretion to erosion (Box CC-CR). The use of seeps as analogues of future OA is limited as pH variability is high at these sites, such that effective values may be lower than indicated by the average change (Hall-Spencer *et al.*, 2008; Porzio *et al.*, 2011). During periods of high pH at the seeps, they are recolonized by invertebrates and fishes from neighboring areas with normal pH, compromising assessments of long-term sensitivity thresholds. Overall, findings available from mesocosms and natural analogues indicate losses in diversity, biomass and trophic complexity of benthic marine communities due to elevated CO_2 (*high confidence*) and support the projection of similar shifts in other systems with continued OA (*medium confidence*).

Enhanced freshwater input by poorly buffered rivers or by precipitation, into estuaries, brackish oceans like the Baltic (30.5.3.1.4), and into freshening polar oceans, reduces salinity and alkalinity at rising atmospheric pCO_2 and thereby, alters the carbonate system and enhances OA (6.1.1). Estuaries usually have OMZs, where background pCO_2 is elevated. Its reduction by dilution causes the acidification effect to be somewhat less. Enhanced pH reduction and variability in hyposaline waters may constrain the distribution of sensitive species further (*low confidence*, Miller *et al.*, 2009; Denman *et al.*, 2011).

6.3.2.5.4. Conclusions

Natural analogues, laboratory and mesocosm experiments provide evidence for differential effects of ocean acidification on species and communities. Sensitivity to OA is species-specific (*high confidence*); differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (*low* to *medium confidence*). OA may stimulate global net primary production (*low confidence*) and nitrogen fixation (*medium confidence*). OA will increase the abundance and primary production of non-calcifying macrophytes, but will be harmful to calcifying algae and heterotrophs (*medium confidence*). Ecosystems relying on calcified structures and at risk of dissolution under OA include warm-water coral reefs (*high confidence*) and their cold-water equivalent (*medium confidence*). Further studies need to explore how OA may change the composition of communities, impact food webs and affect higher trophic levels.

6.3.3. Life in Hypoxia and Anoxia

6.3.3.1. Principles

Hypoxia constrains organisms which rely on aerobic metabolism (6.1.1, FAQ 6.2). Below O_2 concentrations of 60 µmoles kg^{-1}, commonly termed hypoxic (6.1.1.3), communities undergo species losses and replacements and are transformed into communities with species showing characteristic hypoxia adaptations. However, O_2 can limit animal life at even higher levels, just below air saturation (Gilly *et al*., 2013). Organisms' tolerance thresholds have been defined by either the critical O_2 partial pressure (P_c) or concentration (O_2crit). Thresholds vary across domains and are highest for large multicellular organisms. Among these, the P_c at rest varies depending on species, body size, and lifestage. In animals below the P_c aerobic metabolic rate fails to be maintained and anaerobic metabolism contributes to energy production (Pörtner and Grieshaber, 1993). The critical oxygen threshold is set by the capacity of ventilatory and circulatory systems to supply O_2 and cover demand. The threshold increases once metabolism is stimulated by muscular activity, temperature, or food uptake (Pörtner, 2002a; Ekau *et al.*, 2010; Seibel, 2011; Figure 6-11). At extreme temperatures, O_2crit approaches the oxygen content of air-saturated water (Pörtner, 2010; McBryan *et al*., 2013), indicating high sensitivity to hypoxia in the warmth. Most animals can only sustain anaerobic metabolism temporarily, even if they are energy-efficient and survive long periods of anoxia (Grieshaber *et al.*, 1994). Such time-limited tolerance is higher in large than in small individuals or larvae, related to the higher capacity of anaerobic metabolism in large specimens (Gray *et al.*, 2002; Jessen *et al*., 2009).

6.3.3.2. Microbes

Bacteria and protists consume ambient oxygen down to very low levels in ‘oxygen minimum zones’ and sustain OMZs by their metabolic diversity (Figure 6-11; WGI Box 6.5, Figure 1). OMZs form habitat for both anaerobic and aerobic microbes which can utilize very low (< 1 µmoles kg^{-1}) O_2 concentrations (Stolper *et al.*, 2010). Hypoxia is paralleled by elevated pCO_2 and enhanced acidification. Microbial life will benefit from expanding OMZs (*high confidence*) .

6.3.3.3. Animals and Plants

In mesopelagic OMZs, zooplankton also contribute to the development of hypoxia (Robinson *et al*., 2010, FAQ 6.2). During daytime zooplankton congregate at the upper margin of OMZs, where the degradation of organic material causes intensified respiration and oxygen depletion (Bianchi *et al*., 2013). Animals living permanently in the OMZ cover virtually all energy demand by aerobic metabolism. This requires special adaptations leading to a reduction in O_2 and energy demand, and the improved ability to efficiently use available O_2. Enhanced hypoxia tolerance reflected in low O_2crit values is supported by small body size and by cold temperature (Vetter *et al.*, 1994; Pörtner, 2002b; Levin *et al.*, 2009). Accordingly, low O_2 levels support abundant meiofauna (very small fauna, <1mm) which benefit from abundant food and reduced predation by larger organisms (Levin, 2003). Under suboxia only specialists can survive (Vaquer-Sunyer and Duarte, 2008). Expansion of suboxic and anoxic centres of pelagic OMZs and benthic dead zones will lead to loss of habitat for animal life (*high confidence*).

Large, more active animals like fishes, crustaceans, and muscular (as opposed to ammoniacal) squids tend to have high O_2 demands associated with high O_2crit thresholds, and are therefore excluded from permanently hypoxic water bodies. However, even in high-activity animal groups some specialists such as Humboldt squid or bigeye tuna have adapted to enter hypoxic environments though only temporarily (Richards *et al.*, 2009; Seibel, 2011). The time-limited tolerance of animals to hypoxia below the O_2crit is maximized by the depression of energy demand, for example during periods of metabolic arrest (e.g. developmental arrest or diapause of copepods; Auel *et al.*, 2005). Hypoxia-adapted lifeforms will benefit from expanding OMZs (*high confidence*).

There is little information on the hypoxia sensitivity of macrophytes or their O_2crit values. In eelgrass (*Zostera marina*), warming causes the hypoxia threshold to rise due to a strong increase in tissue respiration. Concomitant water or sediment hypoxia can elicit tissue anoxia and sudden die-offs (Raun and Borum, 2013). By contrast, macroalgae attached to rocks rarely encounter anoxia (Raven and Scrimgeour, 1997). Expanding benthic OMZs will constrain the distribution of macrophytes (*medium confidence*).

6.3.3.4. Ecosystems

OMZs, shoaling and expanding vertically and laterally (Gilly *et al*., 2013), will cause habitat and abundance losses for intolerant taxa such as mesopelagic (Koslow *et al*., 2011) and epipelagic fishes with a high O_2 demand (*medium* *confidence,* Prince *et al*., 2010; Stramma *et al*., 2012, FAQ 6.2). In line with the distribution of hypoxia sensitivities (Figure 6-11, 6.3.3.1, 6.3.3.3), expanding OMZs will further constrain the distribution of key zooplankton and nekton species and influence their diurnal and ontogenetic vertical migrations (*medium confidence*, Ekau *et al*., 2010). The composition of microbial and faunal pelagic communities will shift from diverse mid-water assemblages to migrant biota that return to oxygenated surface waters at night (Seibel, 2011). Dissolved O_2, among other factors, plays an important role in shaping large alternating fluctuations of sardine and anchovy abundances, particularly off Peru. Anchovies are not strongly affected by a shallow oxycline (<10m), while sardines actively avoid such conditions (Bertrand *et al*., 2010). Where OMZs intersect the continential shelves, groundfishes (McClatchie *et al.*, 2010) and large benthic invertebrates like crabs display high mortalities (Chan *et al.*, 2008). Susceptibility of early life stages to hypoxia in both pelagic and benthic ecosystems (Ekau *et al*., 2010) threatens population survival. Effects of hypoxia propagate along the food chain, constraining fish stocks and top predators (Stramma *et al.*, 2010; *high confidence*). Hypoxia reduces biodiversity (Levin *et al.*, 2009; Gooday *et al.*, 2010) and causes the marginalization of calcifiers, due to low metabolic rates and high pCO_2 (Levin, 2003; Levin *et al.*, 2009; *high confidence*).

The expansion and enhanced variability of OMZs increases dissimilatory nitrate reduction and anaerobic ammonium oxidation (anammox), both releasing N_2 into the atmosphere, reducing the availability of fixed nitrogen and limiting oceanic primary productivity (*medium confidence*). Water column denitrification and N_2 fixation are spatially and temporally variable (*limited evidence, low confidence*), suggesting that climate effects on these processes are *unlikely* to operate uniformly (Brandes *et al.*, 2007; Fernandez *et al*., 2011; Franz *et al*., 2012).

If O_2 levels decline and OMZs expand, tolerant taxa, such as anaerobic bacteria (Ulloa *et al*., 2012), gelatinous zooplankton (medusae, ctenophores), selected fishes (gobies, hake), and possibly selected cephalopods (Gilly *et al.*, 2006; Bazzino *et al*., 2010), will respond with range expansions or population growth. Similar phenomena are expected with intensified upwelling causing extensive mortalities of coastal fishes and invertebrates (Box CC-UP). A community change toward hypoxia-tolerant fauna will occur in mid-water (*high confidence*). The diversity of macroorganisms will decrease and, finally, higher marine organisms will disappear and heterotrophic microorganisms will dominate (*high confidence*). In isolated water bodies like the Black Sea, warming will lead to the expansion of anoxia and H_2S poisoning, reduce pelagic and bottom faunal distributions, and shape trophic relations, energy flows, and productivity (Daskalov, 2003; Fashchuk, 2011).

[INSERT FIGURE 6-11 HERE
Figure 6-11: (A) Principal mechanisms underlying the formation of hypoxic conditions and their biological background (modified from Levin *et al.,* 2009; Levin and Sibuet, 2012). The buoyancy flux from fluvial discharges produces sharp density stratification at the base of the freshened layer (also valid for ice melt and high precipitation) near the surface and, hence, vertical mixing is greatly reduced. In consequence, the nutrient inputs from the river and the atmosphere accumulate in a narrow upper layer, leading to blooms of phytoplankton, possibly including harmful algae. The enhancement of oxygen consumption due to aerobic decomposition of sinking organic matter results in hypoxic conditions of benthic and midwater OMZs. Enrichment of nutrients (eutrophication) results in coastal dead zones. In the open oceans, heating of the upper layer increases stratification, while the wind-driven upwelling of hypoxic, nutrient-rich water from deeper layers adds to the formation of the OMZs (Box CC-UP) (B) Distribution of free-living marine organisms (microbes such as archaea, bacteria, protists, small and large multicellular animals, and plants) across the ranges of O_2 concentrations in various water layers. Hypoxia tolerance is enhanced in small compared to large organisms, allowing unicellular species and small animals to thrive in extremely hypoxic habitats. Species richness and body size of animals increases with rising O_2 levels.]

6.3.4. Mixed Layer Depth and Light Shaping Net Primary Production

The upper ocean is characterized by physical and chemical gradients in the surface mixed layer that influence the magnitude of photosynthetic carbon fixation, often termed Net Primary Production (NPP). The availability of light and nutrients to photoautotrophs sets daily rates of NPP and may be altered directly or indirectly, through changing mixed layer depths, shifts in the circulation regime at different spatial scales and the physical displacement of organisms (6.1.1.4, Box CC-PP, Figure 6-2). A changing climate will affect mixed layer depth, cloudiness, and/or sea-ice areal extent and thickness and thereby, modulate NPP (*high confidence*). A stronger vertical density gradient will reduce the communication between the sunlit upper ocean where photosynthesis takes place and the underlying nutrient-rich waters (Figure 6-2). The supplies of plant nutrients (macro-nutrients) such as nitrate, and of micro-nutrients such as iron (Pitchford and Brindley, 1999) vary seasonally (Boyd, 2002) and regionally (Moore *et al.*, 2002), such that NPP may be simultaneously limited (co-limited) by more than one resource (6.3.5; Saito *et al.*, 2008).

The changing range and intensity of underwater light will lead to changes in NPP as well as in phytoplankton community composition (Doney, 2006; Boyd *et al*., 2010). The response of phytoplankton to changing sunlight involves photo-physiological acclimation via changes in cellular chlorophyll, but such acclimation is constrained by unidentified limits (Falkowski and Raven, 1997). A longer growing season, with more sea-ice free days between 1998 and 2009, may have increased NPP in open Arctic waters (Arrigo and van Dijken, 2011; Box CC-PP), complemented by massive under-ice blooms as seen in 2011, favored by light that penetrates surface melt ponds and thinner, e.g., first-year ice (Arrigo *et al*., 2012). There are also reports of increased incidences of high phytoplankton stocks, and hence of greater NPP, deeper in the water column (i.e., where it cannot be detected by satellite) during summer in the Arctic, which have implications to assessing changes in NPP from space (Hill *et al.*, 2013). Little is known about shifts from sea-ice algae to free-drifting phytoplankton expected with a decrease in sea-ice cover and effects of increased light in polar waters in the coming decades (*low confidence*). In the Arctic, summer ice melt led to a rapid export of sea-ice algae to the deep ocean (Boetius *et al.*, 2013). As some krill feed primarily on sea-ice algae, it is unclear (*low confidence*) whether they will adapt to feeding mainly on free-drifting phytoplankton (Smetacek and Nichol, 2005).

A range of time-series observations, from in situ phytoplankton abundances to satellite remotes-sensing, have been used to assess whether phytoplankton stocks and hence rates of NPP have altered over recent decades. Increases in phytoplankton stocks were found in regions where colder waters had warmed in the Northeast Atlantic, whereas the opposite trend was observed for warm water regions from a phytoplankton abundance time-series (Richardson and Schoeman, 2004). Lower chlorophyll concentrations at warmer SSTs in nutrient-poor low-latitude waters, based on satellite ocean color data, have been interpreted as an effect of increased stratification on phytoplankton stocks. It has thus been suggested that expanding, permanently stratified, low-chlorophyll, tropical regions (WGI, Ch. 3) indicate declining phytoplankton stocks in the warming oligotrophic waters of the N and S Pacific and N and S Atlantic (*limited evidence*, *low agreement* due to methodological uncertainties, Box CC-PP; Polovina *et al.*, 2008; Signorini and McClain, 2012; 30.5.1.1.2). Furthermore, a transition to conditions favoring increased frequency or even permanence of El Niño in a warmer future (Wara *et al.*, 2005) and further expansion of subtropical ocean gyres (Polovina *et al.*, 2008; 30.5.6), may lead to lower global ocean NPP (*low* to *medium confidence*).

However, these long-term ‘blended’ projections (i.e., constructing a biomass time-series using multiple proxies such as ocean transparency) of a global decrease in phytoplankton biomass (Boyce *et al.*, 2010) have been refuted (McQuatters-Gollop *et al*., 2011; Mackas, 2011; Rykaczewski and Dunne, 2011). Time series shorter than 20 years do not resolve impacts of bidecadal variation such as the Pacific Decadal Oscillation or the lunar nodal cycle (e.g., Watanabe *et al*., 2008; Henson *et al*., 2010). Analysis of continental shelf ecosystems, including field data in the most productive upwelling areas covering the last 20 years (e.g. Chavez *et al*., 2011), revealed a large variety of trends at scales of several decades but a general increase in NPP on most shelves (Sherman and Hempel, 2009; Bode *et al*., 2011), possibly caused by natural climate variability, anthropogenic climate change, and/or anthropogenic eutrophication. Recent field measurements document an increasing rate of both anthropogenic fixed N (Duce *et al*., 2008) and biological fixation of atmospheric nitrogen (Mouriño-Carballido *et al*., 2011) entering the open ocean, which could lead to increased NPP especially in warm, stratified tropical and subtropical oceans provided sufficient phosphate and other growth requirements are present (*low confidence*, e.g., Sohm *et al*., 2011).

For heterotrophs, from bacteria to fish, mammals and birds, the uptake of organic material as food, ultimately provided by NPP, is central not only to productivity but also for fueling energy consuming functions including the resistance of organisms to environmental change and pathogens (6.3.1-2). Any direct influence of climate on the abundance and quality of feed organisms will thus translate to indirect effects on the productivity and well-being of foraging animals (*high confidence*, Figure 6-5A, 6-7A, 6-12).

Overall, pelagic systems respond to climate change by region-specific changes in productivity with the projection of a small net reduction in global ocean NPP by 2100 (*medium confidence*, Box CC-PP). The spatial reorganization of NPP between latitudes affects higher trophic levels by alteration of the composition and functioning of pelagic communities (*medium confidence*).

6.3.5. Concurrent Responses to Multiple Drivers

Climate change alters oceanic properties globally, with concurrent changes in temperature, dissolved CO_2 and O_2, light, and nutrient concentrations (e.g., Sarmiento *et al.*, 1998; Matear and Hirst, 1999; Boyd and Doney, 2002; Ekau *et al.*, 2010; Figure 6-2). Additional direct human interventions at regional scale comprise the introduction of non-native species, overfishing, pollution, long-range atmospheric transport of nitrogen, point-source eutrophication, and habitat destruction (Carlton, 2000; Boyd and Hutchins, 2012). Worldwide alterations in marine ecosystems (Pauly *et al.*, 1998; Österblom *et al.*, 2007) have been linked to direct human activities, especially fishing (Frank *et al.*, 2005; deYoung *et al.*, 2008; Casini *et al.*, 2009), but may also be caused to some extent by climate variability and change (Cheung *et al*., 2013a).

Alteration of each individual property has pronounced effects on organisms from microbes to animals, and hence on ecosystems (6.3.1-4). The cumulative effects of these factors will result in complex patterns of change, from organismal physiology to the areal extent and boundaries of biogeographic regions (Table 6-4). In many organisms, effects of ocean acidification interact with those of other key drivers like temperature and hypoxia (Pörtner, 2012; Boyd, 2011; Gruber, 2011) and translate from molecular to ecosystem level impacts. In phytoplankton, low light (Zondervan *et al.*, 2002) or nitrogen limitation (Sciandra *et al.*, 2003) limit beneficial OA effects on photosynthesis, and have a strong negative effect on plankton calcification (Rokitta and Rost, 2012). Nutrients and light support functional adjustments to OA through gene expression changes (Dyhrman *et al*., 2006; Richier *et al*., 2009).

Similar to today, paleo-events such as the Palaeocene-Eocene Boundary demonstrate concurrent warming, enhanced stratification of the oceans, deoxygenation of deeper waters, and OA, albeit at a rate more than 10 times slower than today's rate (6.1.2). Both the complexity of paleo-ecosystem changes and the complexity of present effects confound the clear attribution of biological trends to individual drivers (Parmesan *et al.*, 2011). For warming and hypoxia, changes are accelerated by effects of shifting seasonal or even diurnal extremes and their frequency on organisms and ecosystems (*medium evidence* and *agreement*) (e.g. Pörtner and Knust, 2007; Díaz and Rosenberg, 2008). This may also apply to effects of anthropogenic OA (*limited evidence* and *low agreement*).

6.3.5.1. Principles

Effects of various climate drivers on ocean ecosystems are intertwined and effects may be exacerbated by responses of biota. For example, warming reduces O_2 solubility and enhances biotic O_2 demand, which exacerbates hypoxia, produces CO_2 and causes acidification (Millero, 1995; Brewer and Peltzer, 2009). Drivers act with either additive, synergistic (i.e., amplification of) or antagonistic (i.e., diminution of) effects. A meta-analysis of 171 experimental studies that exposed marine systems to two or more drivers identified cumulative effects that were either additive (26%), synergistic (36%), or antagonistic (38%) (Crain *et al*., 2008). Effects range from direct impacts of ocean warming on organismal physiology (Pörtner and Knust, 2007), to ocean acidification acting together with warming, e.g., on coccolithophore calcite production and abundances (Feng *et al.*, 2009), or with hypoxia and/or salinity changes (Table 6-4). Interactions of predominantly temperature, ocean acidification, and hypoxia have *likely* been involved in climate-driven evolutionary crises during Earth history (Pörtner *et al*., 2005; 6.1.2).

[INSERT TABLE 6-4 HERE
Table 6-4: Potential interactions between modes of anthropogenic forcing (environmental; foodwebs, harvesting) on different levels of biological organisation. These interactions, from simple to complex, are illustrated with examples from the literature. E, O, and M denote Experiments (lab or field), Observations, or Modeling approaches, respectively. Unknown denotes no published information is available for each of these categories. NA denotes Not Applicable for this category.]

Effects on individual organisms may also reflect intertwined impacts of ocean warming, acidification and hypoxia, which may operate through interrelated functional principles (Pörtner, 2012). Such knowledge helps to reconcile apparently contrasting findings. For example, warming toward the thermal optimum (Figure 6-5A) stimulates resistance to OA; CO_2-induced disturbances of growth and calcification were reversed by concomitant warming (Sheppard-Brennand *et al.*, 2010; Findlay *et al.*, 2010; Walther *et al.*, 2011). Warming to above optimum temperatures, however, constrains performance and exacerbates sensitivity to hypoxia (see below) and/or elevated CO_2 (Figure 6-5, e.g., via decreased calcification, Rodolfo-Metalpa *et al*., 2011), Both hypoxia and/or elevated CO_2 in turn enhance heat sensitivity, as seen for CO_2 in crustaceans (via decreased heat limits, Walther *et al.*, 2009; Findlay *et al.*, 2010), coral reef fishes (via reduced performance, Munday *et al.*, 2009b) and corals (via decreased calcification and CO_2-enhanced bleaching; Reynaud *et al*., 2003; Anthony *et al.*, 2008). This translates into a narrowing of the thermal niche (Walther *et al.*, 2009; Figure 6-5), which will shrink biogeographic ranges, affect species interactions and shift phenologies (Figure 6-7A). Hence, extreme warming and hypoxia exacerbate CO_2 effects and vice versa (*medium confidence*). Such principles need to be reconfirmed across organism taxa (Pörtner, 2012).

Differences in organism adaptation to a climate zone's characteristic temperatures, temperature variability, oxygen content, and ocean chemistry may shape vulnerability to climate change. In high polar species evolutionary cold adaptation enhances vulnerability to warming (*medium confidence*). In oxygen minimum zones, marine sediments, and in polar waters (due to high solubility in the cold), CO_2 levels are elevated and adaptation may reduce sensitivity and reliance on calcified structures (Clark *et al.*, 2009; Walther *et al.*, 2011; Maas *et al*., 2012). The observed shift from 'overcalcified' to 'weakly calcified' coccolithophores *Emiliania huxleyi* in cold waters may reflect a related shift in ecotype dominance (Cubillos *et al.*, 2007, *limited evidence, medium agreement*).

Despite such potential adaptation, polar calcifiers exposed to higher CO_2 and lower carbonate saturation levels have been hypothesized to be highly sensitive to further CO_2 accumulation (*limited evidence, high agreement*; Orr *et al.*, 2005). Here it appears relevant that cold temperature reduces energy demand and thereby lowers resistance to ocean acidification. Both energy demand and resistance are higher in eurytherms than in high polar and deep sea stenotherms (Pörtner, 2006; e.g. crustaceans, Pane and Barry, 2007, cf. Whiteley, 2011; *limited evidence, medium agreement*). In turn, tropical species may be more sensitive than temperate zone species (Pörtner *et al.*, 2011). This rough differentiation of sensitivity is complicated by the local adaptation of populations from within-species genetic variability (*low confidence*).

Temperature influences hypoxia sensitivity (6.3.3). Warming causes the minimum tolerated O_2 level to rise, enhancing vulnerability (*high confidence*). Conversely, hypoxia enhances vulnerability to warming in animals. This may occur fastest in warm oceans, where metabolic rates are higher and animals live closer to upper thermal limits (*medium confidence*, Pörtner, 2010). However, evolutionary adaptation has led to high hypoxia tolerance (low P_c or O_2crit values) in some warm-adapted coral reef fishes. Further warming then causes a rise in P_c which cannot be compensated for (Nilsson *et al*., 2010). Limits to hypoxia adaptation coincide with upper thermal limits (*medium confidence*).

Complexity in responses rises with the number of drivers involved. Enhanced river runoff and increased precipitation cause a shift from marine to more brackish and even freshwater communities, with unclear consequences for effects of other drivers. Falling primary production reduces resilience of higher trophic levels (Kirby and Beaugrand, 2009; Stock *et al.*, 2011). The introduction of non-indigenous species, when supported by climate-induced shifts in interactions, may promote the displacement of ecotypes and shifts in ecosystem functioning, e.g., in the Mediterranean Sea (Occhipinti-Ambrogi, 2007; Coll *et al.*, 2010).

6.3.5.2. Microbes

Both synergistic and antagonistic effects of multiple drivers on microbial biota in the surface ocean have been observed in manipulation or modeling experiments (Boyd *et al.*, 2010; Folt *et al.*, 1999; Gruber, 2011). The productivity of many microbes was simultaneously limited by, for example, availability of nitrate and phosphate, cobalt and iron (Saito *et al.*, 2002; Bertrand *et al.*, 2007), or iron and light (Boyd *et al.*, 2010; 6.2.2). Warming and high CO_2 synergistically enhanced photo-physiological rates of the cyanobacterium *Synechococcus*, whereas the cyanobacterial group *Prochlorococus* showed no change (Fu *et al.*, 2007). The magnitude of CO_2 effects on growth, fixation rates or elemental ratios within single species is often strongly modulated by nutrient availability and light conditions (e.g., Zondervan *et al.*, 2002; Sciandra *et al.*, 2003; Kranz *et al.*, 2010). Such differences cause floristic shifts in phytoplankton with the potential to restructure predator-prey interactions (Table 6-4).

Co-limiting factors vary by group, such as nitrogen fixers (e.g., Hutchins *et al*., 2007; Kranz *et al.*, 2010), diatoms (Boyd *et al*., 2010), and coccolithophores (e.g., Feng *et al*., 2009; Rokitta and Rost, 2012). This limits the ability to project climate change effects (Boyd *et al.*, 2010). The most reliable projections at ocean basin scale come from modeling, which mainly points to synergistic effects, such as those of elevated CO_2, hypoxia, and warming. For example, OA is projected to alter sinking particles (C:N ratio and/or reduced calcite content and slower sinking) with a consequent knock-on effect on water column O_2 demand already stimulated by warming, thereby causing expansion of OMZs (Gruber, 2011).

6.3.5.3. Animals and Plants

High oxygen availability alleviates thermal stress as seen in fish and mollusks (Mark *et al.*, 2002; Pörtner *et al.*, 2006). Conversely, hypoxia reduces heat tolerance (6.3.5.1), but acclimation to hypoxia compensates for this and increases thermal tolerance (Burleson and Silva, 2011), for example by enhancing blood pigment content or reducing energy demand. Tolerances to hypoxia and to high temperature may be positively correlated in some fishes, indicating potential for adaptive evolution under climate change (*low confidence*; McBryan *et al*., 2013).

As a consequence of hypoxia narrowing thermal ranges (6.3.5.1), combined warming and expanding hypoxia may cause mid-water mesopelagic and demersal fish stocks to decline at rates much quicker than anticipated in the California Current Ecosystem (Koslow *et al*., 2011; McClatchie *et al*., 2010). In benthic fauna, warming will also increase vulnerability to hypoxia. Experiments showed a rise in lethal oxygen concentrations by 25 % and thereby reducing survival by 36 % at 4 °C warmer temperatures (Vaquer-Sunyer and Duarte, 2011). Hence, warming is expected to expand the area of ecosystems affected by hypoxia even if oxygen concentrations remain unchanged (*high confidence*). Under combined hypoxia and warming, CO_2 can extend short-term passive tolerance (despite constraining long-term tolerance). It facilitates a reduction in energy demand (Reipschläger *et al*., 1997; Pörtner *et al.*, 2000), thereby extending survival of transient extremes of temperatures or hypoxia (*medium confidence*).

In macroalgae (non-calcifying) light availability modulates the response to elevated pCO_2 and temperature levels (Russell *et al*., 2011; Sarker *et al*., 2013). In warm-water corals, warming acting synergistically with CO_2 reduces calcification and increases sensitivity to bleaching (*high confidence*; Anthony *et al*., 2008). Combined warming and OA following B1 (~RCP4.5, reduced emission) and A1FI (~RCP8.5, business as usual) scenarios in mesocosms caused losses of symbionts and corals, and a nocturnal decalcification of the reef community in summer. Present day conditions already imply reduced resilience to episodic extreme events such as cyclones (Dove *et al.,* 2013, Box CC-CR).

6.3.5.4. Ecosystems

The cumulative impacts of climate change drivers underlie alterations of species interactions and ecosystem structure and functioning, including changes in trophodynamics and the physical and chemical characteristics of habitats (*high confidence*). These effects combine with more indirect effects, such as shifts in stratification and productivity, expanding oxygen minimum zones, and the changing composition and biomass of food (partly resulting from direct effects on prey organisms) (*high confidence*). These complexities reduce the precision and reliability of quantitative projections (6.5), including uncertainties concerning shifts in upwelling and their future role in global primary production and the development of fish stocks (Box CC-UP).

At the level of animal communities, effects of various drivers remain largely unexplored, some are highly complex. For example, the net eastward shift of Pacific skipjack tuna between 1980 and 2009 was linked to the shifting aggregation of macrozooplankton and micronekton, involving complex interactions of climate variability (due to ENSO, 30.5.2), warming ocean surface, shallowing mixed layer depth relative to the position of the warm pool, and the convergence of the pool with the Pacific Equatorial Divergence Province (30.5.6.1.1, Lehodey *et al*., 2011). Interactive drivers will affect the relative performance of interacting species, thereby shifting species ranges, interactions and food webs (*medium confidence*, Figure 6-7A). Adaptation to various climate zones modifies the roles of light and temperature in seasonalities and species interactions (Bradshaw and Holzapfel, 2010). Moderate hypoxia expansion in warming seas, e.g. as the stratified central North Sea (Queste *et al*., 2013) may well influence the degree of temperature-induced species displacements (Figure 6-7B).

Impacts of climate change on benthic ecosystem engineers can also profoundly alter ecosystems. Tropical corals respond to ocean warming and acidification by increased bleaching, impeded calcification rates, and increased incidence of disease (6.3.1-2; 30.5.6; Veron *et al.*, 2009; Veron, 2011, Box CC-CR, *high confidence*). In coral reefs under multiple stressors, differentiation of these large-scale phenomena into species-specific sensitivities is highly uncertain as trend data are virtually non-existent (Brainard *et al*., 2011). Little is known about impacts on deep-water or cold-water corals and sponges, tropical calcified algae, bryozoans, sponges, and tube-forming serpulid worms (Wood, 1999). The reliance of all of these on surface productivity makes them vulnerable to any alteration in food supply. Projected severe stress from increased temperature, hypoxia and ocean acidification will cause reduced performance and increasing mortality in ecosystem engineers (*high confidence*), and a deterioration of habitat characteristics for other organisms (*medium* to *low confidence*).

As a corollary, shifts in the geographical distributions of marine species (e.g., to higher latitudes or deeper waters; Figures 6-7B, 6.5.2) cause changes in community composition and interactions (Simpson *et al*., 2011; Harley, 2011; Hazen et al., 2013). Some species may gain predominance and abundance from fitness benefits (Figure 6-7) while others become less competitive or easier prey (Occhipinti-Ambrogi, 2007). Thereby, climate change will reassemble communities and affect biodiversity, with differences over time and between biomes and latitudes (*high confidence*, Box CC-PP; 6.5, Sala and Knowlton, 2006; Cheung *et al.*, 2009; Parmesan and Matthews, 2005; Parmesan *et al*., 2011).

6.3.6. Food Web Consequences

Community re-assembly under climate change involves a change in species composition and strongly alters food web structure, e.g., causing shifts in trophic pathways (Figure 6-12; Kirby and Beaugrand, 2009; Moloney *et al.*, 2011), some of which are irreversible (Jarre and Shannon, 2010). Through trophic cascades (Cury *et al.*, 2003; Luczak *et al.*, 2011), climate affects predation, competition, and food availability (e.g., via changes in NPP; Figure 6-12; Utne-Palm *et al.*, 2010), including fish resources (Parsons and Lear, 2001; Brown *et al.*, 2010). Trophic amplification then drives an ecosystem towards a new stable structure or regime, which may be difficult to reverse (Folke *et al*., 2004). Warming may result in consumer control of food web structure because respiration of heterotrophic zooplankton and bacteria increases more strongly with warming than does photosynthesis of autotrophic phytoplankton (*medium confidence*, O'Connor *et al*., 2009).

[INSERT FIGURE 6-12 HERE
Figure 6-12: Schematic diagram of expected responses to climate change in a marine food web. A coupled pelagic and benthic food web is structured by the body size spectrum of species. Combined warming, hypoxia and ocean acidification reduce body size, shift biogeographies, change species composition and abundance, and reconfigure trophic linkages and interaction dynamics. Fishing generally removes large-bodied species and truncates the body-size spectrum of the community. This confounds the detection and attribution of food web responses to climate change. Arrows represent species interactions (e.g., between predator and prey or competitors for food or space). Broken lines reflect the potential loss of populations and trophic linkages due to climate change.]

Many impacts of climate change on food webs resemble those caused by fishing, pollution, eutrophication, and associated hypoxia (6.3.3), and habitat change (Brander, 2007); unambiguous attribution to climate remains difficult (*low* to *medium confidence*; Parmesan *et al*., 2011). Some of these factors also affect food web responses to climate change. Fishing truncates the age and size structure of populations, making them more dependent on annual recruitment and reducing their ability to buffer environmental fluctuations (Genner *et al*., 2010; Botsford *et al.*, 2011; Planque *et al.*, 2010, Figure 6-12). Both adult and larval fishes show greater variability in abundance in exploited compared to unexploited populations (Hsieh *et al.*, 2008). Warming, acidification, and removal of top or competing predators may all contribute to large fluctuations in gelatinous plankton (e.g., jellyfish) populations (*low confidence*, Molinero *et al*., 2005; Richardson and Gibbons, 2008; Richardson *et al*., 2009; Condon *et al*., 2012).

Analyzing impacts on key species provides insight into how individual components of a food web will respond to perturbations. However, projections of future states must include the complex food web interactions that influence the species, and system-level responses, which affect stability and resilience of the overall ecosystem (Neutel *et al.*, 2007; Dunne and Williams, 2009; Romanuk *et al.*, 2009). There is no single approach currently available that includes the complex links within and among ecosystems, biogeochemistry, and climate as needed for projections of future states of marine food webs (Fulton, 2011; Moloney *et al.*, 2011). In conclusion, there is *low confidence* in the quantitative projections of such changes (for further discussion see 6.5).

6.3.7. Marine Reptiles, Mammals, and Birds

6.3.7.1. Principles

Marine reptiles (turtles, snakes, crocodiles), mammals, and seabirds breathe air but live mostly in water; some shift or expand their ranges as a result of climate warming. The body temperature of ectothermic reptiles is set by ambient conditions; only at large body size may their body store heat and temperature be higher than ambient. Reptiles are thus more responsive to temperature than homeothermic seabirds and marine mammals (McMahon and Hays, 2006), which regulate their body temperature by adjusting metabolic heat production and insulation from the environment, a trait beneficial especially in the cold. Various degrees of body core insulation in mammals and birds constrain their distribution to either warmer or colder waters (by poor or high insulation, respectively). However, large body sizes enable some aquatic air breathers to travel across the widest temperature ranges possible in some of the largest migrations on Earth.

Changes in water chemistry and hypoxia have minimal direct influences on the air-breathing vertebrates, reflecting their large independence from physical and chemical drivers in the oceans. There is evidence for increased sound propagation in a CO_2-enriched ocean, but no evidence yet for any effect on biota (Ilyina *et al*., 2010). If habitat structures offering retreat or ambush disappear, this will increase the energetic costs of life. Warming waters increases the cost of pursuit-diving as prey fishes increase swimming velocity. The predation success of such mammals (e.g., sea lions) and seabirds (e.g., penguins, cormorants) is thus constrained to waters ≤20 ºC (Cairns *et al*., 2008), a trend that extrapolates into the future (*low* to *medium confidence*). As prey distributions shift, foragers tied to land between trips may be constrained by the physiological costs of finding prey (Hazen *et al*., 2013; Péron *et al*., 2012). If food items are only found in thermally restricted areas or move to greater depths, mammals and birds may become constrained to certain distribution ranges or to the physiological limits of their diving ability (McIntyre *et al*., 2011). Conversely, hypoxic habitat compression for fishes may facilitate foraging opportunities for their air-breathing predators (Hazen *et al*., 2009). Accordingly, many air-breathers encounter changing habitat and food availability with climate change (*high confidence*).

6.3.7.2. Field Observations

Some species of seabirds, marine mammals, and sea turtles have responded to the anomalous ocean climate of the 20th century (*high confidence*, Hughes, 2000). There is insufficient information to assess effects on sea snakes or crocodiles. Poleward distribution shifts of turtles consistent with recent warming have been recorded in almost all marine groups. Decadal-scale climate fluctuations affect their recruitment success and nesting abundance (Van Houtan and Halley, 2011), with an inverse correlation between warming and abundance in various species and regions (Balazs and Chaloupka, 2004; Chaloupka *et al.*, 2008; Mazaris *et al.,* 2009). Extreme weather causes nest flooding, considerably reducing hatching success (Van Houtan and Bass, 2007), projected sea level rise (WGI, ch. 13) will exacerbate such impact. Those with high fidelity to nesting and foraging sites (Cuevas *et al*., 2008) are impacted more than those capable of changing those sites (Fish *et al*., 2009; Hawkes *et al*., 2009). Continued warming, modulated by changing rainfall (Santidrián Tomillo *et al*., 2012), may skew turtle sex ratios towards females, increase egg and hatchling mortality (Fuentes *et al.,* 2009), cause earlier onset of nesting (Pike *et al*., 2006; Mazaris *et al.,* 2008), decrease nesting populations (Chaloupka *et al.,* 2008), and shift dietary breadths (Hawkes *et al.,* 2009), leading to projected recruitment declines (e.g., leatherback turtles; Saba *et al*., 2012). Vulnerability due to shifting sex ratio alone remains unclear, as nesting beaches have persisted with low production of male hatchlings over decades or longer (*low confidence*, Broderick *et al*., 2000; Godfrey *et al*., 1999; Hays *et al*., 2003). The absence of sea turtles in certain regions may be best explained by the temporal unavailability of food resources or strong thermoclines restricting their bottom foraging abilities (Braun-McNeill *et al.,* 2008; Gardner *et al.,* 2008).

Seabird range modifications probably caused by climate change were recorded in polar areas and the temperate zone of the North Atlantic (Grémillet and Boulinier, 2009). Temperate species have shifted their ranges to higher latitudes in both hemispheres (Robinson *et al.,* 2005; La Sorte and Jetz, 2010; Bunce *et al.,* 2002). Some species, like the king penguin, follow shifting foraging zones (Péron *et al*., 2012); others, like the emperor penguin, are affected by changing habitat structure (sea ice, Jenouvrier *et al*., 2012). Warming causes many bird species to breed earlier (Sydeman and Bograd, 2009). High-latitude, cool-water species undergo extended breeding seasons (Chambers *et al.,* 2011). There is often no agreement, whether changes reflect solely ocean warming, or a combination of factors, such as fishing pressure on seabirds' prey species, sea level rise, and pollution (Heath *et al.,* 2009; Galbraith *et al.,* 2005; Votier *et al.,* 2005). Most shifts in range and seasonal activity involve shifts in trophic relationships (*medium confidence*). Seabirds with narrow geographic domains are expected to be more susceptible to climate change (Chambers *et al.,* 2005; Grémillet and Boulinier, 2009), even leading to local extinctions (e.g., the Galápagos penguin, Vargas *et al.*, 2007; or the marbled murrelet, Becker *et al*., 2007).

The distribution, phenology, and migratory timing of marine mammals is also shaped by predator-prey dynamics and climate impacts on specific habitats (Calambokidis *et al.,* 2009; Salvadeo *et al*., 2011). Some marine mammals, i.e. dolphin, porpoise, and whale species shift their distribution poleward to follow the movement of their prey (*medium confidence,* Simmonds and Isaac, 2007; Salvadeo *et al.,* 2010; MacLeod *et al.,* 2005; Springer *et al*., 1999). As in birds, vulnerability to climate change is high for marine mammals with narrow geographic ranges and high habitat dependence. For example, the critically endangered vaquita, endemic to the Northern Gulf of California, cannot move north because of the land barrier (MacLeod, 2009). The polar bear (Laidre *et al.,* 2008; Rode *et al.,* 2012) and the walrus depend on sea ice as a platform for hunting, resting, and giving birth. For polar bears, access to prey such as ringed seals has been disrupted by the later formation and earlier breakup of sea ice in the eastern Canadian Arctic. Seasonal migrants into the Arctic (fin, minke, gray, killer, humpback whales) may increasingly compete with species adapted to operate in habitat with sea ice (some seals, narwhal, bowhead whale, beluga). Both may benefit from the net loss of sea ice, which will offer them better access to foraging in a pelagic-dominated ecosystem (Moore and Huntington, 2008).

6.3.8. Summary and Conclusions

An organism's capacity to perform, but also its access to food energy fueling that performance, shape its sensitivity to climate change (*high confidence*). Extreme temperatures surpassing the fringes of the thermal envelope cause local abundance losses, extinction and shifts in temperature-dependent distribution ranges (6.3.1, *high confidence*).

Some climate change effects detected in the field can be attributed to temperature, but few allow clear attribution to other drivers (6.3.1-5, 6.6). In fishes and invertebrates, specialization in regional climate regimes co-defines sensitivity to warming, acidification and hypoxia (6.3.5, *high confidence*). In marine mammals, birds, and ectothermic reptiles changes in life history and population dynamics have often not been directly attributed to climate drivers (*low confidence*), but rather to the availability of habitat and food (6.3.7, *high confidence*).

Natural climatic variability (Figure 6-1) and anthropogenic change, with a strong role of warming, cause large-scale changes in biogeography, abundance, diversity, community composition and structure of marine species (6.3.1, *very* *high confidence*). Warming reduces body size (6.3.1, *medium confidence*). Differential species responses modify their interactions across trophic levels through trophic amplification (6.3.6, *medium* to *high confidence*).

Some tropical species and ecosystems exist close to upper thermal limits placing them among the marine ecosystems most affected by climate change (6.3.1, *high confidence*). Corals and coral reefs are primary examples. However, other factors change concomitantly, such that quantifying the ecosystem change attributable to warming or other drivers has not always been possible (6.3.5).

Under future climate change ocean acidification will affect marine organisms and ecosystems for centuries (6.3.2, 6.3.5, *high confidence*). To date, very few ecosystem-level changes in the field have been attributed to anthropogenic or local ocean acification (6.3.2, *medium confidence*). Concomitant trends of warming, O_2 depletion, OA, and other drivers prevent clear attribution to OA (6.3.5).

Elevated CO_2 levels stimulate primary production of some macroalgae and seagrass species (*high confidence*), causing them to be more competitive than calcifying organisms (6.3.2, *medium confidence*). High sensitivities to OA are associated with low capacities to maintain pH in internal fluids (*high confidence*). Calcification rates in sensitive invertebrates, including corals, echinoderms, and mollusks, decrease under OA, especially if combined with temperature extremes (6.3.5, *high confidence*). Thresholds beyond which effects occur can be quantified only with *low confidence*; there are differential sensitivities and thresholds between taxa and species (6.3.2, *high confidence*).

Expansion of OMZs leads to community shifts clearly attributable to extreme hypoxia (6.3.3, *high confidence*). Gradual effects of a progressive decline in ocean O_2 levels on communities have not been sufficiently explored.

In general, community re-assembly with new species coming in will occur in the transition to future climates (*medium confidence*) and lead to new ecosystem states (6.3.6, *low confidence*). Climate change interacts with top-down human interferences, like fisheries or other forms of harvesting, which accelerate impacts (*medium confidence*). Non-linearities challenge the projection of marine ecosystem trajectories (FAQ 6.4).

In microbes, a conceptual foundation suitable to support an integrated understanding of climate impacts on individual species and communities is lacking. Specific physiological responses, such as in primary production, N_2 fixation, or calcification, can be attributed to multiple environmental drivers associated with climate change (6.3.1-5, *high confidence*).

6.4. Human Activities in Marine Ecosystems: Adaptation Benefits and Threats

Human societies benefit from resources and processes supplied by marine ecosystems, so-called ecosystem services. Attributing and projecting ecosystem changes and their effects on human communities caused by climate change including ocean acidification (OA) is challenging. Insufficient observations compound an understanding of long-term changes and the definition of baseline conditions. Some of the challenges are related to the difficulty of projecting how human communities will adapt to changing marine ecosystem benefits.

6.4.1. Ecosystem Services

Marine ecosystem services (e.g., WGII, Ch. 5) include products (food, fuel, and biochemical resources), climate regulation and biogeochemical processes (CO_2 uptake, carbon storage, microbial water purification), coastal protection, provision of space and waterways for maritime transport, cultural services (recreational and spiritual opportunities, aesthetic enjoyment), and functions supporting all other ecosystem services (nutrient cycling, photosynthesis, and habitat creation). Most components of the marine environment contribute to more than one major category of ecosystem service: for example, ocean primary productivity is classified as a supporting service, but it affects provisioning services via changes in fisheries, generation of fossil fuel resources, regulating services via the global carbon cycle and climate regulation, and cultural services via the enjoyment of a healthy ecosystem. Rarely has economic damage of climate change to a whole ecosystem been evaluated and projected. The projected loss of tropical reef cover due to ocean acidification under A1 and B2 SRES scenarios will cause damages of 870 and 528 billion USD (year 2000 value) by 2100, respectively (cost rising with parallel economic growth, Brander *et al*., 2012; Box CC-OA). Such loss is felt most strongly in the respective regions.

6.4.1.1. Food from the Sea

Fisheries provide 3 billion people with almost 20 % of their average per capita intake of animal protein (FAO, 2012a), 400 million depend critically on fish for their food (Garcia and Rosenberg, 2010). Total world marine capture fisheries catches stabilized in the mid-1990s at about 90 million tons per year. Marine aquaculture of primarily mollusks and crustaceans contributes over 63 million tons annually to seafood production, mostly concentrated in coastal areas (FAO, 2012b). The growth of aquaculture has decelerated, but is still considered a development opportunity and a strong need in regions such as Africa and Latin America (WGII, Ch. 7.4.2.2).

Climate-induced shifts in ecosystems and fisheries production will create significant challenges to sustainability and management (7.5.1.1.3), particularly for countries with fewer resources and lower adaptive capacity, including many low-latitude and small island nations (*high confidence,* Allison *et al.,* 2009; Worm *et al.*, 2009; Cooley *et al*., 2012; 7.2.1.2, 7.4.2.1, 30.6.2, WGIII, Ch. 2.1.4). Vulnerability will be exacerbated by increases in the frequency and severity of extreme events (e.g. floods or storms) damaging infrastructure, homes, health, livelihoods or non-marine food security (Kovats *et al.*, 2003; Rosegrant and Cline, 2003; Adger *et al.*, 2005; Haines *et al.*, 2006).

The projected trends in fish stocks will widen the disparity in food security between developing and developed nations. Fish migrations due to warming (6.3.1) have already shifted the composition of fisheries catches (Pinsky and Fogarty, 2012; Cheung *et al*., 2013a) and altered stock distributions (Sabatés *et al*., 2006). Further warming may be beneficial for fisheries productivity in some regions such as the North Atlantic, because of the poleward shift of exploited species and changes in primary productivity (Box 6-1, 30.5.1.1.1; Arnason, 2007; Stenevik and Sundby, 2007; Cheung *et al*., 2010), or for some Pacific Islands due to the eastward redistribution of tuna stocks (Lehodey, 2000; Lehodey *et al.,* 2011). Resulting changes in accessibility and fishing operations costs are projected to straddle economic zones, perturb international fishery agreements and cause excessive exploitation (Hannesson, 2007; Sumaila *et al*., 2011; 7.3.2.6; WGIII, Ch. 4.3.7).

Invertebrate fisheries and aquaculture appear very vulnerable to the impacts of ocean acidification (Barton *et al*., 2012; Box CC-OA; Figure 6-10). This concerns especially shelled mollusks, with a substantial decline in their global production projected between 2020 and 2060 under the A2 business as usual scenario (Cooley and Doney, 2009; Cooley *et al*., 2012). Effects on calcifying plankton will propagate through the food web, making estimates of economic impact on fish catch by OA difficult, also due to complex interactions with other stressors like warming and fisheries management (Branch *et al*., 2013; Griffith *et al.,* 2012). Model projections suggest a potential loss of up to 13% (A1F1 scenario) to annual total fishery value in the US, or globally over 100 billion USD annually by 2100 (Cooley and Doney, 2009; Narita *et al*., 2012). Vulnerability differs highly between nations according to the contribution of such fisheries to their economy (Cooley *et al*., 2012; 7.3.2.6). These projections are sensitive to the projected vulnerabilities of the organisms to ocean acidification (6.3.2, *medium confidence*).

Fishing reduces abundances at high trophic levels, but increases abundances at mid trophic levels. It reduces species numbers, simplifies ecosystem structure, and increases ecosystem sensitivity to climate change (Perry *et al*., 2010). Exploitation of fish stocks and the alteration of their demography, population dynamics, and life history traits (Planque *et al.*, 2010; Petitgas *et al.*, 2006; Perry *et al*., 2010) can reduce the capacity of fish populations to buffer changes in climate variability (Ottersen *et al.,* 2006; Genner et al., 2010), and increase variability in population size. Interactions between warming, OA, and human activities such as fishing may thus exacerbate climate impacts on a wide range of ocean processes and services, including marine fisheries (*medium confidence*, Table 6-4, 6-6; 30.6.2).

A 2°C global temperature increase by 2050 is estimated to cause global losses in landed value of USD 17-41 billion annually (in 2005 value), with an estimated cost of adaptation for the fisheries of $7 - 30 billion annually over a 40-year timeframe between 2010 and 2050. The largest loss in landed value is projected to occur in East Asia and the Pacific (*low confidence,* Sumaila and Cheung, 2010). Overall impacts and the regional manifestations will partially depend on the flexibility and response capacities of food production systems (Elmqvist *et al.*, 2003; Planque *et al.*, 2011a). Specific implications for the fishing industry are still poorly known, as future projections of shifts in primary production and knock-on effects through food webs and into fisheries remain uncertain (*low confidence* in effects of changing NPP; Planque *et al.*, 2011b; Stock *et al.*, 2011).

6.4.1.2. Other Provisioning Services

Reductions in marine biodiversity due to climate change and other anthropogenic stressors (Tittensor *et al.*, 2010), like OA (CBD, 2009) and pollution, might reduce the discovery of genetic resources from marine species useful in pharmaceutical, aquaculture, agriculture, and other industries (Arrieta *et al.*, 2010), leading to a loss of option value from marine ecosystems. Climate change increases the demand for marine renewable energy such as wind and wave power, though with potential ecosystem impacts of their infrastructure (6.4.2).

6.4.1.3. Climate Regulation and Extreme Events

The effect of climate change on marine biota will alter their contribution to climate regulation, i.e., the maintenance of the chemical composition and physical processes in the atmosphere and oceans (*high confidence*, Beaumont *et al.*, 2007). Regulatory mechanisms in which organisms (especially phytoplankton) play a key role, include control of the level of atmospheric CO_2 through the balance between photosynthesis and respiration (Johnson *et al.*, 2010), and through the biological and alkalinity pump (Feely *et al.*, 2008; Falkowski, 1997). They also include the modulation of further greenhouse gases such as nitrous oxide (N_2O; Jin and Gruber, 2003; Law, 2008; 6.1.1.3), and the modulation of other climatically reactive gases such as dimethylsulphide (DMS; Vogt *et al.*, 2008). A projected decrease in global ocean NPP (6.5.1) may result in decreased export of biogenic carbon to the deep ocean (Bopp *et al.*, 2002; Boyd and Doney, 2002; Hashioka and Yamanaka, 2007). A positive feedback on climate change may result, however, many of the factors controlling the pump are poorly understood (Figure 6-4; WGI, Ch. 6).

Coastal marine ecosystems reduce the effects of floods and storm surges which account for most of the natural disasters affecting people in coastal regions (IPCC, 2012a). Empirical and modeling studies show that coral reefs contribute to buffering the impact of tsunamis (Fernando *et al.*, 2005; Gravelle and Mimura, 2008; 5.4.2.4, 30.5; Box CC-CR). Experiments and models indicate that warming and OA slow coral growth by nearly 50% by 2050 (Box CC-CR, 5.4.2.4), making some islands and coastal areas more vulnerable to tsunamis, storm surges, wave energy and coastal erosion (*high confidence*). Wetlands and mangroves provide biologically diverse buffer zones (5.4.2.3). The combined impacts of climate change, pollution, deoxygenation and other overlapping stressors, on mangroves and wetlands have not been determined (Cooley *et al.*, 2009; Cooley, 2012). Some of these stressors enhance each other's effects in coastal systems (Cai *et al.*, 2011; Howarth *et al.*, 2011; Feely *et al.*, 2010).

6.4.1.4. Cultural Services

Cultural services encompass a wide array of services with marine biodiversity as a core component supporting recreation and tourism as the economically most relevant. Tropical coral reefs and their enormous biodiversity sustain substantial tourist industries, presently with global annual net benefits of about 9.6 billion USD (Cesar *et al.*, 2003; Box CC-CR; 30.6.2.2). If reef services degrade, coastal visitors might choose alternative attractions (UNWTO, 2008). Increased travel to see disappearing ecosystem types (e.g., Antarctica, Liggett *et al.*, 2011) or in previously inhospitable areas or seasons (Amelung *et al.*, 2007; Moore, 2010) create new pressures and are unsustainable as the locations of key attractors shift (e.g., cetaceans, Lambert *et al.*, 2010; Salvadeo *et al.*, 2013).

Climate change may endanger harvests of marine species with spiritual and aesthetic importance to indigenous cultures, raising ethical questions about cultural preservation (e.g., Nuttall, 1998). In coastal communities, losing the aesthetic values of marine ecosystems may harm local economies: better water quality and fewer harmful algal blooms are related to higher shellfish landings and real estate prices (Jin *et al.*, 2008).

Some heritage benefits of preserving marine ecosystems consist of the economic value of a healthy, diverse ecosystem to future generations. Any climate-related biodiversity loss or pollution of marine ecosystems would decrease the bank of resources for future opportunities. For example, the research and conservation value of coral reef biodiversity and its non-use value are estimated together at US$ 5.5 billion annually (Cesar *et al.*, 2003). As with spiritual and aesthetic benefits, maintaining heritage benefits under climate change poses challenges for managers concerning equity and ethics as well as multigenerational (and possibly multi-cultural) ethical questions.

6.4.1.5. Supporting Services

Fully identifying the services supporting other ecosystem benefits is virtually impossible, as they are diverse in nature and scale. Ecosystem engineers play an important role in these services. Damage to calcifying algae and corals will reduce habitat for other species (6.3.5), biodiversity, cultural and leisure values and their climate regulation capacity.

Waterways for shipping are expected to change in the next several decades (*very high confidence*, 28, 30.6.2.3). Reductions in Arctic sea ice allow new trade routes such as the Northwest Passage (Wilson *et al.*, 2004; Granier *et al.*, 2006), enabling economically viable trans-Arctic shipping, and access to regional resources for exploitation and tourism. This development would increase emission of greenhouse gases and other pollutants (Lauer *et al.*, 2009; Corbett *et al.*, 2010), and facilitate the invasion of non-indigenous species carried on hulls and in ballast waters (Lewis *et al.*, 2004).

6.4.2. Management-Related Adaptations and Risks

6.4.2.1. Ecosystem Management

A changing climate will have both positive and negative consequences for managing ocean resources (*high confidence*) (6.4.1; Eide and Heen, 2002; Eide, 2007). Ecosystem-based management (EBM, an approach recognizing all, including human interactions within an ecosystem), or the ecosystem approach (EA, a strategy for the integrated management of living resources promoting both conservation and sustainable use), are increasingly adopted globally (FAO, 2003) to deal with the multitude of human pressures on marine ecosystems (Sherman *et al.*, 2005; Hoel, 2009). Extended EBM addresses changes driven by climate and human activities, considering that diverse drivers will interact and confound each other (6.3.5, Planque *et al.*, 2010; Eero *et al.*, 2011). Human activities will undermine resilience to other, including climate, impacts or undermine the effectiveness of mitigation and adaptation measures, by increasing variability (thereby reducing predictability), and limiting scope for adaptation (*high confidence*, e.g., Hughes, 2004; Eero *et al.*, 2011; Sissener and Bjørndal, 2005). Thus, managing ecosystems under climate change increases the resilience of ecosystems and adaptive capacity of management systems through reducing other human perturbations (e.g., overfishing) (Brander, 2008; 7.5.1.1.3). Managing ecosystems also reduces the consequences of ocean acidification until CO_2 emission reduction becomes effective (Box CC-OA; Rau *et al*., 2012; Billé *et al*., 2013; McLeod *et al*., 2013). Ecosystem resilience is enhanced by reducing regional eutrophication (Falkenberg et *al*., 2013), or in aquaculture by avoiding acidified water (Barton *et al*., 2012) and by selecting and cultivating pre-adapted strains (Parker *et al*., 2012).

However, effects of climate change cannot be reversed by reducing the impacts of non-climatic drivers, emphasizing the need for adaptive management. Increased variability of ecosystem responses to climate change and the low predictability of some biological responses undermine the effectiveness of management and conservation measures. A particular risk is that climate change may contribute to large-scale ecosystem regime shifts (6.3.1.5; Box 6-1). Detecting and forecasting such shifts from time-series of environmental and biological data (Carpenter and Brock, 2006; deYoung *et al*., 2008), is constrained by an insufficient number of observations and limited quantitative understanding (6.1.2). Biogeographic shifts challenge spatial management (Box CC-MB; 6.3.1., 6.5), which is a fundamental part of EBM (Douvere, 2008), and demand that “fixed in law forever” site-attached zoning to protect specific species may need to become more flexible to maintain the original objectives as species move or community structures shift (*high confidence*, Soto, 2001; Hawkins, 2012).

6.4.2.2. Geoengineering Approaches

Geoengineering approaches to mitigate climate change and its effects, include Solar Radiation Management (SRM) and Carbon Dioxide Removal (CDR; see Table 6-5; IPCC, 2012b). SRM aims to reduce warming by increasing albedo, for example via stratospheric injection of sulphate aerosol (Crutzen, 2006). SRM may affect marine ecosystems through changes in precipitation. With continued CO_2 emissions it leaves ocean acidification largely unabated as it cannot mitigate rising atmospheric CO_2 concentrations (Vaughan and Lenton, 2011; Williamson and Turley, 2012). Termination of SRM after its implementation involves the risk of rapid climate change and more severe effects on ecosystems (Russell *et al*., 2012).

Proposed CDR techniques include both ocean- and land-based approaches (Vaughan and Lenton, 2011; 30.6.4). CO_2 storage in geological reservoirs may occur beneath the seafloor, e.g., in porous marine aquifers, and includes the risk of CO_2 leakage to the marine environment. Proposals to directly or indirectly sequester CO_2 into the ocean (Table 6-5; Caldeira *et al*., 2005; Boyd, 2008; Shepherd *et al*., 2009; WGIII, Ch. 7.5.5) include, among others, the use of ocean fertilization techniques by nutrient addition, the direct storage of biomass in the deep ocean, the addition of alkalinity for build-up of DIC (dissolved inorganic carbon, i.e. carbonate), and the direct CO_2 injection into the deep ocean (Williamson *et al*., 2012). All of these approaches have potentially negative consequences for marine ecosystems.

[INSERT TABLE 6-5 HERE
Table 6-5: Challenges for the oceans that will arise from the employment of a range of geoengineering methods (SRM, solar radiation management, CDR, carbon dioxide removal).]

Ocean fertilization by adding iron to high-nutrient low-chlorophyll (HNLC) oceanic waters could increase productivity and the net export of organic material to the deep ocean and its consecutive decomposition, causing deep-water accumulation of CO_2. Fertilization would affect all major marine biogeochemical cycles of the ocean with unclear side effects that could include the formation of methane (CH_4) and N_2O (Law, 2008) or the stimulation of harmful algal blooms (Trick *et al*., 2010). The enhanced NPP would add more carbon to the base of food webs (de Baar *et al.*, 2005) and stimulate growth, e.g., of deep-sea benthos (Wolff *et al*., 2011). Any regional increase in organic material (through fertilization or intentional storage of biomass) would cause enhanced O_2 demand and deep-water O_2 depletion (Sarmiento *et al.*, 2010; Table 6-5), increasing the level and extent of hypoxia and associated impacts on marine ecosystems (6.3.3., 6.3.5, 30.5.7). The synergistic effects CO_2-induced acidification will exacerbate the biological impacts (*high confidence*).

Neutralizing the acidifying water by the addition of alkalinity, e.g., calcium oxide, would require large-scale terrestrial mining with associated consequences (Caldeira *et al*., 2005). The biological effects of increased concentrations of Ca^{2+} ions and dissolved inorganic carbon remain insufficiently explored. Direct injection of CO_2 or its localized disposal in the ocean (e.g. as a lake in a deep-sea valley) cause locally highly increased CO_2 and acidification effects on deep-sea organisms (6.3.3.4., *high confidence*, Caldeira *et al.*, 2005). In contrast to long-term ocean fertilization or storage of biomass, this technique leaves the oxygen inventory of the deep ocean untouched (*limited evidence, medium agreement*, Pörtner *et al.*, 2005).

The knowledge base on the implementation of SRM and CDR techniques and associated risks is presently insufficient. Comparative assessments suggest that the main ocean-related geoengineering approaches are very costly and have large environmental footprints (*high confidence*, Boyd, 2008; Vaughan and Lenton, 2011; Russell *et al.*, 2012).

6.4.2.3. Health Issues

Human health and near-shore ecosystems may be directly impacted by climate change effects on harmful algal blooms (HABs, Edwards *et al.*, 2006; 30.6.3) or disease vectors. Planktonic time-series archives and nearshore sediment cores containing HAB cysts have revealed few examples of strong linkages between altered HABs and climate fluctuations (Dale *et al.*, 2006; 30.5.3.1.2). HABs can be stimulated by warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas, and enhanced surface stratification (*medium confidence*). Species-specific responses involve shifts in seasonal cycles and blooms (Johns *et al.*, 2003). Ocean acidification may exacerbate the toxicity of species in coastal oceans under nutrient-limited conditions (Tatters *et al*., 2012; Sun *et al*., 2011). Suitable adaptation measures include appropriate monitoring of biotoxin problems (Hallegraeff, 2010).

Continued warming of tropical and temperate coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, and sea water inundation due to sea level rise are all projected to exacerbate the expansion and threat of cholera (*medium confidence*, 11.5.2.1; 30.6.3), although attribution to climate change is confounded by climate variability and non-climate drivers (Lafferty, 2009; Dobson, 2009). Cholera and its pathogen, the marine bacterium, *Vibrio cholera*, have been widely studied. The pathogen associates with marine organisms, especially chitinized zooplankton (Vezzulli *et al.*, 2010). Where cholera is endemic (e.g, India, Bangladesh, Latin America), outbreaks are correlated with warming and high zooplankton abundance (Lobitz *et al.*, 2000; Lipp *et al.*, 2002). Based on an 18-year climate record for Bangladesh, Pascual *et al.* (2000) reported cholera outbreaks at ENSO events, and the recent reappearance of cholera in Peru has also been linked to the intense 1991-1992 ENSO (Lipp *et al.*, 2002). An increase in sustained maximum temperatures of the Baltic Sea (30.5.3.1.4) has been related to an increase in reported *Vibrio* infections; highest human mortality rates were associated with *V. vulnificus* infections (Baker-Austin *et al*., 2013). Continued warming of tropical and temperate coastal habitats, excessive nutrient loading leading to phytoplankton and zooplankton blooms, and seawater inundation due to sea level rise are all projected to exacerbate the expansion and threat of cholera (*medium confidence*).

Ciguatera poisoning may occur when people consume fish, mainly from tropical reefs, that have ciguatoxins from the epiphytic dinoflagellate *Gambierdiscus* sp. Historical records show significant correlations between ciguatera poisoning and sea surface temperature in South Pacific nations (Hales *et al*., 1999). However, the relationship is non-linear and dependent on the thermal window of the specific dinoflagellate (Llewellyn, 2010). This casts doubt on the accuracy of projected increases in ciguatera poisoning using linear extrapolations from observations (*low confidence*).

6.4.3. Conclusions

Human societies benefit from and depend on marine ecosystem services, including the provisioning of food and other goods, regulation of climate and extreme events, and cultural and supporting services (6.4.1). Attributing and projecting climate-change-mediated shifts in these services remains a challenge, due to the intrinsic difficulty of assessments, lack of baseline and long time-series data and confounding human impacts. However, empirical and modeling studies indicate that climate change impacts on marine ecosystems lead to changes in provisioning, regulating and supporting services (*high confidence*), as well as cultural services (*limited evidence, medium agreement*).

Food production from the sea is facing diverse stressors (6.4.1.1), such as overfishing and habitat degradation, which interact with climate change phenomena, including warming (6.3.1), ocean acidification (6.3.2), and hypoxia (6.3.3). Projections of impacts on capture fisheries are constrained by uncertainties in marine primary production (*medium evidence* and *agreement*, 6.5.1). Negative effects are projected to be most significant in developing nations in tropical regions (*high confidence*). Nations at higher latitudes may even benefit from climate change effects on ocean ecosystems, at least initially (6.5.3).

Climate change effects on biota will alter their climate regulation through mechanisms such as carbonate production, the biological pump, the balance between photosynthesis and respiration, and the modulation of greenhouse gases (6.4.1.3, *high confidence*). However, projections of the direction and magnitudes of feedbacks are at an early stage (*low confidence*).

Future management of ecosystems and fisheries might have to aim for increasing ecosystem resilience to climate change, e.g., through reductions of other human perturbations (6.4.2.1). Active ocean geoengineering strategies to ameliorate climate change may prove detrimental to the functioning of ecosystems, which highlights the need for further research and careful governance (6.4.2.2). There is limited understanding of how harmful algal blooms and pathogens affecting human health will respond to climate change (6.4.2.3, *medium* to *low confidence*).

6.5. Projections of Future Climate Change Impacts through Modeling Approaches

A range of models explore climate change effects on marine biota, from primary producers to higher trophic levels, and test hypotheses about responses of marine species, food webs and ecosystems (Rose *et al.*, 2010; Stock *et al*., 2011; Fulton *et al.*, 2011, FAQ 6.2). Both empirical and mechanistic approaches are used over a range of temporal and spatial scales (Barange *et al*., 2010; Stock *et al*., 2011). There is an increasing need for upscaling from molecular and physiological to ecosystem level (e.g., Le Quesne and Pinnegar, 2012). Uncertainty in projections of changes in marine ecosystems is partly contingent on the level of confidence in climatic and oceanographic projections (6.1.1; WGI, Ch. 9.8). Models are currently useful for developing scenarios of directional changes in net primary productivity, species distributions, community structure and trophic dynamics of marine ecosystems, as well as their implications for ecosystem goods and services under climate change. However, specific quantitative projections by these models remain imprecise (*low confidence*, Rose *et al.*, 2010; Hannah *et al.,* 2010; Stock *et al*., 2011; FAQ 6.4).

Earth System Models couple atmosphere, cryosphere, and hydrosphere (including the oceans), as well as climate and carbon cycles and project changes in ocean biogeochemistry under a range of CO_2 emission scenarios (WGI, Ch. 6). Models focusing on population and species level responses comprise models of population dynamics, models of species distribution, and models which explicitly link effects of changes in ocean physics and chemistry to changes in interactions between species at different trophic levels, or human activities such as fishing and aquaculture (Rose *et al*., 2010).

6.5.1. Oceanic Primary Production

Climate induced effects on global ocean NPP comprise changes in its long-term average, seasonal timing, and peak amplitude (Henson *et al*., 2013). The magnitude, direction, and pattern of projected changes vary with differences in model structure and parameterization (Box CC-PP; Figure 6-13). Unknown accuracy of current NPP observations further increases the uncertainty of projections, as does the incomplete understanding of effects of multiple drivers on NPP (6.3.1-5, 6.4). Global coupled climate-ocean biogeochemical Earth System Models (WGI Ch. 6) project an increase in NPP at high latitudes but a decrease in permanently stratified oceans at mid-latitudes, in the tropics (west tropical Pacific, tropical Indian Ocean, tropical Atlantic) and in the North Atlantic (Steinacher *et al*., 2010; Bopp *et al*., 2013, *medium confidence*) (Figure 6-13). The overall result is a reduction in global mean NPP under all RCP scenarios (*medium confidence* in the direction of projected trends, *low confidence* in the magnitude of change).

[INSERT FIGURE 6-13 HERE
Figure 6-13: Multi-model annual mean changes of projected vertically-integrated net primary production (small and large phytoplankton) under the low emission scenario RCP2.6 (A) and the high emission scenario RCP8.5 (B) for the period 2090 to 2099 relative to 1990 to 1999 (after Bopp *et al.*, 2013). To indicate consistency in the sign of change, regions are stippled where 80% of the ten models from the Coupled Model Intercomparison Project Phase 5 (Bopp *et al*. 2013) agree on the sign of change.]

6.5.2. Higher Trophic Levels

Projected future changes in temperature and other physical and chemical oceanographic factors are expected to affect the distribution and abundance of marine fishes and invertebrates, as elaborated by species distribution models. Limits of distribution ranges of 1066 exploited species are projected to undergo shifts by a median of around 50 km per decade to higher latitudes by 2050 relative to 2000 under the SRES A1B (RCP6.0) scenario (Cheung *et al.*, 2009). Some species shift towards the equator following a regional temperature gradient (Burrows *et al*., 2011;

Cheung *et al.*, 2013b; Pinsky *et al.*, 2013). The rate of range shifts is projected to be three times higher for pelagic than for demersal fishes (Cheung *et al.*, 2009), the latter shifting at a rate of around 27 – 36 km per decade (Cheung *et al.*, 2013b). However, the expansion of hypoxic waters may have a greater impact than warming on demersal fishes (Koslow *et al.*, 2011). As a result of distribution shifts, high-latitude regions (the Arctic, Southern Ocean) are projected to have high rates of species invasions. Intermediate latitudes are expected to undergo both invasions and local extinctions. High rates of local extinction are projected for the tropics and semi-enclosed seas (e.g. Mediterranean Sea, Persian Gulf). In addition, the future productivity and distribution of higher trophic level organisms are projected to change due to changes in primary productivity (6.3.6). For example, the migration route of Pacific sardine is projected to shift because of changes in primary productivity and food availability (Ito *et al.* 2010). The global pattern of distribution shifts is generally consistent with regional-scale projections and past observations (e.g., Lenoir *et al.*, 2011; Cheung *et al.*, 2013a). However, detailed quantitative projections are sensitive to model structure and assumptions (Hare *et al.*, 2012; Jones *et al.*, 2013) and responses of specific populations may differ from average species responses (Hazen *et al.*, 2013).

[INSERT FIGURE 6-14 HERE
Figure 6-14: Climate change effects on the biogeography, body size and fisheries catch potential of marine fishes and invertebrates. (A) Shifts in distribution range and reduction in body size of exploited fish driven by projected warming, oxygen depletion and sea-ice retreat (cf. Figure 6-7). Whenever the shift in distribution does not fully compensate for warming and hypoxia, the result will be a decrease in body size. Shifts in (B) latitudinal and (C) depth distribution of 610 exploited demersal fishes are projected to have a median (central line of the box) of 31 km decade^{-1} and 3.3 m decade^{-1}, respectively, with variation between species (box boundary: 25th and 75th percentiles) from 1991-2010 to 2041 - 2060 under the SRES A2 (between RCP6.0 - 8.5) scenario (Cheung *et al*., 2011; Cheung *et al*., 2013b). (D) Combining species' range shift with projected changes in NPP leads to a projected global redistribution of maximum catch potential (Analysis includes ~1,000 species of exploited fishes and invertebrates, under warming by 2°C according to SRES A1B (~RCP6.0), comparing the 10-year averages 2001-2010 and 2051-2060; redrawn from Cheung *et al*. 2010). (E) Changes in species distribution and individual growth are projected to lead to reduced maximum body size of fish communities at a certain site. The analysis includes 610 species of marine fishes, from 1991-2010 to 2041-2060 under the SRES A2 (~RCP6.0 to 8.5, Cheung *et al.*, 2013b). Key assumptions of the projections are that current distribution ranges reflect the preferences and tolerances of species for temperature and other environmental conditions and that these preferences and tolerances do not change over time. Catch potential is determined by species range and net primary production. Growth and maximum body size of fishes are a function of temperature and ambient oxygen level.]

Coral reefs are projected to undergo long-term degradation by 2020 to 2100 relative to the 2000s under RCP 2.6, 4.5 and 8.5 or their equivalent (30.5.6). Reefs projected to be threatened most by bleaching under the SRES A1B scenario by 2100 include the Central and Western Equatorial Pacific, Coral Triangle and parts of Micronesia and Melanesia (Teneva *et al*., 2012). These projections assume that coral bleaching occurs when SST exceeds a certain threshold, and that there is limited potential to shift such threshold by adaptation. Reef degradation will impact ecosystem services (Hoegh-Guldberg, 2011; 6.4; Box CC-CR).

Some groups of marine air-breathing fauna are projected to shift in distribution and abundance (6.3.7). Cetacean richness will increase above 40° latitude in both hemispheres, while at lower latitudes both pinniped and cetacean richness are projected to decrease by 2040-2049 relative to 1990-1999 under the SRES A1B scenario (Kaschner *et al*., 2011). Using SST as a predictor, the distribution of loggerhead turtles is projected to expand poleward in the Atlantic Ocean and to gain habitat in the Mediterranean Sea by 2070-2089 relative to 1970-1989 (Witt *et al*., 2010). Leatherback turtle may decrease in abundance at a rate of 7% per decade because of reduced hatching success with warming following the SRES A2 scenario (Saba *et al*., 2012). Abundances of some seabirds such as European breeding seabirds (Huntley *et al*., 2007), Cassin's auklet in the California Current ecosystem or Emperor penguin in Antarctica, are projected to decline because of climate induced changes in oceanographic conditions, such as temperature and upwelling intensity (Box CC-UP; Wolf *et al.*, 2010), or summer sea ice conditions (Jenouvrier *et al*., 2012). The diversity of megafaunal responses to climate change will have cascading ecosystem impacts, and will affect ecosystem services such as tourism (6.3.7, 6.4.1, *high confidence*).

6.5.3. Ecosystems and Fisheries

One of the most direct impacts of climate change on marine ecosystem services is through fisheries (6.4.1; 7.2.1.2, 7.3.2.4, 7.4.2). Projected climate impacts on fisheries are based on recruitment, growth, mortality, abundance and distribution of fish stocks as well as changes in ocean NPP (Cheung *et al*., 2008), evaluated from chlorophyll concentration and other variables such as sea surface temperature (Campbell *et al*., 2002). Friedland *et al*. (2012) suggested that chlorophyll concentration, indicating both phytoplankton production and biomass, is a better predictor of the fishery yield in large marine ecosystems than NPP. While the principle holds that catch potential is dependent on energy from primary production, quantitative projections of catch potential are limited by residual uncertainty on the best possible indicators of primary production and biomass.

Assuming that the potential fish catch is proportional to NPP, the fish catch in the North Pacific Ocean subtropical biome is projected to increase by 26% through expansion of the biome, while catches in the temperate and equatorial biomes may decrease by 38 and 15%, respectively, through contraction of the biomes by 2100 relative to 2000 under the SRES A2 (RCP6.0 to 8.5) scenario (Polovina *et al*., 2011). Changes in phytoplankton size structure are projected to affect fisheries catch potential (Cheung *et al*., 2011), resulting in a 0 up to 75.8% decrease in the potential catch of large fishes in the central North Pacific and increases of up to 43% in the California Current region over the 21st century under the SRES A2 scenario (Woodworth-Jefcoats *et al*., 2013). Globally, climate change is projected to cause a large-scale redistribution of global catch potential, with an average 30 - 70 % increase in yield at high latitudes and up to 89% in some regions, after 2°C warming from pre-industrial periods following SRES A1B (RCP6.0) (Figure 6-14; Cheung *et al.*, 2010; Blanchard *et al*., 2012). Redistribution between areas, with average catch potential remaining unchanged, will occur at mid latitudes. A 40 - 60% drop will occur in the tropics and in Antarctica by the 2050s relative to the 2000s (*medium confidence* for direction of trends in fisheries yields, *low confidence* for the magnitude of change). This highlights high vulnerabilities in the economies of tropical coastal countries (Allison *et al*., 2009; 6.4).

Fisheries targeting specific species may show more complex responses to climate change. For example, driven by changes in temperature and primary production, catches of skipjack and bigeye tuna in the south Pacific are projected to increase by 2035 relative to 1980-2000 under the SRES B1 and A2 scenario, but for 2100, skipjack tuna catch is projected to decrease under the A2 scenario, while bigyeye tuna catch decreases under both A2 and B1 scenarios (Lehodey *et al*., 2011). Regionally, tuna catches in the western Pacific are projected to decrease, while those in the eastern Pacific will increase (Lehodey *et al*., 2011). Mollusk fisheries under ocean acidification is discussed under 6.4.1.

Identifying responses to climate change is complicated by species interactions and multiple stressors. Major marine habitats and biodiversity hotspots are projected to encounter cumulative impact from changes in temperature, pH, oxygen and primary productivity by the end of the 21st century (RCP4.5 and 8.5) (Mora *et al*. 2013). Acidification and hypoxia will reduce maximum catch potential over 50 years from about 2000 onward in both the North Atlantic and Northeast Pacific (Ainsworth *et al*., 2011; Cheung *et al*., 2011). Changes in O_2 content as well as warming will drive a global decrease of community-averaged maximum body size of 14-24% of exploited demersal marine fishes by 2050 relative to the 2000s under the SRES A2 (RCP6.0 to 8.5) scenario (Cheung *et al*., 2013b, Figure 6-14). The decrease in maximum body size may affect natural mortality rates, trophic interactions, and reduce yield-per-recruit and, thus, potential catch. Responses of exploited marine species and their fisheries may interact with other human stressors such as overfishing, exacerbating their impacts (e.g., Lindegren *et al*., 2010; Ainsworth *et al*., 2011). Through species shifts climate change may also cause overlap of habitats of species targeted by fishing with habitat of threatened species, potentially increasing the chances of the latter of being caught as bycatch (Jones *et al*. 2013). Moreover, differences in vulnerability and adaptive capacity of species to changing environmental and ecosystem conditions will affect the responses of fisheries to climate change (e.g., Griffith *et al*., 2011; Le Borgne *et al*., 2011).

The complex and non-linear interactions and responses of both biophysical and socio-economic systems to climate change may lead to changes that have a low probability of occurrence based on empirical data (Doak *et al*., 2008). The risk of such low probability but potentially high impact events may be under-estimated in existing model projections (Williams and Jackson, 2007; Lindenmayer *et al*., 2010). Projected changes in the distribution and production potential of fisheries resources are expected to affect economics, human livelihood and food security

(Allison *et al*., 2009; Sumaila and Cheung, 2010; *low confidence* in the magnitude and direction of the projected socio-economic impacts).

6.5.4. Conclusions

Modeling projects that the distribution of invertebrates, fishes, and some marine mammals, birds and reptiles will shift further under most emission scenarios, with rates and directions of shifts consistent with those observed in the last century (*high confidence*, 6.3.1-7). These projections are valid for those species that adapt not at all or incompletely to warmer temperatures and the associated ecosystem changes, as indicated by present trends (6.3.1, Box CC-MB). For non-adapting species rates of shift will thus increase with increasing rates of warming and higher emission scenarios (*high confidence*), unless the shift is blocked by geographic or other barriers (e.g., light regime, Figure 6-7). The average shift in distribution will continue to be poleward at large spatial scales (6.5.2, Box CC-MB, *high confidence*). Species richness and the abundance of warm-water species will increase at high latitudes (*high confidence*) and decrease in the tropics (6.5.2, *medium confidence*). Projections for individual species and populations are more variable and sensitive to model parameters.

Maximum fisheries catch potential is projected to increase at high and decrease at low latitudes by 2050 under SRES B1 (RCP4.5) and A1B (RCP6.0) climate scenarios (6.5.3, *medium confidence*). Quantifying such projections is constrained by uncertainties in projected primary production rates (6.3.4, 6.5.1), biological responses such as species interactions (6.3.6), and in projected effects of multiple climate drivers and human activities (6.3.5, *low confidence*).

Models that integrate climate and ocean changes with biological responses and interactions, and with current human activities, have led to agreement on species and food web responses to climate change (6.5.3). However, most of these models do not include trophic interactions. They insufficiently consider physiological principles and none include evolutionary adaptation that affect responses of biota to physical and chemical changes.

Projections of ocean biogeochemistry represent the open oceans rather well, but coastal and shelf regions only poorly. From a global perspective, open ocean NPP will decrease moderately by 2100 under both low (SRES B1 or RCP4.5) and high emission scenarios (A2 or RCP6.0 - 8.5; 6.3.4, 6.5.1, *medium confidence*), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (6.3.4, 6.5.1, Box CC-PP, *medium confidence*).

Overall, the projected responses of marine organisms and ecosystems to climate change include changes in primary productivity (*medium confidence*), species' life history (*medium confidence*), distribution, abundance and diversity across marine food webs (*high confidence*) in a time frame of 20 to 80 years from 2010, with substantially larger long-term (end of 21st century) responses under high emission scenarios (*high confidence*). These changes will be largest under business as usual scenarios (RCP8.5) and increase the vulnerability of human societies, by affecting income, employment and food security through their effects on fisheries, tourism, and regulatory services such as coastal protection (6.4.1.3, Box CC-CR, *medium confidence*).

6.6. Chapter Conclusions and Key Uncertainties

This section provides an overview of confidence levels in the detection and projection of climate change effects on ocean systems, and of confidence levels in their attribution to different forcings. It distinguishes between effects previously observed and those projected, and considers confidence in the knowledge of underlying principles as discussed in this chapter. While the anthropogenic signal is conspicuous in the oceans (6.1.1), clear attribution to anthropogenic influences on climate is not always possible in individual case studies, due to the inherent variability of the system (Figure 6-15. Acronyms of relevant processes, capitalized, link between text and figure).

Present day observations and those from the Geological Record (GR, Figure 6-15) show similar signs of response to environmental changes, e.g., warming at high CO_2 levels, and similar ecological consequences in the ocean (*robust evidence, medium agreement* and *confidence*). However, the ongoing rate of anthropogenic CO_2 release and hence ocean acidification is unprecedented in the last 65 Ma (*high confidence*) and probably the last 300 Ma (6.1.2).

[INSERT FIGURE 6-15 HERE
Figure 6-15: Overview of the levels of confidence in detection (left), as well as in projection (right) of climate change effects on ocean systems, in relation to the levels of confidence in attributing these effects to the respective climate forcings. Case studies, processes, and concepts relevant in assessing the effects of climate change are represented by their acronyms in both text and figure. While confidence in the presence of effects is often high, the direct attribution to one driver in field experiments is difficult, as drivers are often highly correlated with each other (e.g., warming with changes in stratification and hence reduced nutrient supply). Some climate change impacts have been condensed into broad categories to avoid overpopulating the figures (e.g., Bio-Geochemical processes, BG). Note that the term "attribution" is used for both present-day detections in the field and future projections, the latter including qualitative and quantitative extrapolations and simulations from fundamental principles and models. Firm knowledge from experiments (field, laboratory and modeling) simulating future conditions enhances the respective confidence levels to those for detection or projection. The empirical observations resulting from those experiments are directly attributable to the respective drivers. Confidence in attribution is enhanced if these experiments identify the underlying mechanisms and their responses. See text for the discussion of depicted examples and categories. Confidence assignments focus on the nature and size of effects, not on model capacity to reliably quantify their magnitude.]

6.6.1. Key Risks Related to Climate Change: Constraints on Ecosystem Services

Empirical studies provide evidence that climate change has impacted marine ecosystems (*high confidenc*e, FAQ 6.4, Table 6-6) and has caused changes in provisioning, regulating, and supportive Ecosystem Services (ES, *medium confidence*). Climate change may also have affected cultural services (*limited evidence* and *medium agreement*) but attribution of impacts to these services remains a challenge (*low confidence*), due to the intrinsic difficulties of assessing these services, the lack of long time-series data and confounding human impacts. In light of available understanding of cause and effect of climate change impacts on marine ecosystems (*high confidence)*, future climate change will affect some ecosystem services (*high confidence* in projection, *medium confidence* in attribution). Projected changes in the availability of marine resources and ecosystem services are expected to affect economics, human livelihood and food security. Vulnerability is highest for the national economies of tropical coastal countries (*high confidence*).

[INSERT TABLE 6-6 HERE
Table 6-6: Coastal and oceanic key risks from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols. Acronyms for oceans sub-regions are as follows: HLSBS: High-Latitude Spring Bloom Systems; EUS: Equatorial Upwelling Systems; SES: Semi-Enclosed Seas; CBS: Coastal Boundary Systems; EBUE: Eastern Boundary Upwelling Ecosystems; STG: Sub-Tropical Gyres, DS: Deep Sea (>1000 m).]

Redistribution and constraints on microbial functions and primary productivity
Laboratory and mesocosm studies have identified various microbially mediated processes responding to climate-induced changes in light, nutrient supply, temperature, CO_2, and hypoxia (*high confidence*). Such processes include nitrogen fixation and the nitrogen cycle, carbon sequestration and export production, calcification, respiration, O_2 production, climate-feedback by DMS (dimethylsulphide) production, and nutrient recycling. However, changes in these Bio-Geochemical processes (BG) in the field are difficult to detect, project and attribute to climate change (*low confidence* 6.3.1-5).

The trends in Net Primary Production (NPP) recently reported for much of the low-latitude ocean using satellite observations differ considerably from those few long-term direct estimates of NPP at oceanic time-series sites (6.1.2, 6.3.4). Increased NPP at high latitudes (hNPP, detected and attributable to climate change with *medium confidence*, 6.3.4, Box CC-PP) are indicated by satellite images (*medium confidence*) and due to reduction and thinning of sea ice. Trends in NPP will be strengthened with further warming (*medium confidence*). Modeling projects that global NPP (gNPP) will decrease by 2100 under RCP scenarios (6.5.1, Box CC-PP, *medium confidence*).

Warming-induced species redistribution, loss of biodiversity and fisheries catch potential

Long-term observations show variability in oceanographic conditions with a key role of temperature and changing oceanographic regimes causing observed changes in ecosystem structure and fish stocks (*very high confidence,* cf. 30.7.1.1). Temperature Effects (TE) reflect the differential specialization of all life forms in limited ambient temperature ranges (*very high confidence*). Temperature exerts strong MAcroorganism Effects (MAE), i.e. on animals and plants. Warming is presently causing and will cause species displacements and largely poleward shifts in biogeographic distribution of zooplankton and fishes, paralleled by altered seasonal activity, species abundance, migration, and body size (6.3.1., *high* to *very high confidence*), and leading to shifts in Community Composition (CC, *high confidence*, Box 6-1). Causes and effects are understood for fishes and most invertebrates via their Oxygen and Capacity Limited Thermal Tolerance (OCLTT, 6.3.1, *robust evidence, medium agreement* and *high confidence*). Such knowledge supports projections into the future (6.5, *high confidence*), which are influenced by the limited potential of organisms to adapt. Alterations in species ABundance (AB) result when organisms encounter shifting mean and extreme temperatures (*high confidence* in detection and attribution). Such trends will be exacerbated during future warming (*high confidence,* 6.5.1).

Among prominent examples, warming has caused and will cause northward shift and expansion of the geographic distribution of North Atlantic Cod (AC, 6.3.1, *high confidence* in detection or projection, *medium confidence* in detection or projection and attribution) and shifting growth patterns in relation to the distribution of Banded Morwong around New Zealand (BM, *high confidence* in detection or projection, *medium confidence* in detection or projection and attribution). Warming has shifted dominant species from Sardines to Anchovies in the Sea of Japan (SAJ, 6.3.1, 6.3.6, *medium confidence* in detection, *medium confidence* in detection and attribution). Warming extremes have reduced and will further reduce the abundance of Eelpout in the Wadden Sea (EWS, 6.3.1, *high confidence* in detection or projection, *high confidence* in detection or projection and attribution). Extreme warming events increase mortalities of Pacific Salmon during spawning migrations (PS, 6.3.1, *high confidence* in detection, *high confidence* in detection and attribution) in Fraser River, Canada. At temperate and high latitudes, communities display increasing fish Species Richness (SR) resulting from latitudinal shifts of species and attributed to warming and loss of sea ice, although the relative contributions of regional climate variation and long-term global trends have not been quantified (6.3.1, 6.5.2, *high confidence* in detection, *medium confidence* in detection and attribution). Latitudinal species shifts are projected to continue in the 21st century under all IPCC emission scenarios (*high confidence*, 6.3.1, 6.3.5, 6.3.7, 6.4.1, 6.5.2).

Climate-induced regime shifts and regional changes in Plankton Phenology (PP, *medium confidence*) have caused and will cause changes in food composition and availability to animals. Species shifts and changing species composition lead to changes in Fishery Catch Potential (FCP, *high confidence*, 5a in Figure 6-15), partly attributable to climate change (*high confidence*) and to sustained fishing pressure (6.5.3). Fisheries Catch Potentials (FCP) will be redistributed, decrease at low latitudes and increase at high latitudes (*high confidence*, 5a in figure). These trends will possibly be strengthened by the projected decrease in NPP at low latitudes and increase in NPP at high latitudes (*medium confidence*, 6.5.2-3, 5b in Figure 6-15). Polar Organisms (PO) that are unable to migrate to cooler waters, and to acclimatize or to adapt to warming, will become marginalized, contributing to the projected high species turnover in polar areas (*high confidence*, 6.3.1, 6.5.2).

Detected effects on Marine Air Breathers (MAB: mammals, seabirds and reptiles) include changing abundances and phenology, shifts in species distribution, and in sea turtle sex ratios (*high confidence*), all of which are partly attributed to climate change (*high confidence*). However, few effects are directly linked to climate drivers (e.g., temperature-driven turtle sex ratio); most effects are due to shifts in habitat structure (e.g., loss of sea ice), changing availability of prey organisms, or changes in foraging efficiency, in both mammals (polar bears, walruses) and birds (penguins, albatrosses). Such trends will be exacerbated by future warming (*high confidence*, 6.3.7, 6.5.2).

Expanding hypoxia affecting marine resources
Hypoxic Zones in marine sediments and pelagic OMZs will continue to expand in the future, due to climate-induced warming trends (6.1.1). Local and regional Hypoxia Effects (HE) have been observed (*medium confidence*) and will be exacerbated in the future (*high confidence*, 6.3.3) causing habitat loss for groundfishes and pelagic predators and affecting the distribution of key zooplankton and nekton species (*medium confidence*). Progressive hypoxia is causing shifts in community composition toward hypoxia-tolerant species, excluding calcifiers due to elevated pCO_2 (*high confidence*), benefiting specialized microbes, and leading to reduced biodiversity and the loss of higher life forms (*high confidence*) (6.3.3). Loss of deep habitat and biomass of Mid-Water Fishes (MWF, 6.3.3, *medium confidence* in detection) off California is also attributed to hypoxia (*medium confidence*). These trends will continue into the future (*medium confidence*).

Constraints on marine calcifiers and associated fisheries and aquaculture due to ocean acidification
Ocean acidification will exert negative effects on species and whole ecosystems and their services, especially those relying on carbonate structures such as warm-water coral reefs (*high confidence*, cf. 30.7.1.2). Presently, only a small number of field observations have detected Ocean Acidification Effects (OAE) (*medium confidence*), but experiments and natural analogues support reliable but qualitative projections and attribution (*high confidence*). A specific glimpse into the future of anthropogenic OA is provided by negative Effects of upwelled CO_2-rich waters on Pacific Oysters (EO) introduced to aquaculture along the North American west coast (*high confidence* in detection, *low confidence* in attribution to anthropogenic causes). Findings in experimental laboratory and field studies as well as at natural analogues support attribution of projected effects to future CO_2 concentrations (*medium confidence*), with species-specific sensitivities across phyla (*high confidence*). Projected effects are most harmful to strong Calcifiers (CAL, *high confidence*), e.g., some echinoderms, bivalves, gastropods, warm-water corals, and crustose algae, and less harmful to some crustaceans and, possibly, fishes. Projections from experimental studies and observations at natural analogues indicate shifts in Community Composition (CC) to more active animals and from calcifiers (CAL) to non-calcifiers in all organism groups (*high confidence* in both projection and attribution to increased CO_2, 6.3.2, Table 6-3).

Interactions of climate-related drivers exacerbating impacts on organisms, ecosystems, and their services
Climate change involves interactions of temperature with other climate related drivers and their effects (ocean acidification, hypoxia, freshening, nutrient supply, organism shifts resulting in changing interactions between species, changes in habitat structure, e.g., loss of sea ice). Strong interactions with other human impacts like eutrophication, fishing, and other forms of harvesting accelerate and amplify climate-induced changes (*high confidence*, 6.3.5; 30.7.1.1). Harmful algal blooms (HABs) will be stimulated by warming, nutrient fluctuations in upwelling areas, eutrophication in coastal areas (Table 6-6), ocean acidification, and enhanced surface stratification (*medium confidence*). Synergistic Effects (SE) will be exacerbated in the future (*medium confidence*), but have not yet been clearly detected and attributed in the field (*low confidence*). For projected future effects, attribution of observed impacts to such synergisms is supported by experimental evidence, especially in animals and plants (*medium confidence*).

Increased bleaching and decreased calcification displayed by several Reef-building Warm-water Corals (RWC, *very high confidence*) over the last three decades are attributed to the ongoing warming trend, and the associated rise in extreme temperature events and amplitudes (*high confidence*, 6.3.1; Box CC-CR; 30.5.6). Such trends will be exacerbated by future warming and synergistic effects (*high confidence*, cf. 30.5.4.2), with some amelioration by latitudinal shifts and evolutionary adaptation (6.3.1, *low confidence*). Ocean acidification will have an increasing influence on reefs (*high confidence*), as indicated by similar phenomena during mass extinctions in Earth history.

6.6.2. Key Uncertainties

Key uncertainties result from insufficient knowledge of ocean systems. International organizations (both inter- and non-governmental) have the opportunity to play a key role in coordinating research concepts and approaches, working toward a coherent picture of climate change effects on the global ocean. Countries around the world have limited capacity and infrastructure to study the ocean's response to climate change. Long-term observational time series are especially lacking, in both quantity and quality. Research has provided valuable insights, but a unifying approach addressing principles across organism domains and ecosystems is still missing. Processes investigated so far differ largely by study organisms (plants, animals, phytoplankton, and bacteria) and by level of organization (ecosystem, whole organism, tissue, cell, molecular). Especially for microbes, available data are patchy and reported trends are often in different directions, partly due to different experimental protocols and/or over-reliance on species or strains of microbes that are readily culturable, and hence have been used for decades in laboratory research. The knowledge base of climate impacts on species, strains or communities in the field is insufficient. Scaling from physiological studies on individual species to ecosystem changes has been successful in individual cases but has not been widely implemented, e.g., to shifts in species interactions or food webs. An integrated framework of climate sensitivity at the ecosystem level that considers multiple drivers and their interactive effects needs to be developed further. This includes an in depth understanding of ecosystem structure (physical and biological) and functioning, of ecosystem complexity and species interactions, and of the resulting implications for biogeochemical processes. For all climate drivers, especially ocean warming, acidification, and hypoxia, studies integrating mechanistic knowledge and evolutionary adaptation over generations are needed. Research should also cover various climate zones and biomes. Laboratory and modeling experiments are needed to test hypotheses building on long-term field observations and observations at natural or paleo-analogues. Models should better integrate observations and mechanism-based understanding, and better project future interactions between human and natural systems in a changing climate.

Frequently Asked Questions

FAQ 6.1: Why are climate impacts on oceans and their ecosystems so important?
[to be placed in 6.1, before 6.1.1

Oceans create half the oxygen (O_2) we use to breathe and burn fossil fuels. Oceans provide on average 20% of the animal protein consumed by more than 1.5 billion people. Oceans are home to species and ecosystems valued in tourism and for recreation. The rich biodiversity of the oceans offers resources for innovative drugs or biomechanics. Ocean ecosystems such as coral reefs and mangroves protect the coastlines from tsunamis and storms. About 90% of the goods the world uses are shipped across the oceans. All these activities are affected by climate change.

Oceans play a major role in global climate dynamics. Oceans absorb 93% of the heat accumulating in the atmosphere, and the resulting warming of oceans affects most ecosystems. About a quarter of all the carbon dioxide (CO_2) emitted from the burning of fossil fuels is absorbed by oceans. Plankton converts some of that CO_2 into organic matter, part of which is exported into the deeper ocean. The remaining CO_2 causes progressive acidification from chemical reactions between CO_2 and seawater, acidification being exacerbated by nutrient supply and with the spreading loss of oxygen content. These changes all pose risks for marine life and may affect the oceans' ability to perform the wide range of functions that are vitally important for environmental and human health.

The effects of climate change occur in an environment that also experiences natural variability in many of these variables. Other human activities also influence ocean conditions, such as overfishing, pollution, and nutrient runoff via rivers that causes eutrophication, a process that produces large areas of water with low oxygen levels (sometimes called 'Dead Zones'). The wide range of factors that affect ocean conditions and the complex ways these factors interact make it difficult to isolate the role any one factor plays in the context of climate change, or to identify with precision the combined effects of these multiple drivers.

FAQ 6.2: What is different about the effects of climate change on the oceans compared to the land, and can we predict the consequences? *[to be placed in 6.3, before 6.3.1]*

The ocean environment is unique in many ways. It offers large-scale aquatic habitats, diverse bottom topography, and a rich diversity of species and ecosystems in water in various climate zones that are found nowhere else.

One of the major differences in terms of the effect of climate change on the oceans compared to land is ocean acidification. Anthropogenic CO_2 enters the ocean and chemical reactions turn some of it to carbonic acid, which acidifies the water. This mirrors what is also happening inside organisms once they take up the additional CO_2. Marine species that are dependent on calcium carbonate, like shellfish, seastars and corals, may find it difficult to build their shells and skeletons under ocean acidification. In general, animals living and breathing in water like fish, squid, and mussels, have between five and 20 times less CO_2 in their blood than terrestrial animals, so CO_2 enriched water will affect them in different and potentially more dramatic ways than species that breathe in air.

Consider also the unique impacts of climate change on ocean dynamics. The ocean has layers of warmer and colder water, saltier or less saline water, and hence less or more dense water. Warming of the ocean and the addition of more freshwater at the surface through ice melt and higher precipitation increases the formation of more stable layers stratified by density, which leads to less mixing of the deeper, denser, and colder nutrient-rich layers with the less dense nutrient-limited layers near the surface. With less mixing, respiration by organisms in the mid-water layers of stratified oceans will produce oxygen-poor waters, so-called oxygen minimum zones (OMZs). Large, more active fish can't live in these oxygen poor waters, while more simple specialized organisms with a lower need for oxygen will remain, and even thrive in the absence of predation from larger species. Therefore, the community of species living in hypoxic areas will shift.

State-of-the-art ecosystem models build on empirical observations of past climate changes and enable development of estimates of how ocean life may react in the future. One such projection is a large shift in the distribution of commercially important fish species to higher latitudes and reduced harvesting potential in their original areas. But producing detailed projections, e.g. what species and how far they will shift, is challenging because of the number and complexity of interactive feedbacks that are involved. At the moment, the uncertainties in modeling and complexities of the ocean system even prevent any quantification of how much of the present changes in the oceans is being caused by anthropogenic climate change or natural climate variability, and how much by other human activities such as fishing, pollution, etc.

It is known, however, that the resilience of marine ecosystems to adjust to climate change impacts is likely to be reduced by both the range of factors and their rate of change. The current rate of environmental change is much faster than most climate changes in the Earth's history, so predictions from longer term geological records may not be applicable if the changes occur within a few generations of a species. A species that had more time to adapt in the past may simply not have time to adapt under future climate change.

FAQ 6.3: Why are some marine organisms affected by ocean acidification? *[to be placed in 6.3.2, before 6.3.2.1]*

Many marine species, from microscopic plankton to shellfish and coral reef builders, are referred to as calcifiers, species that use solid calcium carbonate ($CaCO_3$) to construct their skeletons or shells. Seawater contains ample calcium but to use it and turn it into calcium carbonate, species have to bring it to specific sites in their bodies and raise the alkalinity (lower the acidity) at these sites to values higher than in other parts of the body or in ambient seawater. That takes energy. If high CO_2 levels from outside penetrate the organism and alter internal acidity levels, keeping the alkalinity high takes even more energy. The more energy is needed for calcification, the less is available for other biological processes like growth or reproduction, reducing the organisms' weight and overall competitiveness and viability.

Exposure of external shells to more acidic water can affect their stability by weakening or actually dissolving carbonate structures. Some of these shells are shielded from direct contact with seawater by a special coating that the animal makes (as is the case in mussels). The increased energy needed for making the shells to begin with impairs the ability of organisms to protect and repair their dissolving shells. Presently, more acidic waters brought up from the deeper ocean to the surface by wind and currents off the Northwest coast of the United States are having this effect on oysters grown in aquaculture.

Ocean acidification not only affects species producing calcified exoskeletons. It affects many more organisms either directly or indirectly and has the potential to disturb food webs and fisheries. Most organisms that have been investigated display greater sensitivity at extreme temperatures, so as ocean temperatures change, those species that are forced to exist at the edges of their thermal ranges will experience stronger effects of acidification.

FAQ 6.4: What changes in marine ecosystems are likely because of climate change? [*to be placed after 6.3.8]*

There is general consensus among scientists that climate change significantly affects marine ecosystems and may have profound impacts on future ocean biodiversity. Recent changes in the distribution of species as well as species richness within some marine communities and the structure of those communities have been attributed to ocean warming. Projected changes in physical and biogeochemical drivers such as temperature, CO_2 content and acidification, oxygen levels, the availability of nutrients, and the amount of ocean covered by ice, will affect marine life.

Overall, climate change will lead to large-scale shifts in the patterns of marine productivity, biodiversity, community composition and ecosystem structure. Regional extinction of species that are sensitive to climate change will lead to a decrease in species richness. In particular, the impacts of climate change on vulnerable organisms such as warm water corals are expected to affect associated ecosystems, such as coral reef communities.

Ocean primary production of the phytoplankton at the base of the marine food chain is expected to change but the global patterns of these changes are difficult to project. Existing projections suggest an increase in primary production at high latitudes such as the Arctic and the Southern Ocean (because the amount of sunlight available for photosynthesis of phytoplankton goes up as the amount of water covered by ice decreases). Decreases are projected for ocean primary production in the tropics and at mid-latitudes because of reduced nutrient supply. Alteration of the biology, distribution, and seasonal activity of marine organisms will disturb food web interactions such as the grazing of copepods (tiny crustaceans) on planktonic algae, another important foundational level of the marine food chain. Increasing temperature, nutrient fluctuations, and human-induced eutrophication may support the development of harmful algal blooms in coastal areas. Similar effects are expected in upwelling areas where wind and currents bring colder and nutrient rich water to the surface. Climate change may also cause shifts in the distribution and abundance of pathogens such as those that cause cholera.

Most climate change scenarios foresee a shift or expansion of the ranges of many species of plankton, fish and invertebrates towards higher latitudes, by tens of kilometres per decade, contributing to changes in species richness and altered community composition. Organisms less likely to shift to higher latitudes because they are more tolerant of the direct effects of climate change or less mobile may also be affected because climate change will alter the existing food webs on which they depend.

In polar areas, populations of species of invertebrates and fish adapted to colder waters may decline as they have no place to go. Some of those species may face local extinction. Some species in semi-enclosed seas such as the Wadden Sea and the Mediterranean Sea, also face higher risk of local extinction because land boundaries around those bodies of water will make it difficult for those species to move laterally to escape waters that may be too warm.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

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

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection and appealing environments for tourism (Wild *et al*., 2011). About 275 million people live within 30 km of a coral reef (Burke *et al*., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling) and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5) and more than half of the world's reefs are under medium or high risk of degradation (Burke *et al*., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*.,

2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see 6.3.1. for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs towards net dissolution (*medium confidence*; 5.4.2.4). Ocean warming and acidification have synergistic effects in several reef-builders (5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg *et al*., 2007). The abundance of reef building corals is in rapid decline in many Pacific and SE Asian regions (*very high confidence*, 1-2% per year for 1968-2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner *et al*., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski *et al*., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones *et al*., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world’s coral reefs are projected to be subject to long-term degradation (next few decades) under the RCP3-PD scenario (Frieler *et al*., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan *et al*., 2013). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

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

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton *et al*. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the SRES A2 emissions scenario (Bell *et al*., 2013).

- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard *et al*., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke *et al*., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the Global Domestic Product but their economic importance can be high at the country and regional scales (Pratchett *et al*., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001-2011; Laurans *et al*., 2013). At the local scale, these two services provided in 2009-2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans *et al*., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour *et al*., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod *et al*., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig *et al*., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau *et al*., 2012; Billé *et al*., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm *et al*. 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod *et al*., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann *et al*., 2012) and coastal pollutants enriched with fertilizers can increase acidification (Kelly *et al.*, 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; 5.2.4.4, 30.5).

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Box CC-MB. Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

[Elvira Poloczanska (Australia), Ove Hoegh-Guldberg (Australia), William Cheung (Canada), Hans O. Pörtner (Germany), Michael Burrows (UK)]

WGII AR4 presented detection and attribution of a global climate change fingerprint on natural systems (AR4, Ch 1, SPM Figure 1), but studies from marine systems were mostly absent. Since AR4, there has been a rapid increase in studies that focus on climate change impacts on marine species, which represents an opportunity to move from more anecdotal evidence to examining and potentially attributing detected changes within the Ocean to climate change (6.3, Figure MB-1). Recent changes in populations of marine species and the associated shifts in diversity patterns are resulting, at least partly, from climate change-mediated biological responses across ocean regions (6.2, Table 6.7, 30.5) (*robust evidence, high agreement, high confidence*).

Poloczanska *et al*. (2013) assess a potential pattern in responses of ocean life to recent climate change using a global database of 208 peer-reviewed papers. Observed responses (n=1735) were recorded from 857 species or assemblages across regions and taxonomic groups, from phytoplankton to marine reptiles and mammals (Figure MB-1). Observations were defined as those where the authors of a particular paper assessed the occurrence change in a biological parameter (including distribution, phenology, abundance, demography or community composition) and, if change occurs, the consistency of the change with that expected under climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term-climate variability.

[INSERT FIGURE MB-1 HERE
Figure MB-1: 1735 observed responses to climate change from 208 single- and multi-species studies. Changes attributed to climate change (blue), inconsistent with climate change (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite or equivocal) observations within each region. Note: 57% of the studies included were published since AR4 (from Poloczanska *et al.*, 2013).]

The results of this meta-analysis show that climate change has already had widespread impacts on species' distribution, abundance, phenology, and subsequently, species richness and community composition across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, changes in phenology, distribution and abundance were overwhelmingly (81%) in a direction that was consistent with theoretical responses to climate change (6.2). Knowledge gaps exist, especially in equatorial sub-regions and the Southern Hemisphere (Figure MB-1).

The timing of many biological events (phenology) had an earlier onset. For example, over the last 50 years, spring events shifted earlier for many species with an average advancement of 4.4 ± 0.7 days decade^{-1} (mean ± SE) and summer events by 4.4 ± 1.1 days decade^{-1} (*robust evidence, high agreement, high confidence*) (Figure MB-2). Phenological observations included in the study, range from shifts in peak abundance of phytoplankton and zooplankton, to reproduction and migration of invertebrates, fishes and seabirds (6.3.2, 30.5).

The distributions of benthic, pelagic and demersal species and communities have shifted by 10s to 1000s of km, although the range shifts have not been uniform across taxonomic groups or ocean regions (6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at 72.0 ± 13.5 km decade^{-1} and trailing edges contracted in a poleward direction at 15.8 ± 8.7 km decade^{-1} (Figure MB-2) revealing much higher current rates of migration than the potential maximum rates reported for terrestrial species (Figure 4.6) despite slower warming of the Ocean than land surface (WG1 3.2).

[INSERT FIGURE MB-2 HERE
Figure MB-2. Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range

location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations (from Poloczanska et al., 2013).]

Poleward distribution shifts have resulted in increased species richness in mid to high latitude regions (Hiddink and ter Hofstede, 2008) and changing community structure (Simpson *et al.*, 2011) (28.2.2). Increases in warm-water components of communities concurrent with regional warming have been observed in mid to high latitude ocean regions including the Bering Sea, Barents Sea, Nordic Sea, North Sea, and Tasman Sea (Box 6.1, 30.5). Observed changes in species composition of catches from 1970–2006 that is partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in sub-tropical and higher latitude regions, and reduction in abundance of sub-tropical species in equatorial waters (Cheung *et al*., 2013), with implications for fisheries (6.5, 7.4.2, 30.6.2.1)

The magnitude and direction of distribution shifts can be related to temperature velocities (i.e., the speed and direction at which isotherms propagate across the Ocean's surface (30.3.1.1, Burrows *et al.* 2011). Pinsky *et al.* (2013) showed that shifts in both latitude and depth of benthic fish and crustaceans could be explained by climate velocity with remarkable accuracy, using a database of 128 million individuals across 360 marine taxa from surveys of North American coastal waters conducted over 1968 to 2011. Poloczanska *et al.* (2013) found that faster distribution shifts generally occur in regions of highest surface temperature velocity, such as the North Sea and sub-Arctic Pacific Ocean. Observed marine species shifts, since approximately 1950s, have generally been able to track observed velocities (Fig MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities, but with considerable variability within and among taxonomic groups (Poloczanska *et al.* 2013).

Biogeographic shifts are also be influenced by other factors such as nutrient and stratification changes, species' interactions, habitat availability and fishing (6.3). Rate and pattern of biogeographic shifts in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g., of the Mediterranean (Bianchi, 2007), coastal upwelling e.g., Lima *et al.* (2007)). Geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram *et al.*, 2010), with associated niches filled by alien species, either naturally migrating or artificially introduced (Philippart *et al.*, 2011).

Whether marine species can continue to keep pace as warming rates, hence climate velocities, increase (Fig MB-3b) is a key uncertainty. Climate velocities on land are expected to outpace the ability of many terrestrial species to track climate velocities this century (4.3.2.5, Figure 4.6) For marine species, the observed rates of shift are generally much faster than those land for land species, particularly for primary producers and lower trophic levels (Poloczanska *et al. 2013*). Phyto- and zooplankton communities (excluding larval fish) have extended distributions at remarkable rates (Figure MB-3b), such as in the North-east Atlantic (30.5.1) with implications for marine food webs.

Geographical range shifts and depth distribution vary between coexisting marine species (Genner *et al*., 2004; Perry *et al*., 2005; Simpson *et al*., 2011) as a consequence of species-specific thermal window widths and associated vulnerabilities (Figure 6.5). Warming therefore causes differential changes in growth, reproductive success, larval output, early juvenile survival, and recruitment, implying shifts in the relative performance of animal species and, thus, their competitiveness (Pörtner and Farrell, 2008; Figure 6.7A). Such effects may underlie abundance losses or local extinctions, "regime shifts" between coexisting species, or critical mismatches between predator and prey organisms. Changes in local and regional species richness, abundance, community composition, productivity, energy flows and invasion resistance result. Even among Antarctic stenotherms such differences related to mode of life, phylogeny and associated metabolic capacities exist (6.3.1.4). As a consequence, marine ecosystem functions may be substantially reorganized at the regional scale, potentially triggering a range of cascading effects (Hoegh-Guldberg and Bruno, 2010). A focus on understanding the mechanisms underpinning the nature and magnitude of responses of marine organisms to climate change can help forecast impacts and the associated costs to society and facilitate adaptive management strategies effective in mitigating these impacts (6.3, 6.4).

[INSERT FIGURE MB-3 HERE
Figure MB-3. A. Rate of climate change for the Ocean (sea surface temperature (SST) °C); B. corresponding climate velocities for the Ocean and median velocity from land (adapted from Burrows et al., 2011); and C. observed rates of displacement of marine taxonomic groups over several decades until 2010. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.008 °C yr^{-1} correspond to ca. 2.4 km yr^{-1}median climate velocity in the Ocean. When compared to observed rates of displacement, many marine taxonomic groups have been able to track these velocities, except phyto- and zooplankton where rates of displacement greatly exceed climate velocity. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (A) Observed rates of climate change for Ocean SST (Black dotted line) are derived from HadISST1.1 data set, all other rates are calculated based on the average of the CMIP5 climate model ensembles (Table S30-3) for the historical period and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window. (B) Median climate velocity calculated from HadISST1.1 dataset over 1960–2010 using the methods of Burrows et al., 2011. The three axes represent estimated median climate velocities are representative of areas of slow velocities such as Pacific subtropical gyre (STG) system (Purple line), the global Ocean surface (excluding polar seas, Blue line), and areas of high velocities such as the Coral Triangle and North Sea (Orange line). Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2010. The Red line corresponds to the median rate over global land surface calculated using historical surface temperatures from the CMIP5 model ensemble (Table S30-3). (C) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. 2013 using published studies (Figure MB-2 Black data set). Note the displacement rates for phytoplankton exceed the axis, so values are given.]

Box CC-MB References

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Box CC-OA. Ocean Acidification

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

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Fig. CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30.8, 30.9). Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several metaanalyses (6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea-floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves and gastropods reducing the competitiveness with non-calcifiers

(5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; 6.1.2).

Projections of ocean acidification effects at ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (5.4.2.2).

Due to an incomplete understanding of species-specific responses and trophic interactions the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, 5.4.2.4) and the goods and services that they provide such as fisheries, tourism and coastal protection (*limited evidence, high agreement*; Box CC-CR, 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially-exploited shelled mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global GDP, it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e. reduce anthropogenic emissions of CO_2), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (6.4.2.1).

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Box CC-PP. Net Primary Production in the Ocean

[Philip W. Boyd (New Zealand), Svein Sundby (Norway), Hans-Otto Pörtner (Germany)]

Net Primary Production (NPP) is the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for cellular respiration and maintenance by autotrophic planktonic microbes and benthic plants (6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, carbon dioxide, and temperature (Panel A). These drivers in turn, are influenced by oceanic and atmospheric processes, including cloud cover, sea-ice extent, mixing by winds, waves and currents, convection, density stratification, and various forms of upwelling induced by eddies, frontal activity and boundary currents. Temperature has multiple roles as it influences rates of phytoplankton physiology and heterotrophic bacterial recycling of nutrients, in addition to stratification of the water column and sea-ice extent (Panel A). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI, Ch. 3), and on ecosystem structure and functioning (*medium confidence*, 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity: from <50 g C m^{-2} $year^{-1}$ in nutrient-poor subtropical waters and light-limited Arctic waters to >> 300 g C m^{-2} $year^{-1}$ in productive upwelling regions and highly eutrophic coastal regions (Panel B).

The oceans currently provide ~50 x 10^{15} g C $year^{-1}$, or about half of global NPP (Field *et al*. 1998). Global estimates of NPP are mainly obtained from satellite remote-sensing (6.1.2), which provides unprecedented spatial and temporal coverage, and may be validated regionally against oceanic measurements. Observations reveal significant changes in rates of NPP when environmental controls are altered by episodic natural perturbations, such as volcanic eruptions enhancing iron supply, as observed in high-nitrate low-chlorophyll waters of the NE Pacific (Hamme *et al*., 2010). Climate variability can drive pronounced changes in NPP (Chavez *et al*., 2011), such as during El Niño to La Niña transitions in Equatorial Pacific, when vertical nutrient and trace element supply are enhanced (Chavez *et al*., 1999).

Multi-year time-series records of NPP have been used to assess spatial trends in NPP in recent decades. Behrenfeld *et al*. (2006) using satellite data, reported a prolonged and sustained global NPP decrease of 190 x 10^{12} g C $year^{-1}$, for the period 1999 to 2005 - an annual reduction of ~0.4 % of global NPP. In contrast, a time-series of directly measured NPP between 1988 to 2007 by Saba *et al*. (2010) (i.e. *in situ* incubations using the radiotracer ^{14}C-bicarbonate) revealed an increase (2 % $year^{-1}$) in NPP for two low latitude open ocean sites. This discrepancy between *in situ* and remotely-sensed NPP trends points to uncertainties in either the methodology used and/or the extent to which discrete sites are representative of oceanic provinces (Saba *et al*., 2010, 2011). Modeling studies have subsequently revealed that the <15 year archive of satellite-derived NPP is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson *et al*., 2010; Beaulieu *et al*., 2013). Although multidecadal, the available time-series of oceanic NPP measurements are also not of sufficient duration relative to the timescales of climate variability modes (up to 60-70 years for AMO, for example, Figure 6-1). Recent attempts to synthesize longer (i.e. centennial) records of chlorophyll as a proxy for phytoplankton stocks (e.g., Boyce *et al*., 2010) have been criticized for relying on questionable linkages between different proxies for chlorophyll over a century of records (e.g., Rykaczewski and Dunne, 2011).

Models in which projected climate-change alters the environmental drivers of NPP provide estimates of spatial changes and of the rate of change of NPP. For example, four global coupled climate-ocean biogeochemical Earth System Models (WGI Ch. 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP particularly in Northern and Southern Hemisphere 'subpolar gyre' biomes (Steinacher *et al*., 2010). However, this regional increase in NPP was more than offset by decreases in NPP at lower latitudes and at mid-latitudes due to the reduced input of macro-nutrients into the photic zone. The reduced mixed-layer depth and reduced rate of circulation may cause a decrease in the flux of macronutrients to the photic zone (Figure 6-2). These changes to oceanic conditions result in a reduction in global mean NPP by 2 to 13% by 2100 relative to 1860 under a high emission scenario (Polovina *et al*., 2011; SRES A2, between RCP6.0 and RCP8.5). This is consistent with a more recent analysis based on 10 Earth System Models (Bopp *et al*., 2013), which project decreases in global NPP by 8.6 (±7.9), 3.9 (±5.7), 3.6 (±5.7), 2.0 (±4.1) % in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5 and RCP2.6, respectively. However, the magnitude of projected changes varies widely between models (e.g. from 0 to 20% decrease in NPP globally under RCP 8.5). The various models show very large differences in NPP at regional (i.e. provinces, see panel B) scales.

Earlier model projections had predicted changes in global NPP from a decrease of > 10% (Field *et al*., 1998; Boyd and Doney, 2002) to an increase of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0) (Sarmiento *et al*., 2004; Schmittner *et al*., 2008). These projections did not consider the potential contribution of primary production derived from atmospheric nitrogen fixation in tropical and subtropical regions, favoured by increasing stratification and reduced nutrient inputs from mixing. This mechanism is potentially important, although such episodic increases in nitrogen fixation are not sustainable without the presence of excess phosphate (e.g. Moore *et al*., 2009; Boyd *et al*., 2010). This may lead to an underestimation of NPP (Mohr *et al*., 2010; Mulholland *et al*., 2012; Wilson *et al*., 2012), however, the extent of such underestimation is unknown (Luo *et al*., 2012).

Care must be taken when comparing global, provincial (e.g. low latitude waters, for example Behrenfeld *et al*., 2006) and regional trends in NPP derived from observations, as some regions have additional local environmental influences such as enhanced density stratification of the upper ocean from melting sea ice. For example, a longer phytoplankton growing season, due to more sea-ice free days, may have increased NPP (based on a regionally validated time-series of satellite NPP) in Arctic waters (Arrigo and van Dijken, 2011) by an average of 8.1 Tg C year^{-1} between 1998 and 2009. Other regional trends in NPP are reported in 30.5.1-6. In addition, although future model projections of global NPP from different models (Steinacher *et al*., 2010; Bopp *et al*., 2013) are comparable, regional projections from each of the models differ substantially. This raises concerns as to which aspect(s) of the different model NPP parameterizations are responsible for driving regional differences in NPP, and moreover, how accurate model projections are of global NPP.

From a global perspective, open ocean NPP will decrease moderately by 2100 under both low (SRES B1 or RCP4.5) and high emission scenarios (A2 or RCP6.0 - 8.5, 6.3.4, 6.5.1, *medium confidence*), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*).

[INSERT FIGURE PP-1 HERE
Figure PP-1: A) Environmental factors controlling Net Primary Production (NPP). NPP is mainly controlled by three basic processes: 1) Light conditions in the surface ocean, i.e. the photic zone where photosynthesis occurs, 2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, 3) Regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic

zone. All three processes are influenced by physical, chemical and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. B) Annual composite map of global areal NPP rates (derived from MODIS Aqua satellite climatology from 2003-2012; NPP was calculated with the Carbon-based Production Model (CbPM, Westberry *et al*., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.]

Box CC-PP References

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Box CC-UP. Uncertain Trends in Major Upwelling Ecosystems

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Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These waters trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the Planet, the Equatorial Upwelling System (EUS, 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE, 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25 % to global fish production (Figure 30.1B, Table S30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of ‘bottom-up’ trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds and marine mammals.

There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI 3.2, 3.4.4, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, due to the uncertainty in wind speed trends (WGI, 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the early 1990s (WGI, 9.4.1.3.4). Observations and modelling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the the difference in heat gaining rates between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping, and the upwelling of nutrient rich, cold waters (Figure CC-UP). Some regional records support this hypothesis, others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems making it difficult to predict changes in the intensity of all Eastern Boundary Upwelling Ecosystems (30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts are highly relevant since these are the most biologically active systems in the ocean. Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO_2 enrichment in deeper water layers. Once this water returns to the surface through upwelling benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (high confidence, 6.3.2, 6.3.3; 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller *et al.*, 2010), reduce the fisheries catch potential and impact aquaculture in coastal areas (5.4.3.3, 6.3.7, 30.5.1.1.2, 30.5.5.1.3, Barton *et al.*, 2012). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulphide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor . This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia’s most valuable fishery (Hamukuaya *et al*., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (6.4.1, Chp 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean , upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N_2-fixing microorganisms (Deutsch *et al*., 2007; Deutsch and Weber, 2012), but field observations of N2 fixation in these regions have not supported these predictions (Fernandez *et al*., 2011; Franz *et al*., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O_2 and CO_2 inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO_2 concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending upon pCO_2 of the upwelled water, and potentially increasingly impact the biota of Eastern Boundary Upwelling Ecosystems.

[INSERT FIGURE UP-1 HERE
Figure UP-1: Upper panel: Schematic hypothetic mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decreased coastal fisheries due to an augmented exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.]

Box CC-UP References

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Table 6-1: To assess how a changing climate will alter the ocean's biological pump (Figure 6-4) and determine the resulting biogeochemical feedbacks on global climate, changes in a wide range of processes from cells to ocean basins, and from epipelagic to mesopelagic, must be quantified. This table illustrates the complexity of the integrated knowledge platform needed to provide evidence of these biogeochemical ramifications and thus the present limits to clear conclusions about climate-induced effects on the biological pump (C, Carbon; TEP, Transparent Exopolymer Particle; DOM, Dissolved Organic Matter; POM, Particulate Organic Matter).

Alteration of physiological rates	**Biogeographical changes / community shifts**	**Altered foodweb structure - Trophodynamics**	**Changes to particle dynamics**	**Biogeochemical changes / climatic feedbacks**
NPP (Bopp *et al*., 2002, 2013)	Microbial community structure (Giovannoni and Vergin, 2012)	Altered prey-predator linkages (Lewandowska,and Sommer, 2010)	Faecal pellet geometry (Wilson *et al*., 2008)	Particle flux/C sequestration (Bopp *et al*., 2002)
Particle solubilization through bacterial ectoenzymes (Christian and Karl, 1995)	Phytoplankton community structure – biomes (Boyd and Doney, 2002)		C partitioning between DOM vs. POM – TEP (Riebesell *et al*., 2007)	Shifts in elemental stoichiometry of planktonic communities (Karl *et al*., 2003)
TEP production (Engel *et al*., 2004)	Alteration of zooplankton biomes (Beaugrand *et al.*, 2009)		Sinking rates/seawater viscosity (Lam and Bishop, 2008)	Remineralization rate – [O_2]; hypoxia; nutrient resupply (Gruber, 2011)
Microzooplankton grazing rates (Rose *et al*., 2009)	Faunistic shifts at depth (Jackson and Burd, 2001)		Ballasting - calcite versus opal (Klaas and Archer, 2002)	Activity of the microbial loop; vertical carbon export (Grossart *et al.*, 2006; Piontek *et al*., 2010)

Table 6-2: Selected examples of species responses and underlying mechanisms to changing temperature, oxygen level and ocean acidification (OA). References are indicated by superscript numbers and in the footnote.

Phenomenon	**Key drivers**	**Mechanism / Sensitivity**
<u>*Biogeography*</u>		
Northward shift in the distribution of North Sea cod (*Gadus morhua*) stocks between 1977 and 2001 [1,2]	Temperature	Bottlenecks of high sensitivity during early life stages as well as adult spawning stage in winter/early spring
Shift from sardines (*Sardinops melanostictus*) to anchovies (*Engraulis japonicus*) in the western North Pacific observed between 1993 and 2003 [3,4]	Temperature	Thermal windows of growth and reproductive output are found at higher temperatures for anchovies than sardines, food preferences of the competing species being similar.
Variable sensitivity of Pacific tuna species to the availability of dissolved O_2. Bigeye tuna routinely reach depths where ambient O_2 content is below 1.5 ml L^{-1} (≈ 60 µmoles kg^{-1}) [5, 6]	Oxygen	Oxygen transport via hemoglobin is adapted to be highly efficient supporting high metabolic rates as needed during feeding in the OMZ.
Northward movement of species and the conversion of polar into more temperate and temperate into more subtropical system characteristics in the European Large Marine Ecosystems between 1958–2005 [7, 8]	Warming and current advection	Effects are attributed to climate change but may be influenced by nutrient enrichment and overfishing.

<u>*Abundance*</u>		
Increase in abundance of arctic boreal plankton species, notably the copepods *Calanus hyperboreus*, *Calanus glacialis* and the dinoflagellate *Ceratium arcticum* between 1960 and 2000 in the Newfoundland Shelf, Northwest Atlantic [9,10]	Temperature	Temperature sensitivity of phyto- and zooplankter resulting from cooling due to increased influx of Arctic water
A benthic fish species, the eelpout (*Zoarces viviparus*) at its southern distribution limit, the German Wadden Sea, displayed abundance losses during warming periods and rising summer extreme temperatures between 1993 and 2005, with early disappearance of the largest individuals [11]	Temperature	Temperature extremes exceed organism's thermal windows, with largest individuals being relatively less tolerant to high temperature than smaller individuals.
Variable sensitivities to OA within and across animal phyla (Figure 6-10 B) [12 - 21]	Anthropogenic OA, Sea water acidification by elevated pCO_2 in OMZs, upwelling areas, involving anthropogenic ocean acidification.	– Lowered extracellular (blood plasma) pH causing a lowering of the rates of ion exchange and metabolism in muscle or liver (hepatocytes) of vertebrates and invertebrates. – High sensitivity at reduced energy turnover in tissues and/or whole organism by reduced ion exchange, – use of more energy efficient transport mechanisms, – reduced protein synthesis, enhanced nitrogen release from amino acid catabolism and protein degradation, – slower growth
<u>*Phenology*</u>		
Migration time of pink salmon (*Oncorhynchus gorbuscha*) in Alaska is almost two weeks earlier in 2010s relative to 40 years ago [22]	Warming	Rapid microevolution for earlier migration timing.
In the waters around the U.K., during a period of warming between 1976 and 2005, the seasonal timing of biological events of all major marine taxonomic groups (plant/phytoplankton, invertebrate and vertebrates) advanced on average, by 0.31 to 0.43 days year^{-1} [23]	Warming	Sensitivity to seasonal temperature changes as a result of specific thermal windows of different organisms;
Body size and growth		
Asymptotic size of different populations of Atlantic cod (*Gadus morhua*) and Atlantic Herring (*Clupea harengus*) are negatively related to temperature [24, 25]	Warming	At large body size, oxygen supply limitations are exacerbated and the organism reaches its long-term heat tolerance limits at lower temperatures, thus limiting the maximum body size that can be reached.

1. Perry *et al.*, 2005; 2. Pörtner *et al.*, 2008; 3. Takasuka *et al*., 2007; 4. Takasuka *et al*., 2008; 5. Lehodey *et al*., 2011; 6. Seibel, 2011; 7. Beaugrand *et al.*, 2009; 8. Philippart *et al.*, 2011; 9. Johns *et al.*, 2001;10. Greene and Pershing, 2003; 11. Pörtner and Knust, 2007; 12. Reipschläger and Pörtner, 1996; 13. Pörtner *et al.*, 2000; 14. Vezzoli *et al.*, 2004; 15. Langenbuch and Pörtner, 2003; 16. Fernández-Reiriz *et al.*, 2011; 17. Langenbuch and Pörtner, 2002;18. Langenbuch *et al.*, 2006; 19. Michaelidis *et al.*, 2005; 20. Pörtner *et al.*, 1998; 21. Stumpp *et al.*, 2012; 22. Kovach *et al*., 2012; 23. Thackeray *et al*., 2010; 24. Taylor 1958; 25. Brunel and Dickey-Collas, 2010.

Table 6-3: Tolerances to ocean acidification in marine taxa, assessed from laboratory and field studies of species in the pCO_2 range from <650 to >10 000 µatm, compared to present day atmospheric levels of 400 µatm. (It should be noted that anthropogenic CO_2 emissions add to the natural variability of CO_2 concentrations in marine environments, which can reach much higher than atmospheric levels). Variables studied include growth, survival, calcification, metabolic rate, immune response, development, abundance, behavior and others. Neither all life stages, nor all variables, including the entire range of CO_2 concentrations, were studied in all species. *Confidence* is based on the number of studies, the number of species studied and the agreement of results within one group. +: denotes that possibly more species or strains (genetically distinct populations of the same species) were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: more than 5% of species in a group will be negatively affected by 2100; tolerant: more than 95% of species will not be affected by 2100. RCP 6.0: representative concentration pathway with projected atmospheric pCO_2 = 670 µatm; RCP 8.5: pCO_2 = 936 µatm in 2100 (Meinshausen *et al.*, 2011). *Confidence* is limited by the short- to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary timescales, i.e., across generations (see separate reference list, online supplementary material). Note that the assessment of variability between species from the same animal phylum has revealed an increase in the fraction of sensitive species with rising CO_2 levels, see Figure 6-10. *Rather than a sensitivity threshold the entire range of investigated pCO_2 values is given for groups of photosynthetic organisms. In all studies photosynthetic rates are stimulated to different, species-specific degrees by elevated pCO_2, indicating low vulnerability. Coccolithophores and calcifying algae are assessed as being more sensitive than other photosynthetic organisms due to reduced calcification and shell dissolution. NA, not availaible, [+]confidence levels for fishes were converted from medium to low, in light of uncertainty on the long-term implications of behavioral disturbances.

Taxon	No. of studies	No. of para-meters studied	Total no. of species studied	pCO_2 where the most vulnerable species is negatively affected or investigated pCO_2 range* (µatm)	Assessment of tolerance to RCP 6.0 (*confidence*)	Assessment of tolerance to RCP 8.5 (*confidence*)
Cyanobacteria	17	5	9+	180-1250*	Beneficial (*low*)	Beneficial (*low*)
Coccolithophores	35	6	7+	740	Tolerant (*low*)	Vulnerable (*medium*)
Diatoms	22	5	28+	150-1500*	Tolerant (*low*)	Tolerant (*low*)
Dinoflagellates	12	4	11+	150-1500*	Beneficial (*low*)	Tolerant (*low*)
Foraminifers	11	4	22	588	Vulnerable (*low*)	Vulnerable (*medium*)
Seagrasses	6	6	5	300-21000*	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (non-calcifying)	21	5	21+	280-20812*	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (calcifying)	38	10	36+	365	Vulnerable (*medium*)	Vulnerable (*high*)
Warm-water corals	45	13	31	467	Vulnerable (*medium*)	Vulnerable (*high*)
Cold-water corals	10	13	6	445	Vulnerable (*low*)	Vulnerable (*medium*)
Annelids	10	6	17+	1200	Tolerant (*medium*)	Tolerant (*medium*)
Echinoderms	54	14	35	510	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (benthic)	72	20	38+	508	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (pelagic)	7	8	8	550	Vulnerable (*low*)	Vulnerable (*medium*)
Mollusks (cephalopods)	10	8	5	2200 (850 for trace elements)	Tolerant (*medium*)	Tolerant (*medium*)
Bryozoans	7	3	8+	549	Tolerant (*low*)	Vulnerable (*low*)
Crustaceans	47	27	44+	700	Tolerant (*medium*)	Tolerant (*low*)
Fish[+]	51	16	40	700	Vulnerable (*low*)	Vulnerable (*low*)

Table 6-4: Potential interactions between modes of anthropogenic forcing (environmental; foodwebs, harvesting) on different levels of biological organisation. These interactions, from simple to complex, are illustrated with examples from the published literature. E, O, and M denote studies using manipulation Experiments (lab or field), Observations, or Modelling approaches, respectively. Unknown denotes no published information is available for each of these categories. NA denotes Not Applicable for this category.

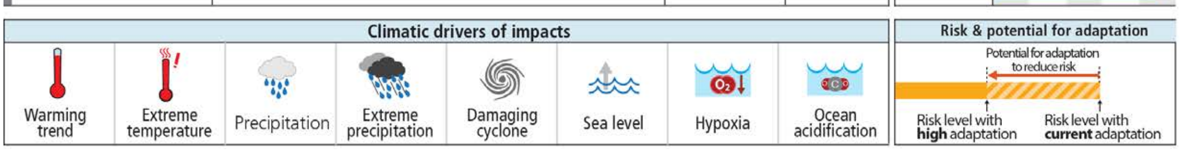
Biological Organisation studied at ecosystem level	**Anthropogenic Forcing**			
	Single Environmental Driver	*Multiple Environmental Drivers*	*Fishing / Foodwebs*	*Fishing / Climate change*
Individuals	Lab experiments and field observations show that warming alters organismal physiology and thereby, growth (Pörtner and Knust, 2007) E & O	Shipboard manipulation experiment addressing interactive effects of temperature and CO_2 on coccolithophore calcification (Feng *et al.*, 2009) E	NA	Unknown
Population	Physiological effects of warming change population abundance *in situ*, (Pörtner and Knust, 2007) E & O. Lab cultures show how altered pH elicits different responses of coccolithophore species (Langer *et al.*, 2006) E	Lab cultures show differential responses of cyanobacterial groups to temperature and CO_2 (Fu *et al.*, 2007) E	Altered maturation age and growth rate of populations due to fishing (Fairweather *et al.*, 2006; Hseih *et al.*, 2006) O	Interactive effects on cod populations of fishing and alteration of salinity (Lindegren *et al.*, 2010) M
Ecosystem	Mesocosm experiments simulating the effect of individual drivers (e.g. ocean acidification effects on benthos: Christen *et al*. 2013; and on pelagic communities: Riebesell *et al.*, 2013) E, O or M	Mesocosm experiments studying differential effects of light and temperature, on copepods versus diatoms (Lewandowska and Sommer, 2010) E	Effects of fishing on ecosystem structure – trophic cascades (Frank *et al.*, 2005) O	Interplay of fishing and climate pressures on ecosystems promotes lower trophic levels (Kirby *et al.*, 2009) O; enhances diversity loss in benthic communities (Griffith *et al.*, 2011) M
Biome	Time-series observations on warming and geographical shifts of zooplankton biomes (Beaugrand *et al.*, 2009) O	Unknown	Unknown	Unknown

Table 6-5: Challenges for the oceans that will arise from the employment of a range of geoengineering methods (SRM, solar radiation management, CDR, carbon dioxide removal).

Topic	**Brief Description**	**Challenge and Impact**	**References**
Solar radiation management techniques	Deflection of approximately 1.8 per cent of sunlight, by various techniques, is able to offset the global mean temperature effects of a doubling of atmospheric carbon dioxide content from preindustrial values	Will leave ocean acidification unabated (*high confidence*). Response of primary production to light reduction unclear.	Crutzen, 2006; Caldeira and Wood, 2008
Ocean storage by direct injection	Capture of CO_2 post-combustion from mainly coastal power plants, followed by injection of liquid CO_2 by pipeline or from a ship into the deep ocean.	Will add to ocean acidification and create localized harm to marine life (*high confidence*). Quantities will be small relative to the atmospheric invasion signal. CO_2 injected will dissolve and be transported by ocean circulation with eventual surface exposure.	Caldeira *et al.*, 2005
Sub-sea geologic storage	Capture of CO_2 from extracted gas or from post-combustion followed by well injection into a porous submarine aquifer beneath impermeable geologic strata.	Extensive experience in place from the Norwegian Sleipner field activity in the North Sea. No evidence of ocean impact from leakage to date.	Benson *et al.*, 2005
Ocean Fertilization	Spreading of trace amounts of reduced iron, over very large areas of the surface ocean where excess nutrients occur. Overcoming the local iron deficiency creates extensive phytoplankton blooms drawing down sea surface pCO_2. Fertilization can also be carried out by using direct or indirect (ocean pipes) addition of macronutrients to oceanic regions where they are depleted.	Much of the exported organic matter is remineralized at shallow depths creating local oxygen stress and shallow CO_2 enrichment, methane and N_2O production. These effects are temporary and the effective retention time is short. If sustained, reduced surface-ocean and increased deep-ocean acidification. O_2 loss in ocean interior (*medium confidence*).	de Baar *et al.*, 1995; de Baar *et al.*, 2005; Pörtner *et al.*, 2005; Boyd *et al.*, 2007; Buesseler *et al.*, 2008; Law, 2008; Cao and Caldeira, 2010
Artifical upwelling or downwelling	Ocean fertilization by bringing nutrient rich deep water (from 200 - 1000 m) to the surface. Downwelling occurs in parallel, transporting physically dissolved CO_2 into the deep ocean.	Deep water contains high levels of CO_2, which if released counteracts the binding of CO_2 by fertilization. No evidence available.	Lovelock and Rapley, 2007 Oschlies *et al*., 2010
Sequestration of organic carbon	Storage of terrestrial biomass in the coastal or deep ocean	Physical impact, regional loss of oxygen, CO_2 accumulation and acidification during degradation, increases in methane, N_2O and H_2S. No evidence available.	Metzger and Benford, 2001; Strand and Benford, 2009
Carbonate neutralization	Dissolution of power plant flue gas into sea water yielding an acidic solution which is neutralized by addition of crushed limestone. The resulting bicarbonate rich fluid is discharged to the ocean.	Involves the transport and crushing to fine scale of large quantities of limestone and the processing of very large quantities of sea water. Environmental impact issues not yet explored.	Rau, 2011
Accelerated olivine weathering	Uses wind powered electrochemical processes to remove HCl from the ocean and neutralizes the acid with silicate minerals such as olivine for disposal. The net result is to add alkalinity to the ocean akin to natural silicate weathering processes.	Complex system as yet untested in pilot processes. Involves mining and crushing large quantities of silicate minerals. Very long time scale consequences uncertain.	House *et al.*, 2007; Köhler *et al.*, 2010

Table 6-6: Coastal and oceanic key risks from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols. Acronyms for oceans sub-regions are as follows: HLSBS: High-Latitude Spring Bloom Systems; EUS: Equatorial Upwelling Systems; SES: Semi-Enclosed Seas; CBS: Coastal Boundary Systems; EBUE: Eastern Boundary Upwelling Ecosystems; STG: Sub-Tropical Gyres, DS: Deep Sea (>1000 m).

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Risks to ecosystems and adaptation options					
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans (*medium confidence*)	Adaptation options are limited to the translocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, or to the expansion of aquaculture.		6.5.1, 6.3.4, Box CC-NPP	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Distributional shift in fish and invertebrate species, fall in fishery catch potential at low latitudes, e.g., in EUS, CBS and STG regions (*high confidence*)	Evolutionary adaptation potential of fish and invertebrate species to warming is limited as indicated by their ongoing latitudinal shifts. Human adaptation options involve the large scale translocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential as well deploying flexible management that can react to variability and change. Further options include improving fish resilience to thermal stress by reducing other stressors like pollution and eutrophication, or the expansion of aquaculture.		6.3.1, Box CC-Bio	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects (*high confidence*)	Human adaptation options involve the large scale translocation of industrial fishing activities as a consequence of the hypoxia induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Special fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running of coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.		6.3.3, 30.5.3.2, 30.5.4.1-2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae (*high confidence*)	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely limited by the CO2 concentrations and high temperatures reached; adaptation options include the shift to exploiting more resilient species or the protection of habitats with low natural CO2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.		5.3.3.5, 6.X.X., 30.X.X, Box CC-OA	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat induced mass coral bleaching and mortality increases, e.g., in CBS, SES, and STG regions (*high confidence*)	Evidence of rapid evolution by corals is very limited or non-existent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely given estimates that they need to move at the speed of 10-20 km per year. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.		5.4.2.4, 6.4.2, 30.3.1.1, 30.5.2, 30.5.3, 30.5.4, 30.5.6, Box CC-CR	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Coastal inundation and habitat loss due to sea level rise and intensified precipitation events, e.g., in CBS and STG subregions *medium to high confidence*)	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing and aquaculture. Loss of ecosystems such as sea grass, mangroves and coral reefs can be reduced by reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients.		5.5.2, 5.5.4, CC-CR, 30.5.6.1.3, 30.6.2.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Marine biodiversity loss with high rate of climate change (*medium confidence*)	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from tourism and fishing.		Box CC-Bio, 6.3.1, 30.X.X	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Risks to fisheries					
Decreased production of global shellfish fisheries (*high confidence*)	Effective shift to alternative livelihoods, changes in food consumption patterns and adjustment of (global) markets.		6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2.1, CC-OA	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Global redistribution and decrease of low latitude fisheries yields are paralleled by a global trend to catches having smaller fishes (*medium confidence*)	Increasing coastal poverty at low latitudes as fisheries becomes smaller - partially compensated by the growth of aquaculture and marine spatial planning, as well as enhanced industrlalized fishing efforts.		6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific tuna fisheries (*high confidence*)	International fisheries agreements and instruments, such as the tuna commissions, may have limited success in establishing sustainable fisheries yields.		6.3.1, 6.4.3, Table 30.4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Variability of small pelagic fishes in Eastern Boundary Upwelling systems is becoming more extreme at interannual to multidecadal scales, making industry and management decisions more uncertain (*medium confidence*)	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity increases resilience of the fisheries.		6.3.2, 6.3.3, 30.5.2, 30.5.5, CC-UP	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction (*high confidence*)	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).		6.4.1, 30.5.3-4, 30.5.6, CC-CR	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Current spatial management units, especially the MPAs may fail in the future due to shifts in species distribution and community structure (*high confidence*)	Continuous revision and shifts of MPA borders, and of MPA goals and performance.		6.3.1, 6.4.2.1, 30.5.1, CC-BIO	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Risks to humans and infrastructure					
Coastal socio-economic security (*high confidence*)	Human adaptation options involve (1) Protection using coastal defences (e.g. seawalls) and soft measures (e.g. mangrove replanting and enhancing coral growth), (2) Accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure, and (3) Managed retreat as a last viable option. Vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		5.5.2, 5.5.4, 30.6.5, 30.7.1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Reduced livelihoods and increased poverty (*medium confidence*)	Human adaptation options involve the large scale translocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal local fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other species of interest.		6.4.1-2, 30.6.2, 30.6.5	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

*high confidence in existence of adaptation measures, low confidence in magnitude of risk reduction

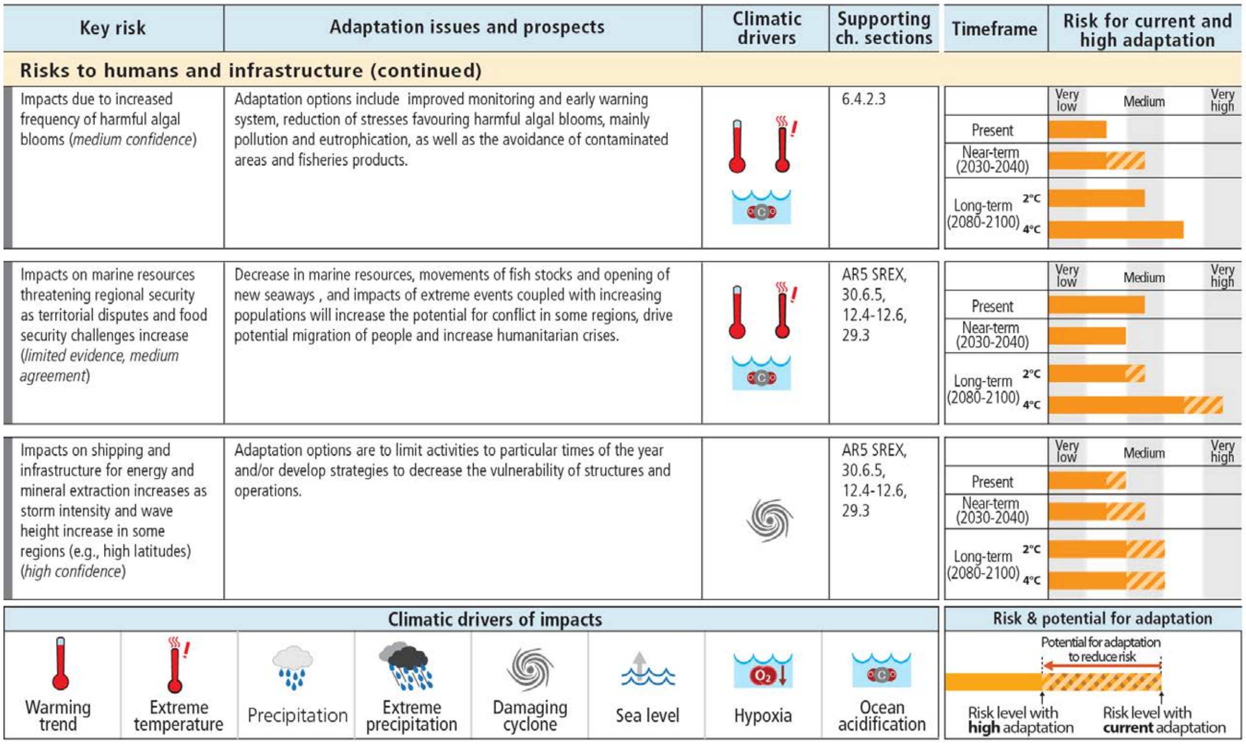
Climatic drivers of impacts

Warming trend | Extreme temperature | Precipitation | Extreme precipitation | Damaging cyclone | Sea level | Hypoxia | Ocean acidification

Risk & potential for adaptation

Potential for adaptation to reduce risk

Risk level with **high** adaptation | Risk level with **current** adaptation



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Risks to humans and infrastructure (continued)					
Impacts due to increased frequency of harmful algal blooms (*medium confidence*)	Adaptation options include improved monitoring and early warning system, reduction of stresses favouring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		6.4.2.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*)	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people and increase humanitarian crises.		AR5 SREX, 30.6.5, 12.4-12.6, 29.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*)	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		AR5 SREX, 30.6.5, 12.4-12.6, 29.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high

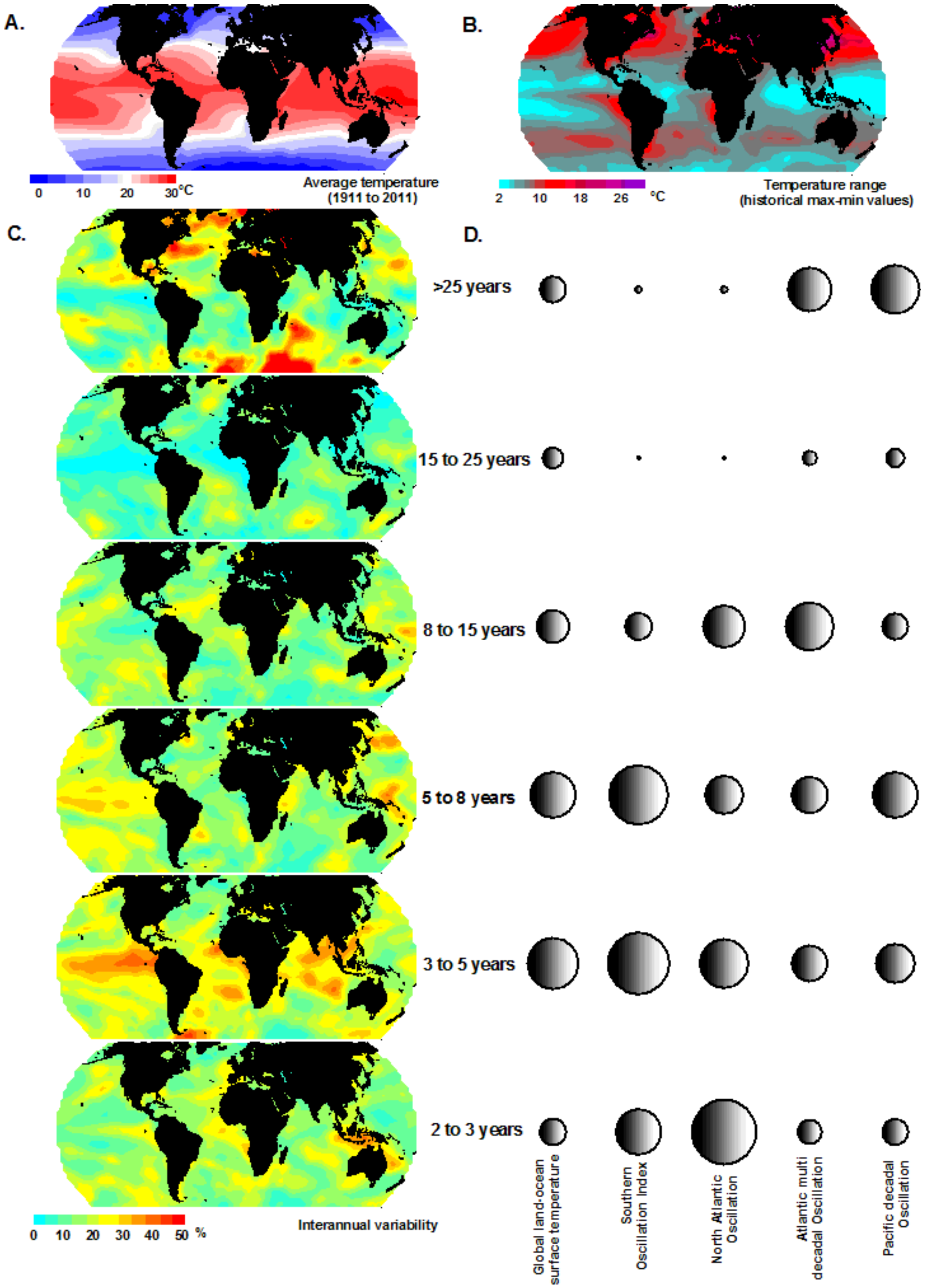

A.
0 10 20 30°C
Average temperature
(1911 to 2011)
B.
2 10 18 26 °C
Temperature range
(historical max-min values)
C.
D.
>25 years
15 to 25 years
8 to 15 years
5 to 8 years
3 to 5 years
2 to 3 years
0 10 20 30 40 50 %
Interannual variability
Global land-ocean surface temperature
Southern Oscillation Index
North Atlantic Oscillation
Atlantic multi decadal Oscillation
Pacific decadal Oscillation

Figure 6-1: Sea surface temperature variability between 1911 and 2011. The top left map shows the sea surface temperature average for the period. The top right map illustrates the temperature range calculated as the difference between the maximum and minimum values for each grid component during the century. The spatial distribution of variability by time scales (left hand map series, based on the Extended Reynolds Sea Surface Temperature, NOAA, 2012) corresponds to the multidecadal (25 to 40 years), bidecadal (15 to 25 years), decadal (8 to 15 years), low ENSO (El Niño Southern Oscillation) frequency (5 to 8 years), high ENSO frequency (3 to 5 years), and very high frequency (2 to 3 years) scales. The summed variabilities from the same 2°x2° box in all six maps corresponds to 100% of the time series variability. The areas of the right hand bubbles show the spectral density of some of the most widely used climate indices, accumulated in the same frequency windows: the Global Average Temperature and SST Anomalies (GSST), the Southern Oscillation Index (SOI), the North Atlantic Oscillation (NAO), the Multidecadal Atlantic Oscillation (AMO), and the Pacific Decadal Oscillation (PDO). The sum of bubble surface areas for each vertical column (each climate index) corresponds to 100% of the time series variability between the 2 and 40 year periods. Climate indices where obtained from the NOAA ESRL Physical Sciences Division website. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

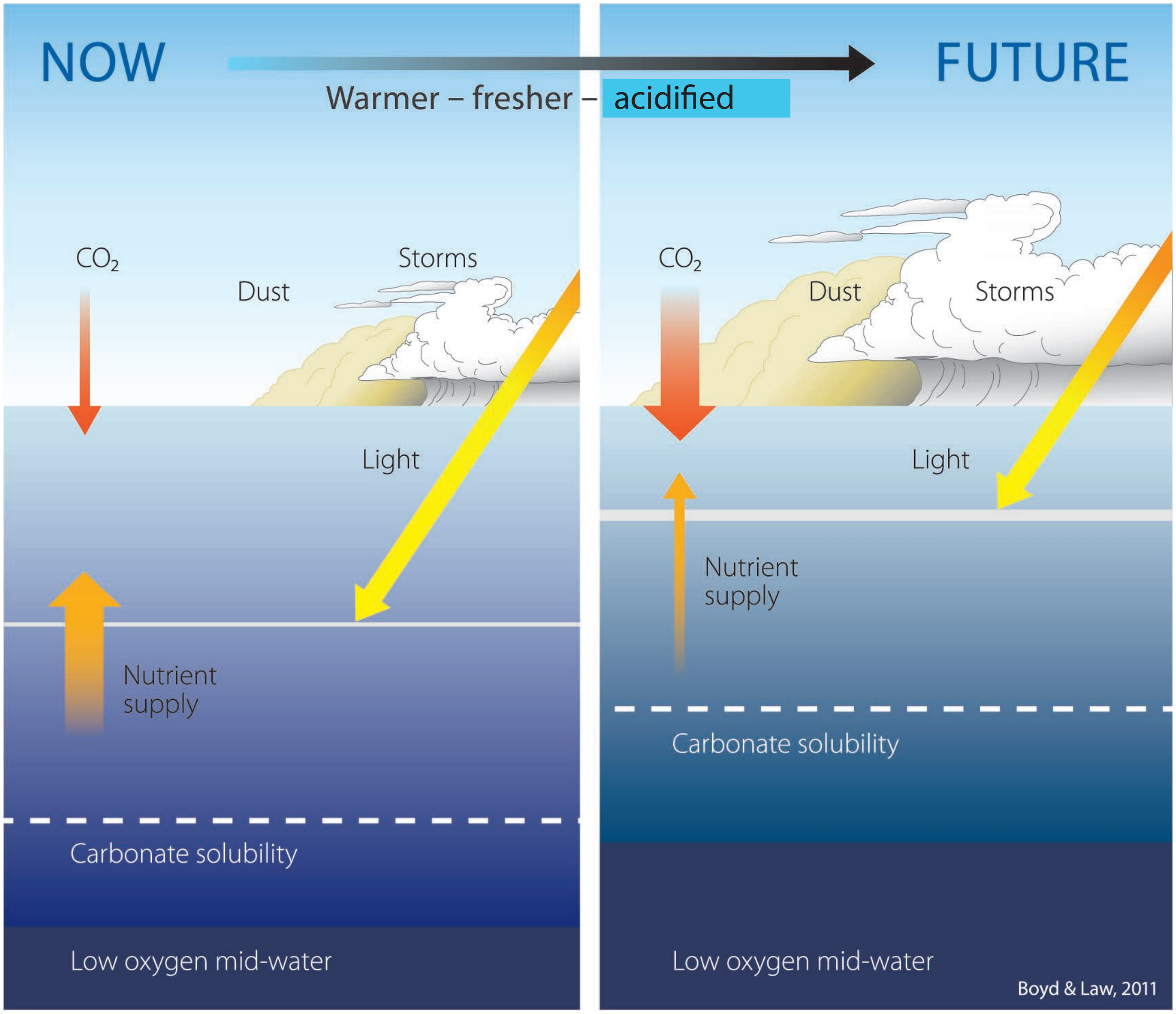


Figure 6-2: Projected alteration (magnitude and frequency) of oceanic fluxes and atmospheric events due to a changing climate in the coming decades. Ocean properties will be altered from the sunlit surface layer to the mid-water stratum. In the surface ocean, the depth of the mixed layer (solid horizontal line) will shallow resulting in higher mean light levels. Increased density stratification (i.e., a strengthening sea water density gradient represented by the increasing thickness of the solid horizontal line) will reduce the vertical supply of nutrients for photosynthesizing organisms residing in the mixed layer. Anthropogenic CO_2 will acidify, i.e., lower the pH of the surface ocean (note this happens in a pH range higher than 7 such that oceans will remain alkaline but less so due to acidification). The penetration of acidified waters to depth will result in a shallower depth (dashed horizontal line) at which calcium carbonate structures, such as shells, dissolve. At depth, the location of low oxygen waters will progressively become shallower. In addition, changes in storm activity and dust deposition will influence ocean physics and chemistry, with consequent effects on ocean biota and hence ecosystems (courtesy of Reusch and Boyd, 2013). **[Illustration to be redrawn to conform to IPCC publication specifications.]**

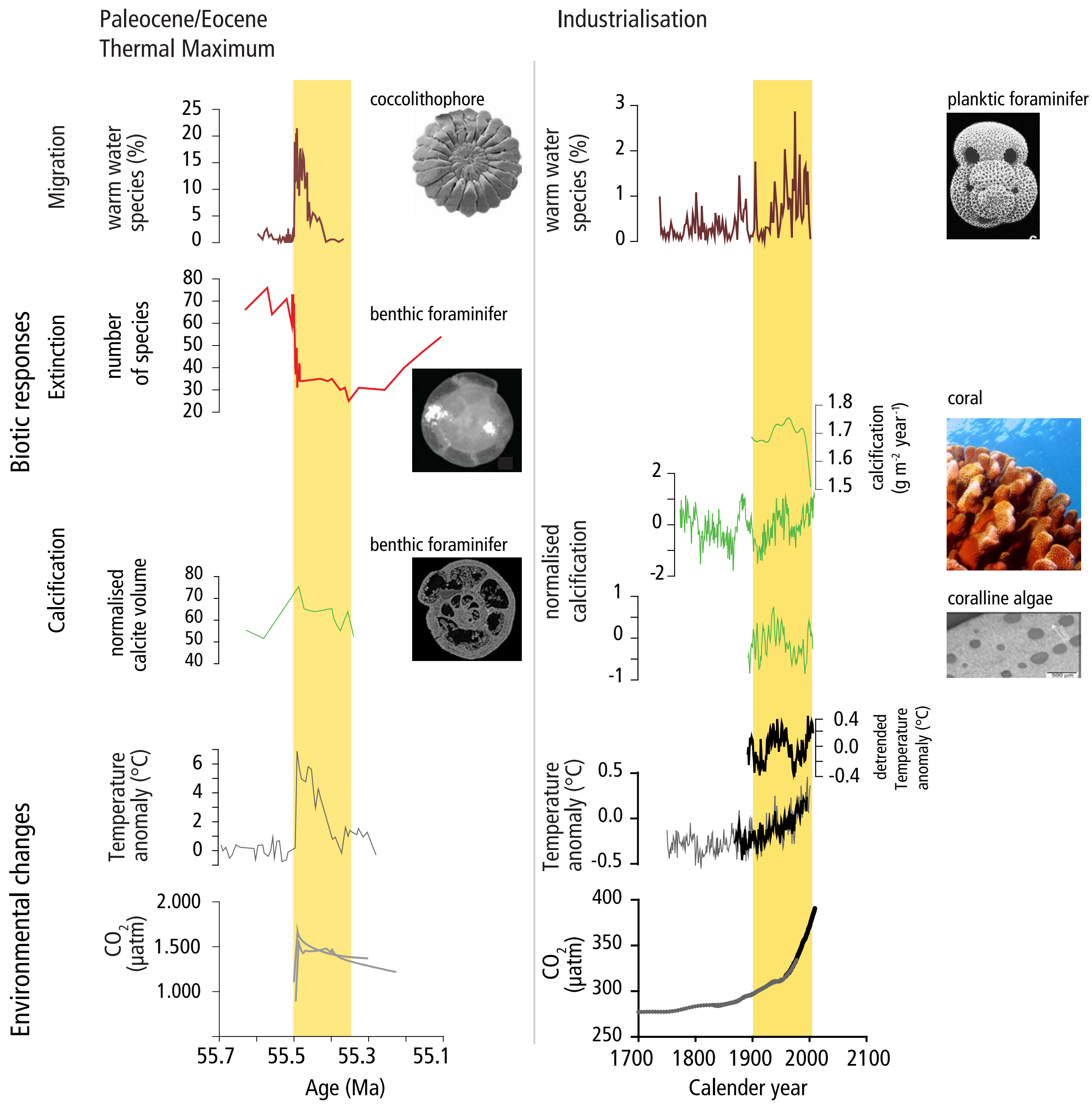


Figure 6-3: Environmental changes (bottom) and associated biological responses (top) for the Paleocene Eocene Thermal Maximum (PETM, left) and the industrial era (right). The PETM represents the best geological analogue for the future ocean in terms of biological responses. Episodes of largest environmental change are indicated with yellow bars. Note the different time scale between the two columns. Both time intervals are characterized by rapid warming both on land and in the ocean and increases in CO_2. Atmospheric CO_2 and temperature are described with direct measurements (black), proxy reconstructions (grey) and model results (light grey). For the recent anthropocenic record, the AMO is shown to highlight high frequency natural temperature fluctuations (Enfield *et al.*, 2001) and their influence on marine biota. Biological responses to the environmental forcing are divided into calcification, extinction and migration. Note the highly group-specific responses to the environmental change, especially with regards to calcification with decreases, increases and high variability. While there was extinction during the PETM, there is currently no evidence for climate-related extinction in the marine record. The warming led to migration of warm water species into previous cold water habitats indicating range expansion due to warming

(modern: planktic foraminifera, *Gs. ruber* Field *et al.*, 2006; PETM: coccolithophores, *Discoaster* spp. Bralower, 2002). CO_2 data: Mauna Loa (Keeling *et al.*, 2005), ice core records (Etheridge et al. 1996) and model output for the PETM (Zeebe *et al*., 2009; Ridgwell and Schmidt, 2010). Sea surface temperatures modern: Wilson *et al.*, 2006 and PETM: Kennett and Stott, 1991. Biotic responses: growth changes in coralline algae (Halfar *et al.*, 2011, bottom) and corals (Vásquez-Bedoya *et al.*, 2012, middle, De'ath *et al.*, 2009, top); calcification changes (Foster *et al*., 2013) and extinction in benthic foraminifers (Thomas, 2003) for the PETM.
[Illustration to be redrawn to conform to IPCC publication specifications.]

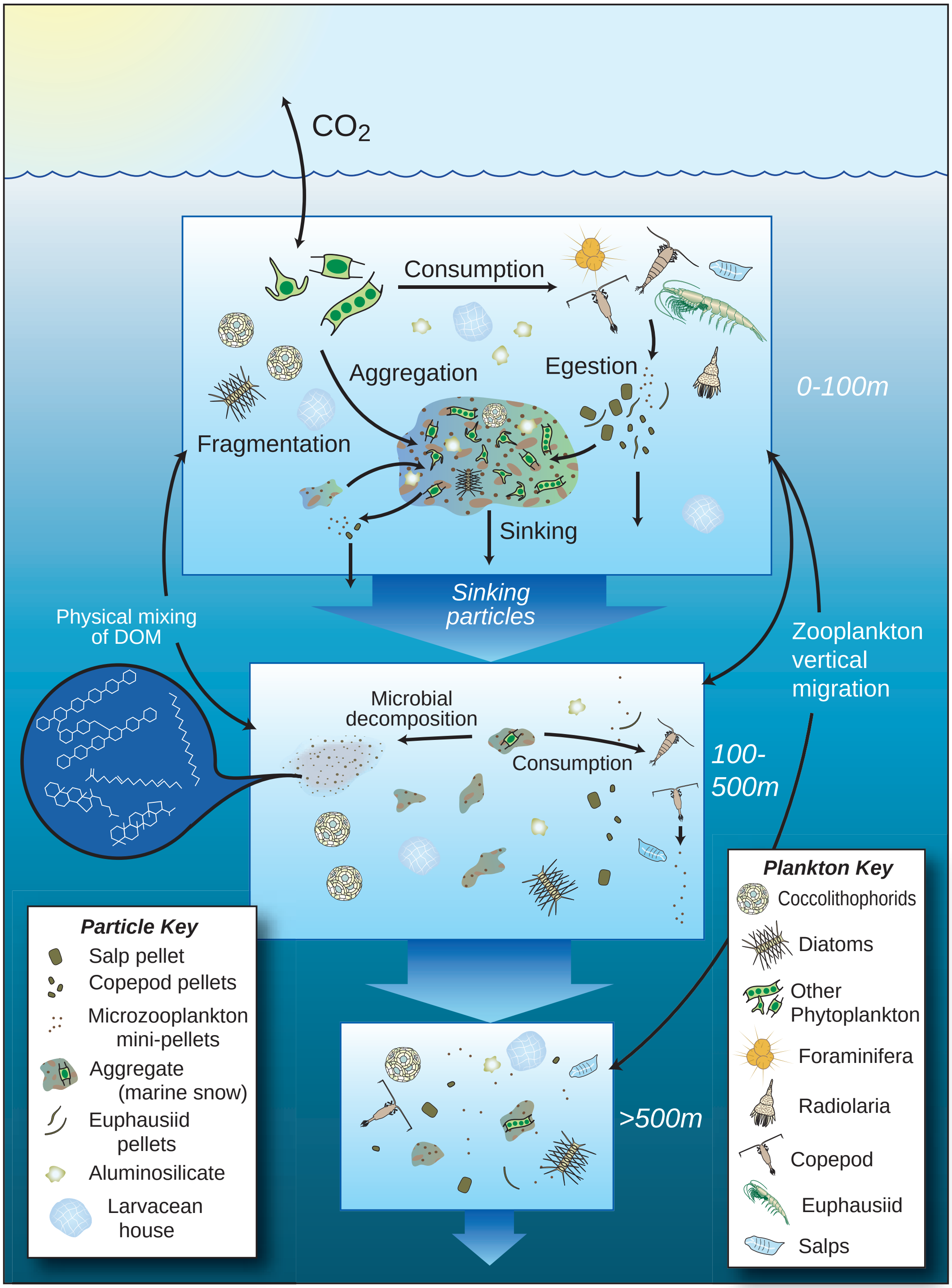


Figure 6-4: A schematic representation of the ocean's biological pump, which will be influenced by climate change and is a conduit for carbon sequestration. It is difficult to project how the pump might be altered (Table 6-1) and whether it would represent a positive or negative feedback to climate change through the cumulative effects of affected processes, surface to depth (Table 6-1): shifts in Net Primary Production, floristic and faunistic community composition in the pelagic realm, and in grazing rates; alterations to the ballasting of settling particles and the proportion of NPP released as DOM (Dissolved Organic Matter); modified bacterial enzymatic rates and particle solubilization; faunistic shifts at depth. Modified from Buesseler *et al.* (2008) by J. Cook (WHOI).
[Illustration to be redrawn to conform to IPCC publication specifications.]

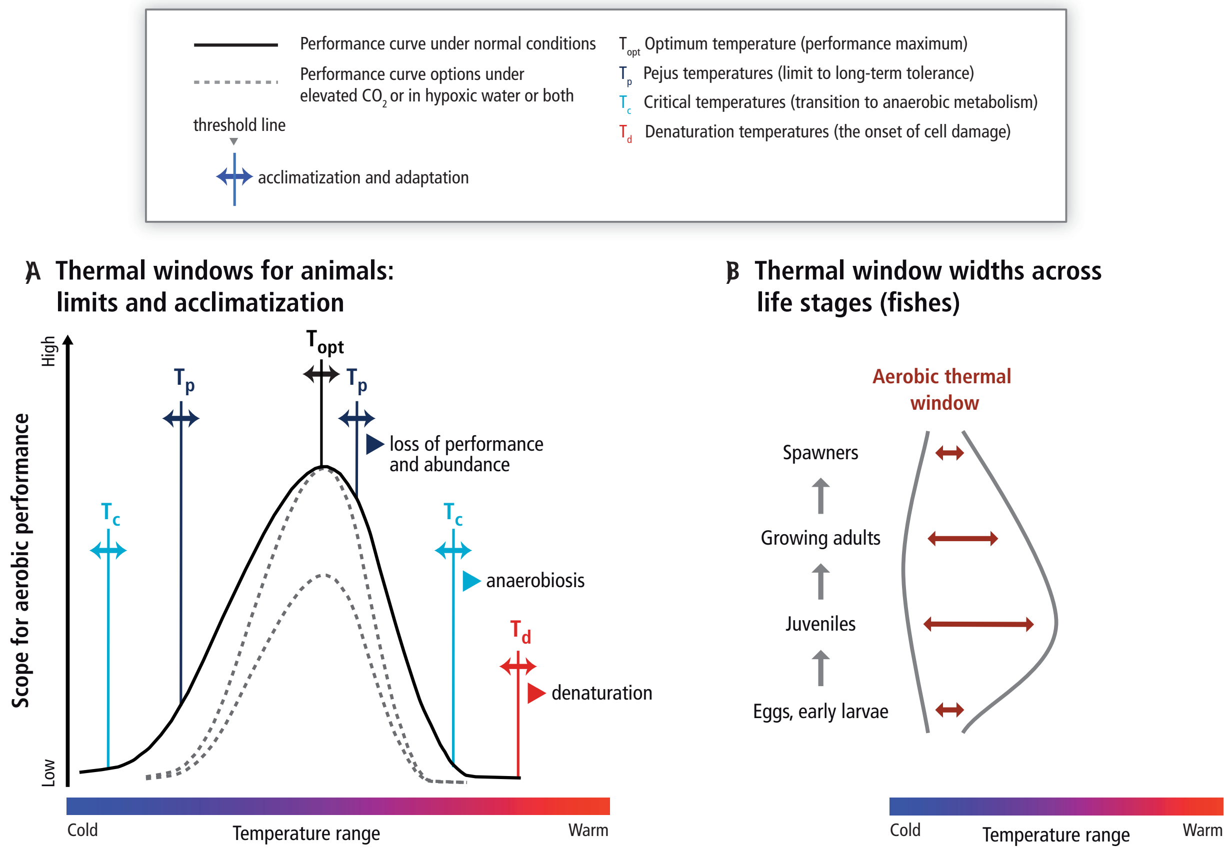


Figure 6-5: Thermal specialization of an organism explains the why, how, when, and where of climate sensitivity. (A) The thermal tolerance range and performance levels of an organism are described by its performance curve (exemplified for an animal). Each Performance (e.g., exercise, growth, reproduction) is maximal at its optimum temperature (T_{opt}), and becomes progressively constrained during cooling or warming. Surpassing the first low and high temperature thresholds (T_p, p, pejus: getting worse) means going into time-limited tolerance. Once further cooling or warming surpasses the next low or high thresholds (T_c, c, critical), oxygen availability becomes insufficient and an anaerobic metabolism begins. Denaturation temperatures (T_d) are even more extreme and characterized by the onset of damage to cells and proteins. Horizontal arrows indicate that T_p, T_c, and T_d-thresholds of an individual can shift, within limits, between summer and winter (seasonal acclimatization) or when the species adapts to a cooler or warmer climate over generations (evolutionary adaptation). Under elevated CO_2 levels (ocean acidification) and in hypoxic waters performance levels can decrease and thermal windows narrow (dashed grey curves). (B) The width of the thermal range (horizontal arrows) also changes over time when an individual develops from egg to larva to adult and gains weight and size. Blue to red colour gradients illustrate the range between cold to warm temperatures (after Pörtner, 2002a, 2012; Pörtner and Farrell, 2008).

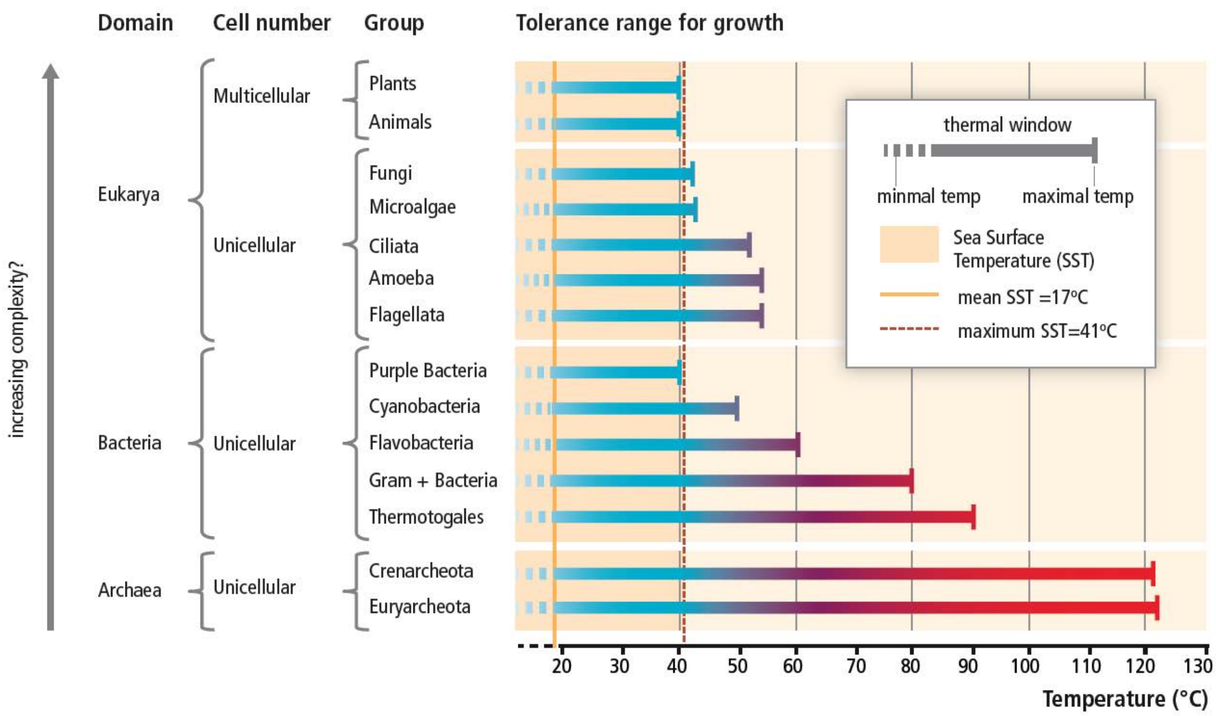


Figure 6-6: Maximal values of temperature covered by various domains and groups of free-living marine organisms (bacteria to animals, domains, and groups modified after Woese *et al*.,1990). High organizational complexity is hypothesized to be associated with decreasing tolerance to heat and to enable an increase in body size which in turn, decreases heat tolerance further (Alker *et al*., 2001; Baumgartner *et al*., 2002; Campbell *et al*., 2006; Chevaldonné *et al*., 2000; De Jonckheere *et al*., 2009, 2011; Pörtner, 2002a,b; Sorokin and Kraus, 1962). In the domain Bacteria, the Thermotogales are less complex and most tolerant to high temperatures (Abed *et al*., 2002; Huber *et al*., 1986; Takai *et al*., 1999; Tenreio *et al*., 1997; Ventura *et al*., 2000). The highest temperature, at which growth can occur is 122°C for hydrothermal vent archaea, seen under elevated hydrostatic pressure in laboratory experiments (Kashefi and Lovley, 2003; Takai *et al*., 2008.)

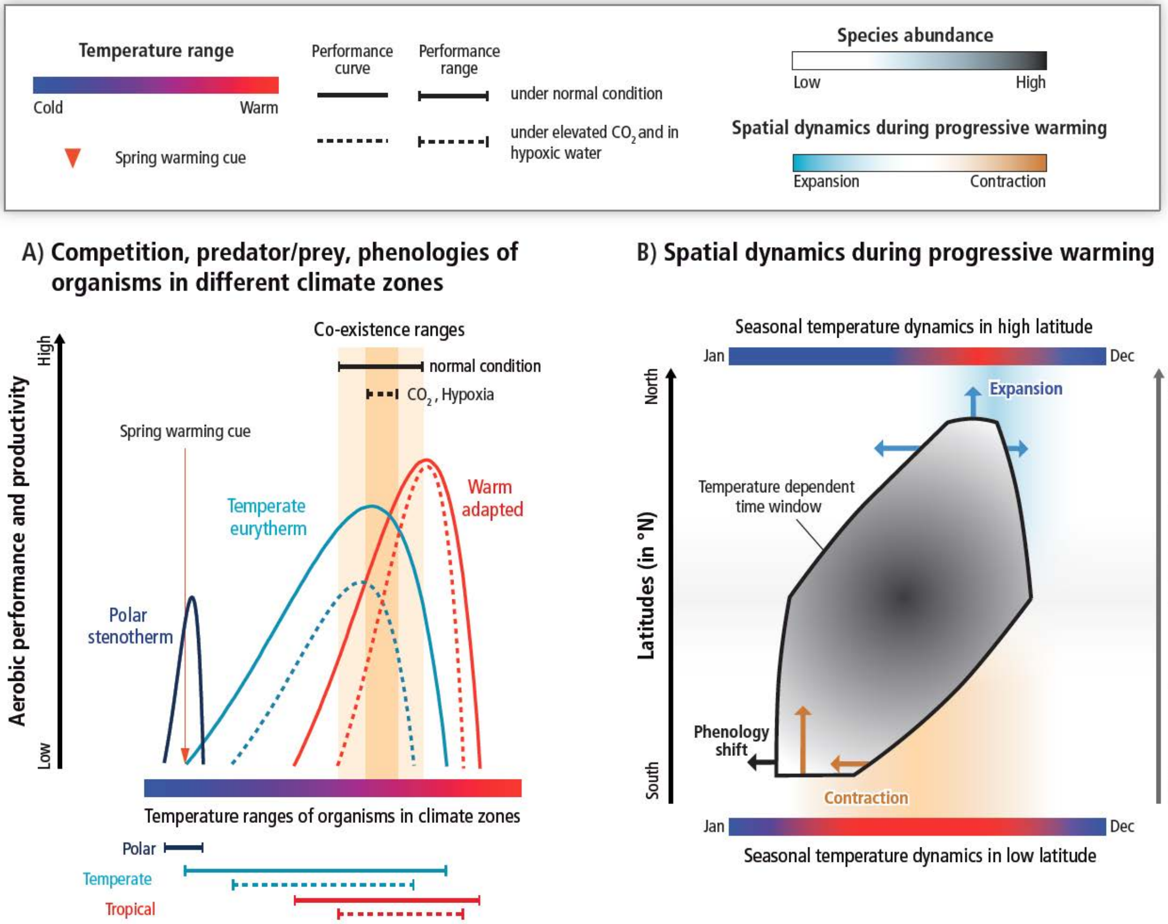


Figure 6-7: Role of thermal tolerance and performance of organisms at ecosystem level. (A) Thermal tolerance ranges (Figure 6-5) differ between species across polar, temperate and tropical climate zones, then overlapping between coexisting species. Shifting temperatures and specific effects of additional drivers on the respective performance curves (dashed lines) change the fitness of coexisting species relative to each other as well as their temperature range of coexistence (after Pörtner and Farrell, 2008). Warming alters the timing of seasonal activities (e.g., elicited by spring warming cues) earlier, or can benefit only one of two interacting species (e.g. in predator-prey dynamics or competition) causing shifts in predominance. (B) During climate warming a largely unchanged thermal range of a species causes it to follow its normal temperatures as it moves or is displaced, typically resulting in a poleward shift of the biogeographic range (exemplified for the Northern hemisphere, modified after Beaugrand, 2009). The polygon delineates the distribution range in space and seasonal time; the level of grey denotes abundance. The southern time window of tolerated temperatures shifts to earlier and contracts, while the northern one dilates (indicated by arrows). Species display maximum productivity in low latitude spring, wide seasonal coverage in the center, and a later productivity maximum in the North. The impact of photoperiod (length of daily exposure to light) increases with latitude (grey arrow). Water column characteristics or photoperiod may overrule temperature control in some organisms (e.g. diatoms), limiting northward displacement.

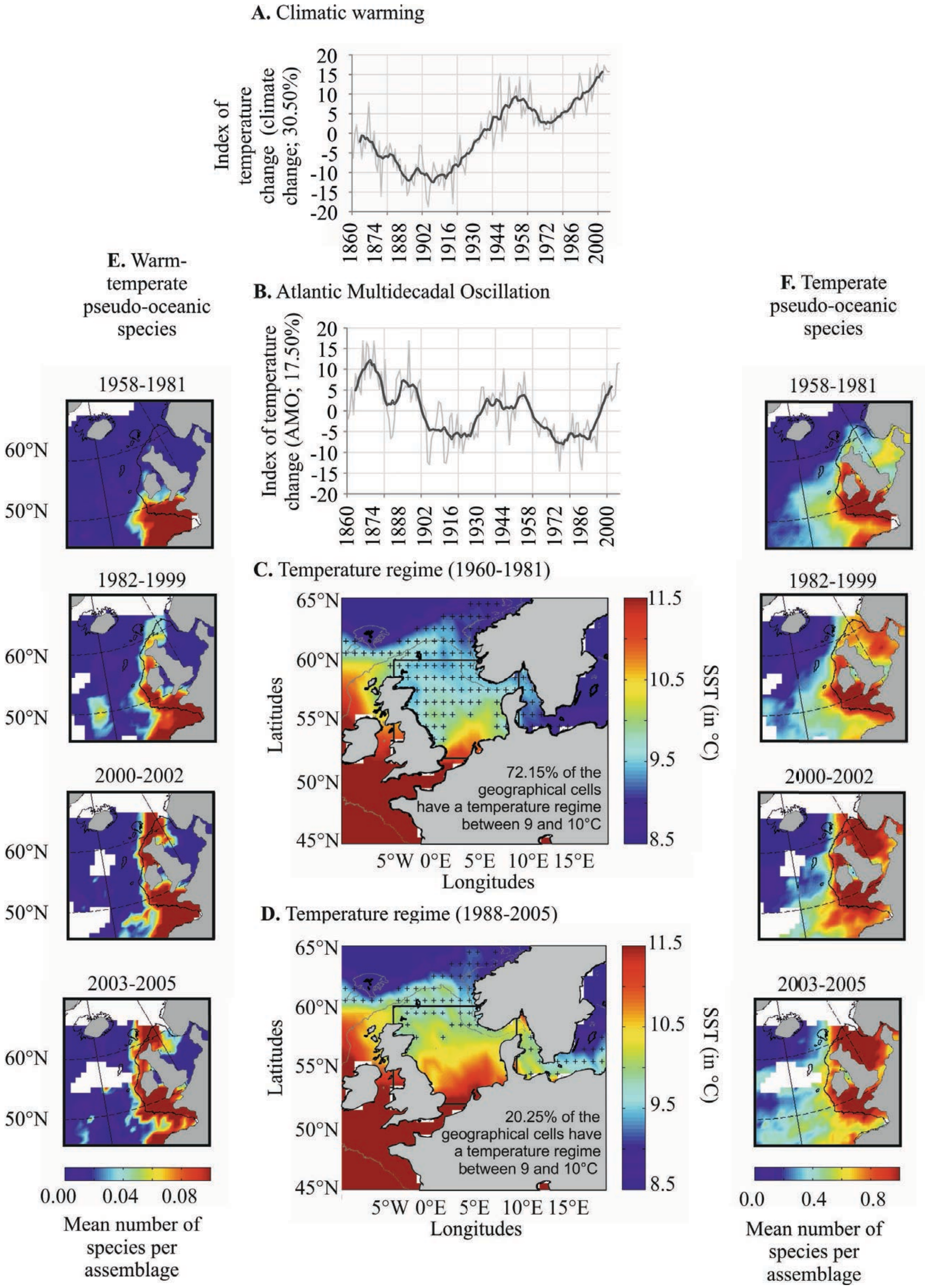

A. Climatic warming
Index of temperature change (climate change; 30.50%)
B. Atlantic Multidecadal Oscillation
Index of temperature change (AMO; 17.50%)
C. Temperature regime (1960-1981)
72.15% of the geographical cells have a temperature regime between 9 and 10°C
D. Temperature regime (1988-2005)
20.25% of the geographical cells have a temperature regime between 9 and 10°C
Latitudes
Longitudes
SST (in °C)
E. Warm-temperate pseudo-oceanic species
F. Temperate pseudo-oceanic species
1958-1981
1982-1999
2000-2002
2003-2005
Mean number of species per assemblage

Figure 6-8: Multi-decadal changes in ecosystem structure in the NE Atlantic driven by warming from both anthropogenic climate change and natural climate variability. **A.** Index of temperature change over the North Atlantic (31°N-65°N and 99°W-11°W) reflecting climate change. This index is the first principal component (i.e., explaining 30.5% of observed variability) based on a Principal Component Analysis (PCA) performed on sea surface temperature. **B.** Index of temperature change (17.5% of observed variability) reflecting the Atlantic Multidecadal Oscillation (AMO). The index is the second principal component. **C-D.** Observed mean annual sea surface temperature in the North Sea during 1960-1981 (**C**) and 1988-2005 (**D**). The location of the critical thermal boundary (9-10°C) is indicated by '+'. **E**. Long-term changes in the mean number of warm-temperate pseudo-oceanic species from 1958 to 2005. **F**. Long-term changes in the mean number of temperate pseudo-oceanic species from 1958 to 2005. The period 1958-1981 was a period of relative stability and the period 1982-1999 was a period of rapid northward shifts, indicating that the abrupt ecosystem shift observed in the North Sea was part of a large-scale response of the zooplankton biodiversity to warming temperatures (see **A**-**D**). Average values are below 1 because they are annual averages. Note that the color bar is 10-fold smaller for warm-temperate pseudo-oceanic species because these species are less frequently observed than their temperate counterparts. Panels A. and B. from Edwards *et al*. (2013), and C. to F. from Beaugrand *et al*. (2008), and Beaugrand *et al*. (2009).
[Illustration to be redrawn to conform to IPCC publication specifications.]

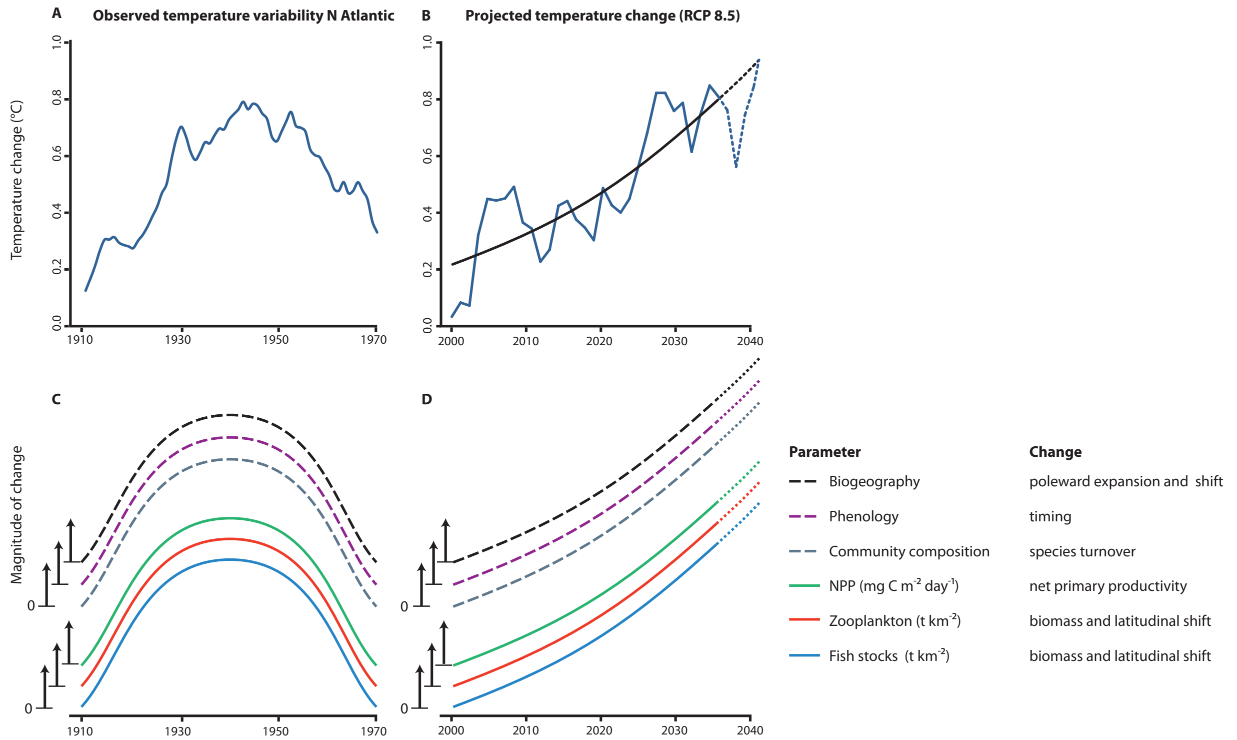


Figure 6-9: Schematic depiction of observed effects of ~1°C ocean warming in the northern North Atlantic driven by climate variability (A, C) versus effects expected from anthropogenic climate change (B, D). A) Transient warming and cooling associated with AMO variability (Drinkwater, 2006), based on the Kola Section temperatures (0-200 m; Stations 3-7, 71.5°-72.5°N, 33.5°E) in the Barents Sea obtained from http://www.pinro.ru and filtered using a 20-year running mean. Similar trends occurred across most of the northern North Atlantic although the amplitude and timing of the peaks and troughs varied spatially. B) Warming driven by climate change for the same region (RCP 8.5 simulations averaged from CMIP5 models, computed as the mean over the upper 200 m in the grid box (2.5x2.5 degrees) centered at 71.25N and 33.75E). C) Warming and subsequent cooling in the northern North Atlantic during the period shown in A resulted in complex multi-faceted changes (shown schematically) in NPP (green curve), zooplankton biomass (red curve) and fish stock abundances (blue curve). There was a general poleward shift and range expansion of many commercial (e.g., Atlantic herring, Atlantic cod, haddock) and non-commercial species, reversed during the subsequent cooling period (denoted by black dashed curve). Polewards shifts in spawning areas (e.g., Atlantic cod) were also reversed as the waters cooled. The purple and grey dashed curve represents shifts in seasonal timing (phenology) and community composition, respectively, that were influenced by earlier arrivals and later retreat of migratory fish (not shown). For more details see Drinkwater (2006). D) Projected effects of climate mediated warming on northern sub-polar and polar biota based on model projections of altered NPP (Bopp *et al.*, 2013), and of the range shift of exploited fishes and invertebrates (Cheung *et al.*, 2009, 2013a). The projected trends in panel D will differ with latitude, e.g., decreased NPP at lower latitudes and no significant change to NPP in temperate waters (Bopp *et al.*, 2013). Higher NPP supported and is projected to support higher trophic levels at high latitudes (C, D, 6.3.4). Note that climate variability will be superimposed on anthropogenic warming (B, see Figure 6-1, 6-8A,B). Dotted lines indicate projected changes to continue beyond the range of historical observations.
[Illustration to be redrawn to conform to IPCC publication specifications.]

(A)

(B)

(C)

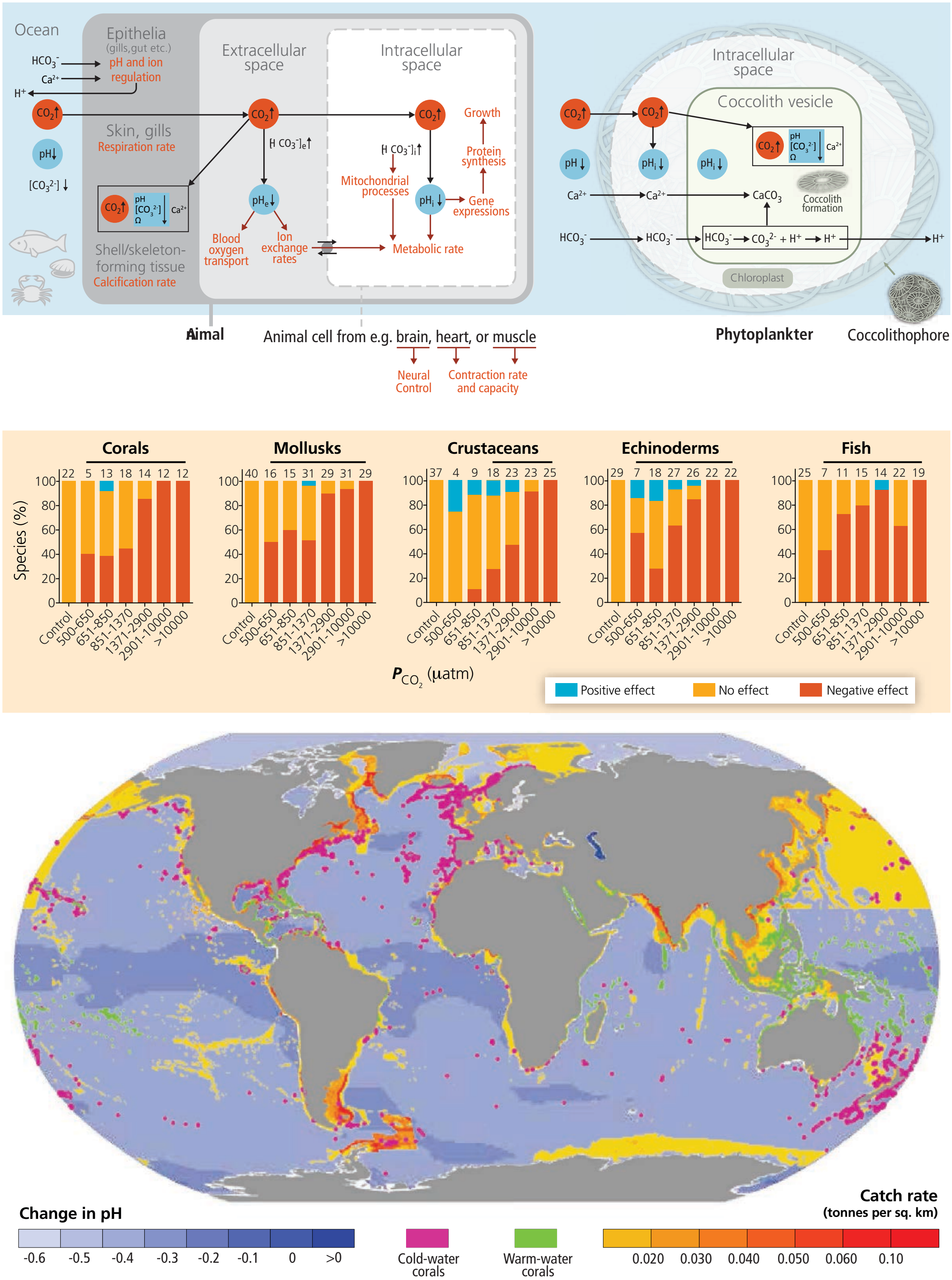

Ocean
Epithelia
(gills,gut etc.)
pH and ion regulation
Extracellular space
Intracellular space
Growth
Protein synthesis
Gene expressions
Mitochondrial processes
Metabolic rate
Skin, gills
Respiration rate
Blood oxygen transport
Ion exchange rates
Shell/skeleton-forming tissue
Calcification rate
Aimal
Animal cell from e.g. brain, heart, or muscle
Neural Control
Contraction rate and capacity
Intracellular space
Coccolith vesicle
Coccolith formation
Chloroplast
Phytoplankter
Coccolithophore
Corals
Mollusks
Crustaceans
Echinoderms
Fish
Species (%)
Control
500-650
651-850
851-1370
1371-2900
2901-10000
>10000
P_{CO_2} (μatm)
Positive effect
No effect
Negative effect
Change in pH
-0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0 >0
Cold-water corals
Warm-water corals
Catch rate
(tonnes per sq. km)
0.020 0.030 0.040 0.050 0.060 0.10

Figure 6-10: A: Responses of a schematized marine animal (left) and a phytoplankter (right) to ocean acidification (OA). Effects are mediated via diffusive CO_2 entry (black arrows) into body and cell compartments, resulting in a rise in pCO_2 (highlighted in red), a drop in compartmental pH (highlighted in blue) and their effects (red arrows) on various processes (red text) in tissues and cellular compartments, as well as on calcium carbonate saturation state (Ω) at calcification sites (after Pörtner, 2008; Taylor *et al*., 2011). Variable sensitivity relates to the degree of pH decline and compensation, depending on the capacity of pH and ion regulation. B: Distribution of sensitivities across species within animal phyla, under progressively rising water CO_2 levels, as percent of studied scleractinian coral, echinoderm, molluskan, crustacean and fish species affected negatively, positively or not at all (for effects considered see text). As not all life stages, variables and pCO_2 ranges were covered in all species two assumptions partially compensate for missing data: 1) Negative effects at low pCO_2 will remain negative at high pCO_2. 2) A positive or neutral outcome at both low and high pCO_2 will be the same at intermediate pCO_2. As responses reported for each species vary for each CO_2 range, variable species numbers result (on top of columns). The total number of species studied in a group is shown as the number above the control column. Horizontal lines above columns represent frequency distributions significantly different from controls (Wittmann and Pörtner, 2013). C: Areas with reported annual catches of marine calcifiers (crustaceans and mollusks) >0.001 t km^{-2} depicted on a global map showing the distribution of ocean acidification in 2100 according to RCP8.5 (WGI AR5 SPM) as well as the distribution of warm-water (green dots) and cold-water coral communities (pink dots).

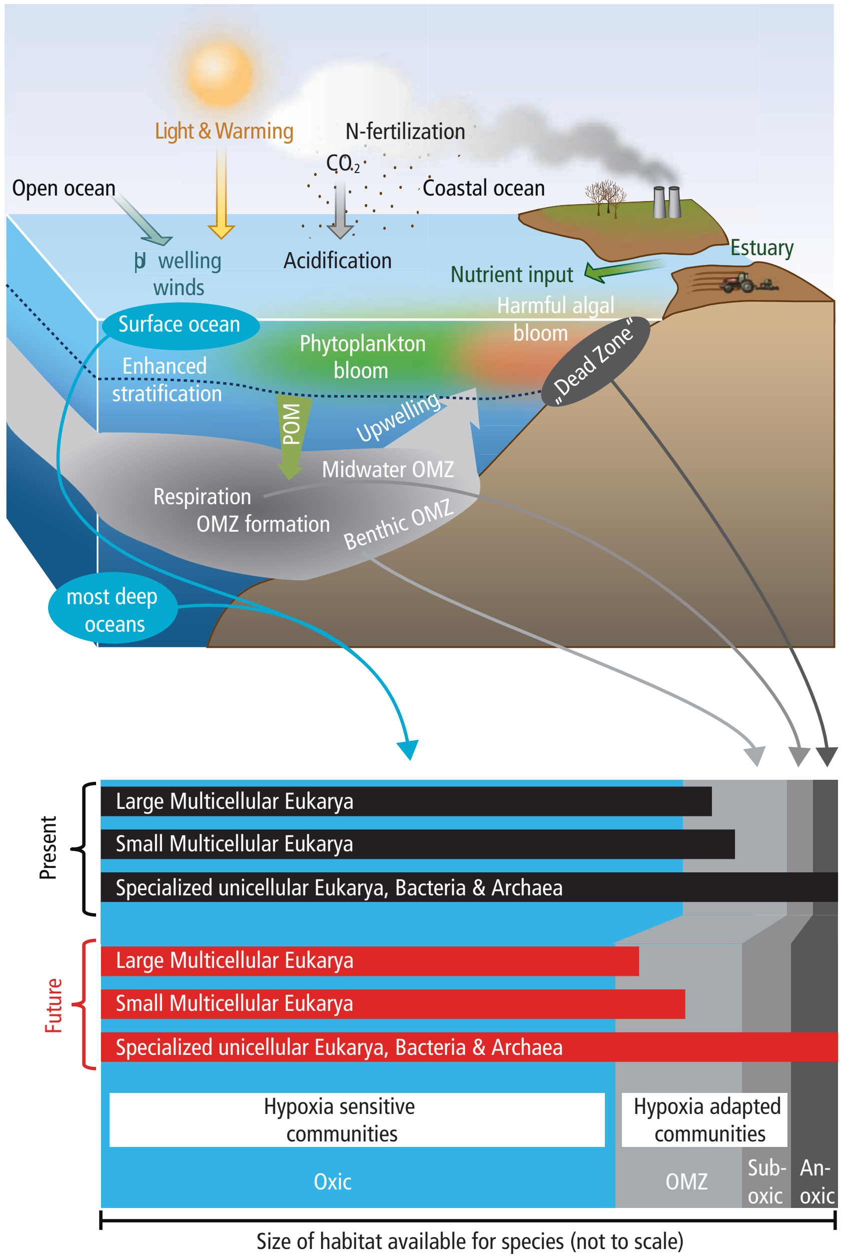


Figure 6-11: (A) Principal mechanisms underlying the formation of hypoxic conditions and their biological background (modified from Levin *et al.*, 2009; Levin and Sibuet, 2012). The buoyancy flux from fluvial discharges produces sharp density stratification at the base of the freshened layer (also valid for ice melt and high precipitation) near the surface and, hence, vertical mixing is greatly reduced. In consequence, the nutrient inputs from the river and the atmosphere accumulate in a narrow upper layer, leading to phytoplankton blooms. The enhancement of oxygen consumption due to aerobic decomposition of sinking organic matter results in hypoxic conditions of OMZs. OMZs also form in the open oceans. Heating of the upper layer increases stratification, while the wind-driven upwelling of hypoxic, nutrient-rich water from deeper layers adds to the formation of the OMZs (Box CC-UP) (B) Distribution of various free-living marine organisms (microbes such as archaea, bacteria, protists, small and large multicellular animals, and plants) across the ranges of O_2 concentrations in vaious water layers. Hypoxia tolerance is enhanced in small compared to large organisms, allowing unicellular species and small animals to thrive in extremely hypoxic habitats. Species richness and body size of animals increases with rising O_2 levels.
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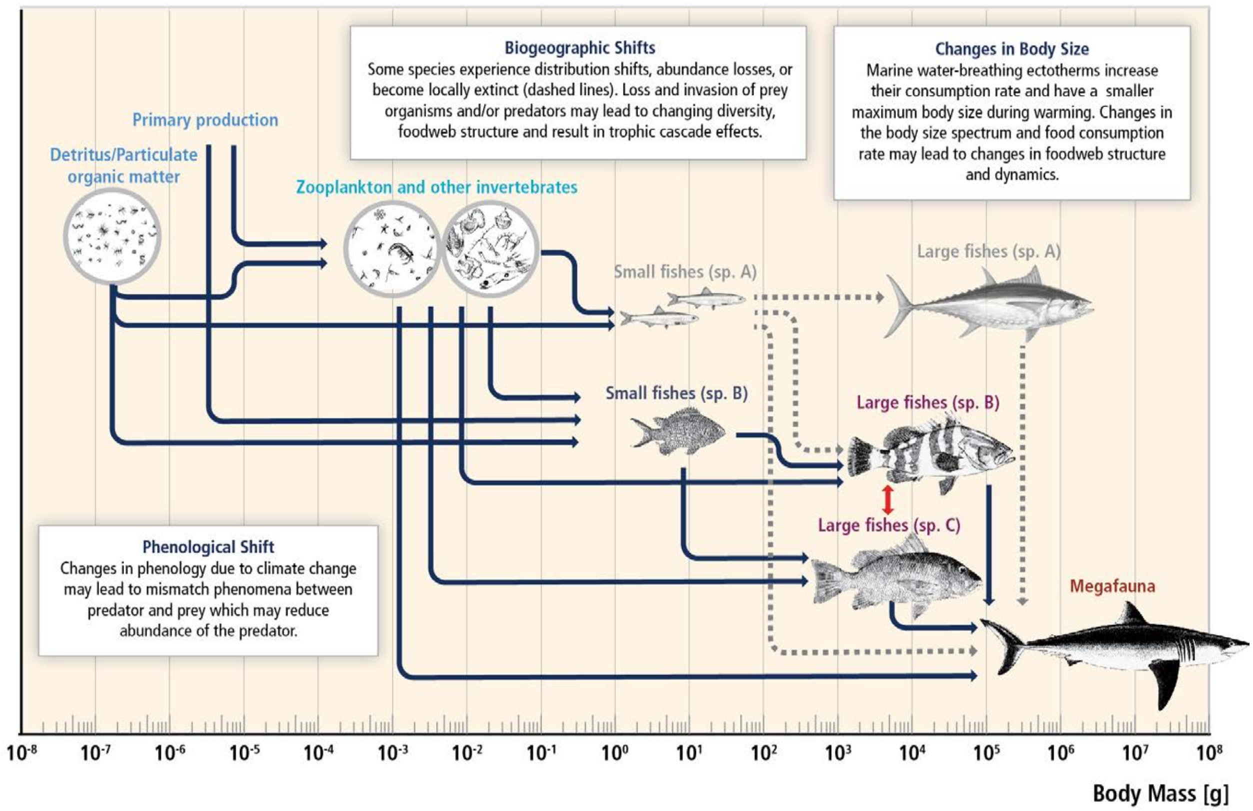

Figure 6-12: Schematic diagram of expected responses to climate change in a marine food web. A coupled pelagic and benthic food web is structured by the body size spectrum of species. Combined warming, hypoxia and ocean acidification reduce body size, shift biogeographies, change species composition and abundance, and reconfigure trophic linkages and interaction dynamics. Fishing generally removes large-bodied species and truncates the body-size spectrum of the community. This confounds the detection and attribution of food web responses to climate change. Arrows represent species interactions (e.g., between predator and prey or competitors for food or space). Broken lines reflect the potential loss of populations and trophic linkages due to climate change.

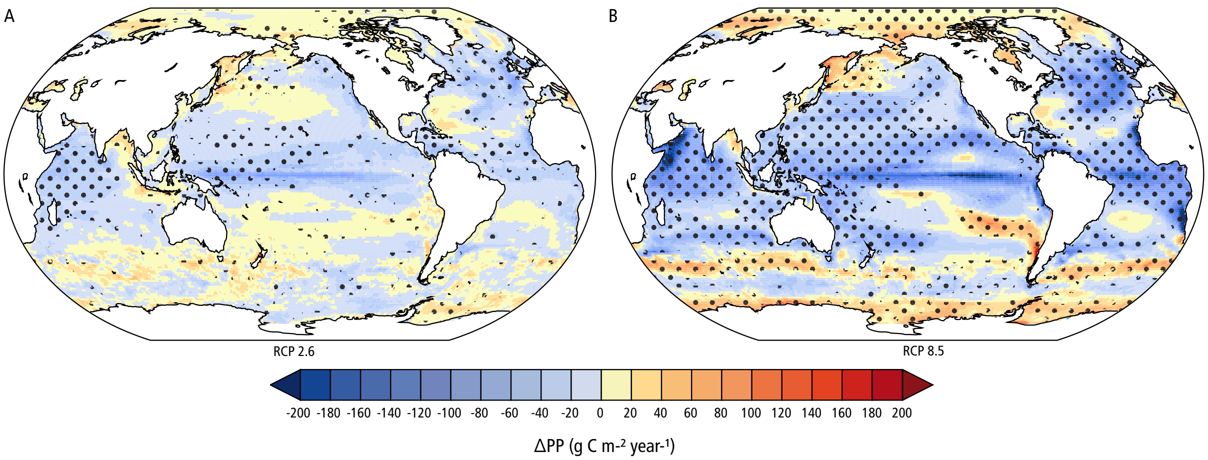

Figure 6-13: Multi-model annual mean changes of projected vertically-integrated net primary production (small and large phytoplankton) under the low emission scenario RCP2.6 (A) and the high emission scenario RCP8.5 (B) for the period 2090 to 2099 relative to 1990 to 1999 (after Bopp *et al.*, 2013). To indicate consistency in the sign of change, regions are stippled where 80% of the ten models from the Coupled Model Intercomparison Project Phase 5 (Bopp *et al*. 2013) agree on the sign of change.

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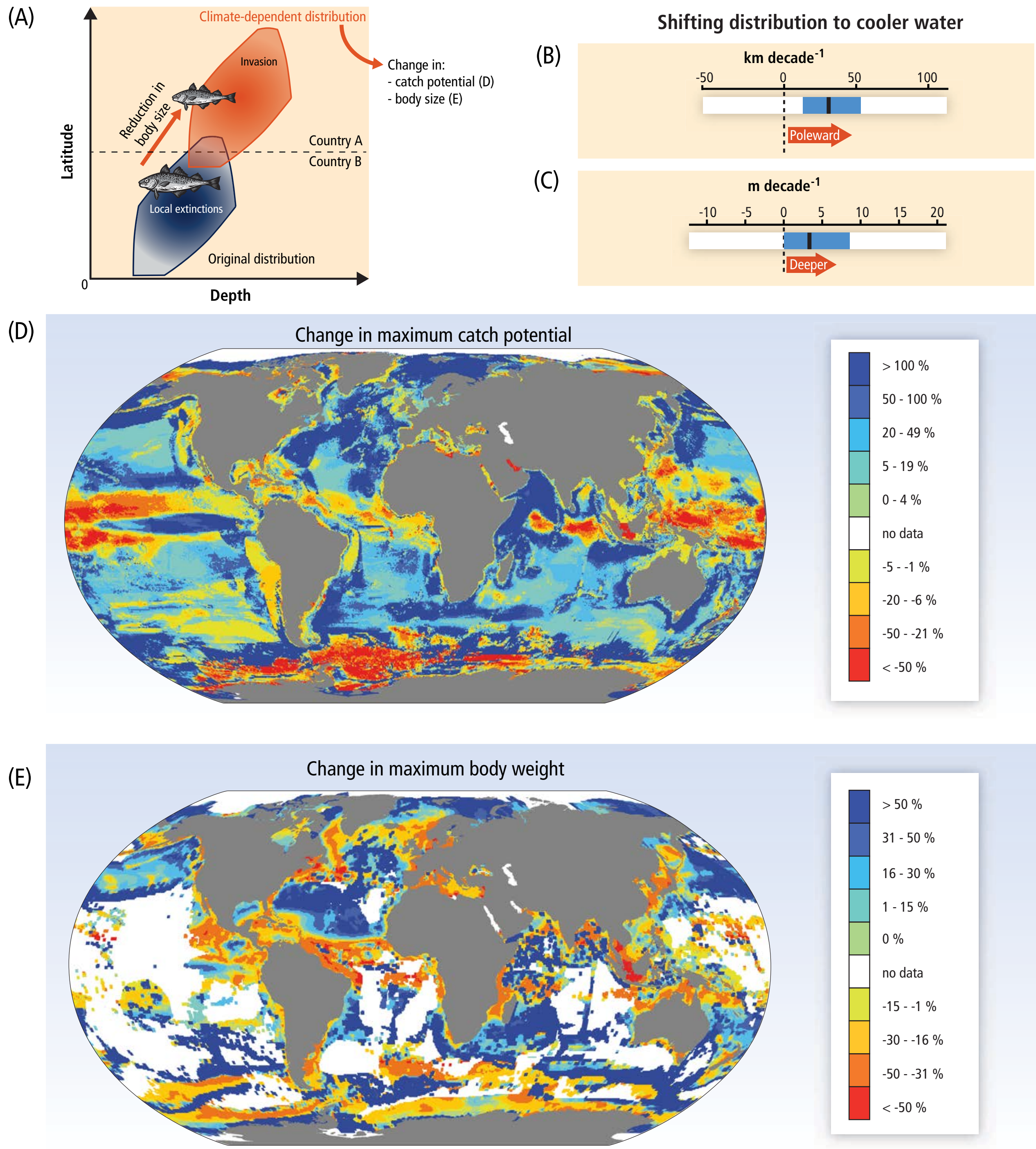
(A)
Climate-dependent distribution
Invasion
Reduction in body size
Change in:
- catch potential (D)
- body size (E)
Country A
Country B
Local extinctions
Original distribution
Latitude
Depth
0
Shifting distribution to cooler water
(B)
km decade-1
-50
0
50
100
Poleward
(C)
m decade-1
-10
-5
0
5
10
15
20
Deeper
(D)
Change in maximum catch potential
> 100 %
50 - 100 %
20 - 49 %
5 - 19 %
0 - 4 %
no data
-5 - -1 %
-20 - -6 %
-50 - -21 %
< -50 %
(E)
Change in maximum body weight
> 50 %
31 - 50 %
16 - 30 %
1 - 15 %
0 %
no data
-15 - -1 %
-30 - -16 %
-50 - -31 %
< -50 %

Figure 6-14: Climate change effects on the biogeography, body size and fisheries catch potential of marine fishes and invertebrates. (A) Shifts in distribution range and reduction in body size of exploited fish driven by projected warming, oxygen depletion and sea-ice retreat (cf. Figure 6-7). Whenever the shift in distribution does not fully compensate for warming and hypoxia, the result will be a decrease in body size. Shifts in (B) latitudinal and (C) depth distribution of 610 exploited demersal fishes are projected to have a median (central line of the box) of 31 km decade^{-1} and 3.3 m decade^{-1}, respectively, with variation between species (box boundary: 25th and 75th percentiles) from 1991-2010 to 2041 - 2060 under the SRES A2 (between RCP6.0 - 8.5) scenario (Cheung *et al*., 2011; Cheung *et al*., 2013b). (D) Combining species' range shift with projected changes in NPP leads to a projected global redistribution of maximum catch potential (Analysis includes ~1,000 species of exploited fishes and invertebrates, under warming by 2°C according to SRES A1B (~RCP6.0), comparing the 10-year averages 2001-2010 and 2051-2060; redrawn from Cheung *et al*. 2010). (E) Changes in species distribution and individual growth are projected to lead to reduced maximum body size of fish communities at a certain site. The analysis includes 610 species of marine fishes, from 1991-2010 to 2041-2060 under the SRES A2 (~RCP6.0 to 8.5, Cheung *et al.*, 2013b). Key assumptions of the projections are that current distribution ranges reflect the preferences and tolerances of species for temperature and other environmental conditions and that these preferences and tolerances do not change over time. Catch potential is determined by species range and net primary production. Growth and maximum body size of fishes are a function of temperature and ambient oxygen level.

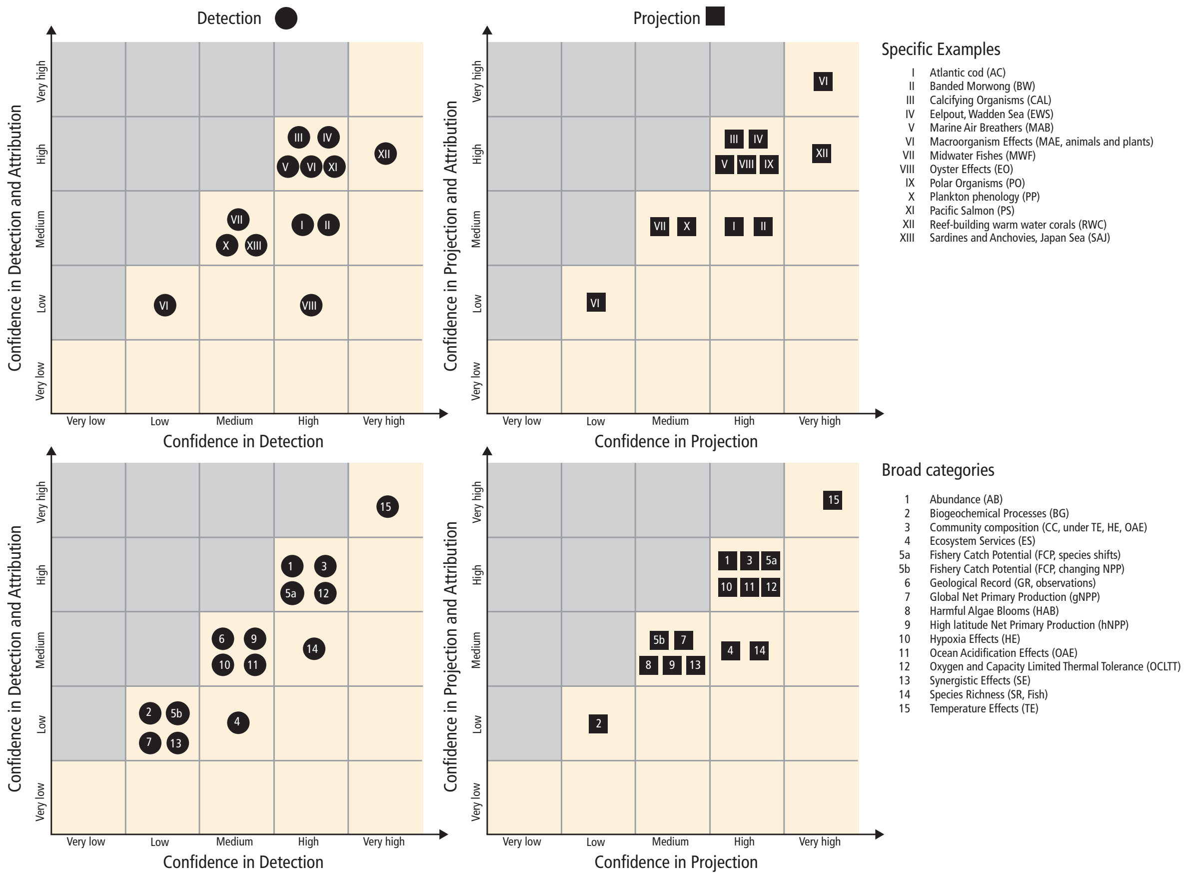

Figure 6-15: Overview of the levels of confidence in detection (left), as well as in projection (right) of climate change effects on ocean systems, in relation to the levels of confidence in attributing these effects to the respective climate forcings. Case studies, processes, and concepts relevant in assessing the effects of climate change are represented by their acronyms in both text and figure. While confidence in the presence of effects is often high, the direct attribution to one driver in field experiments is difficult, as drivers are often highly correlated with each other (e.g., warming with changes in stratification and hence reduced nutrient supply). Some climate change impacts have been condensed into broad categories to avoid overpopulating the figures (e.g., Bio-Geochemical processes, BG). Note that the term “attribution” is used for both present-day detections in the field and future projections, the latter including qualitative and quantitative extrapolations and simulations from fundamental principles and models. Firm knowledge from experiments (field, laboratory and modeling) simulating future conditions enhances the respective confidence levels to those for detection or projection. The empirical observations resulting from those experiments are directly attributable to the respective drivers. Confidence in attribution is enhanced if these experiments identify the underlying mechanisms and their responses. See text for the discussion of depicted examples and categories. Confidence assignments focus on the nature and size of effects, not on model capacity to reliably quantify their magnitude.
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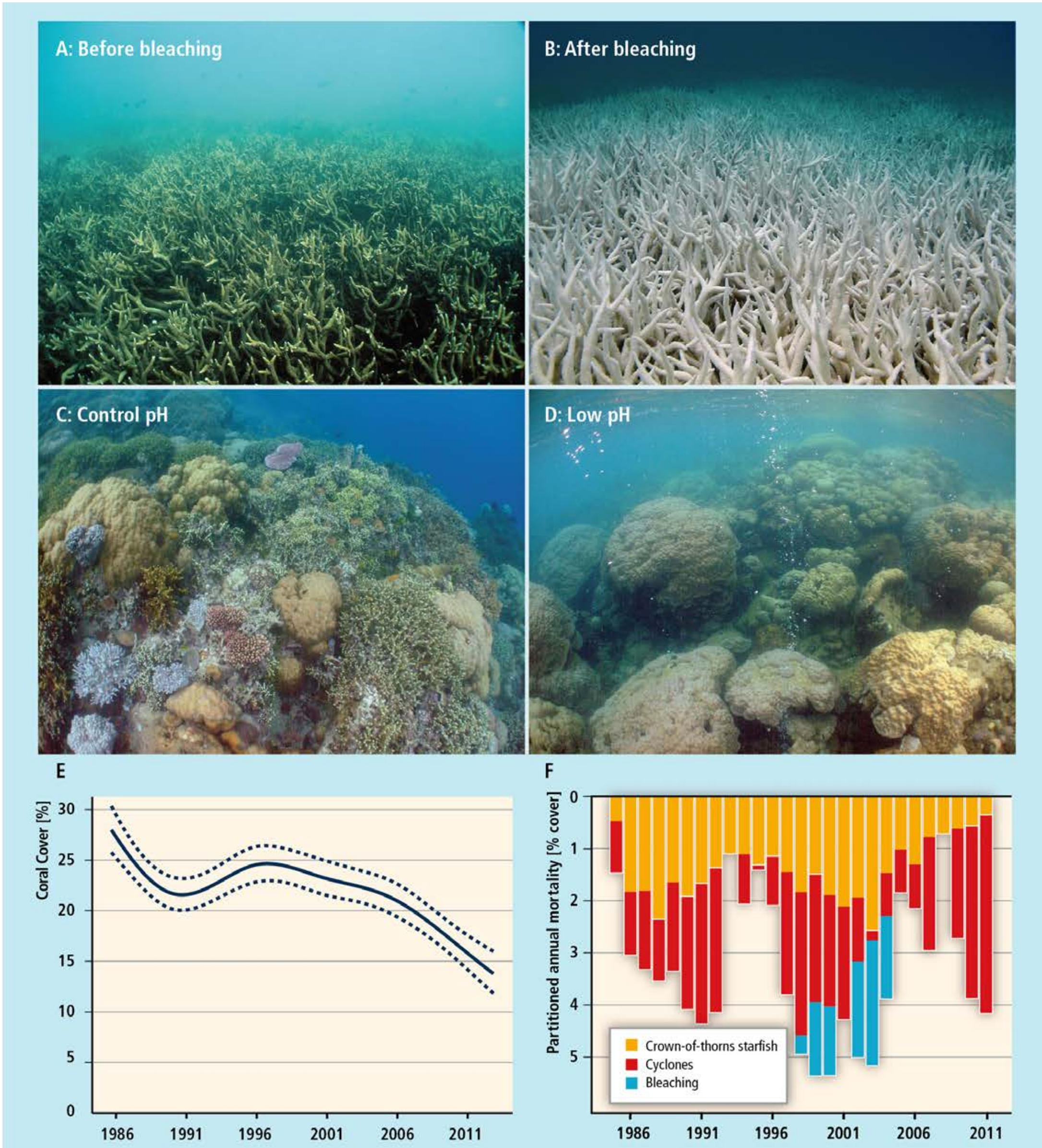

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

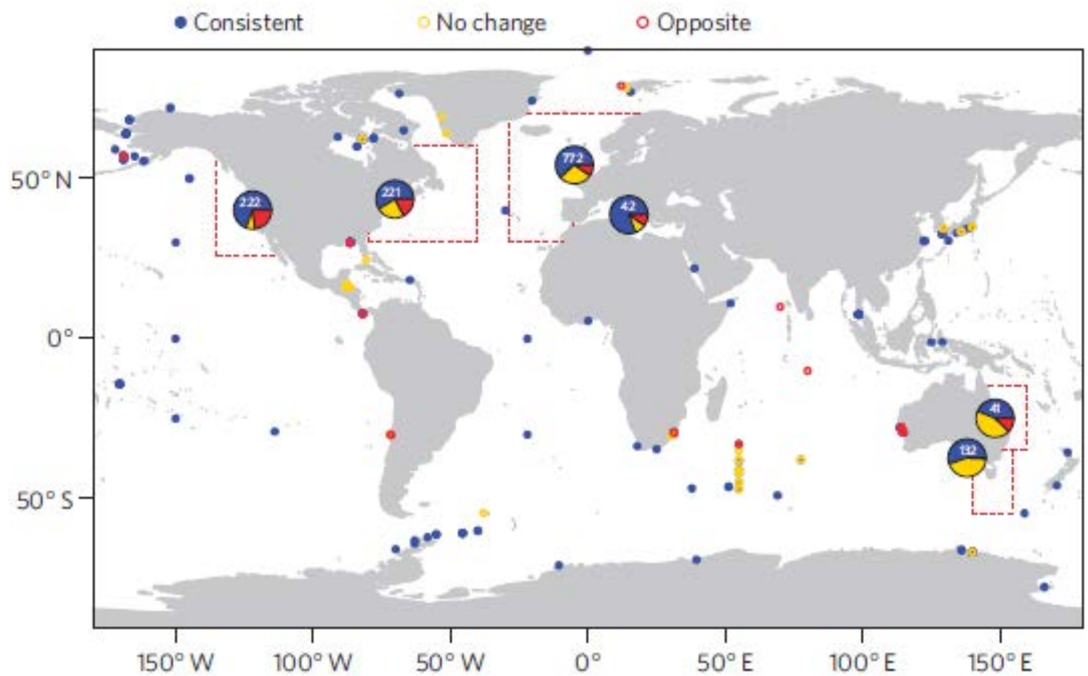

Figure MB-1: 1735 observed responses to climate change from 208 single- and multi-species studies. Changes attributed to climate change (blue), inconsistent with climate change (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite or equivocal) observations within each region. Note: 57% of the studies included were published since AR4 (from Poloczanska *et al.*, 2013).

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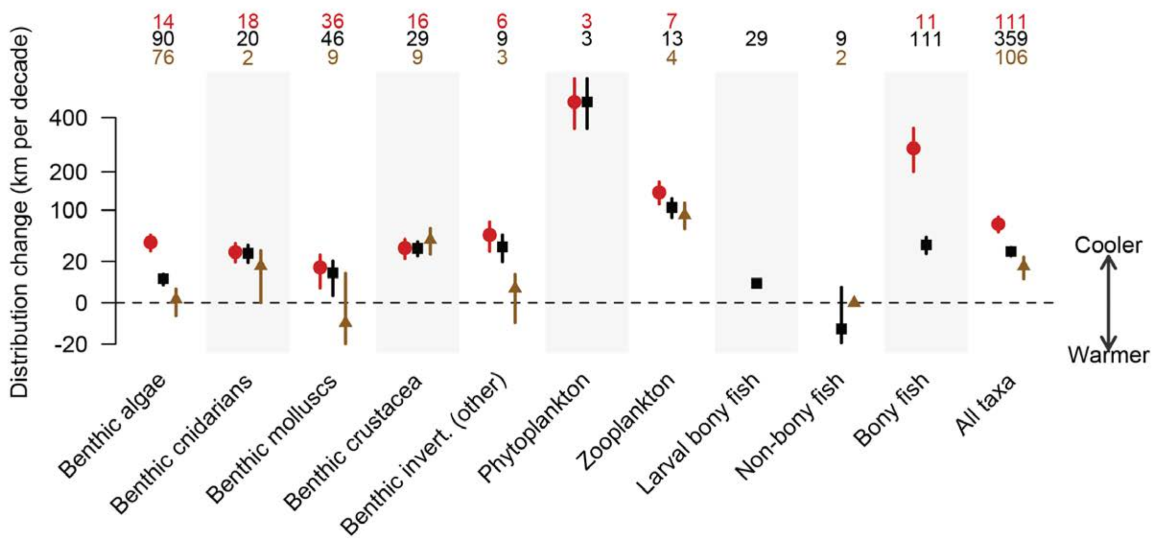

Figure MB-2. Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations (from Poloczanska et al., 2013).

[Illustration to be redrawn to conform to IPCC publication specifications.]

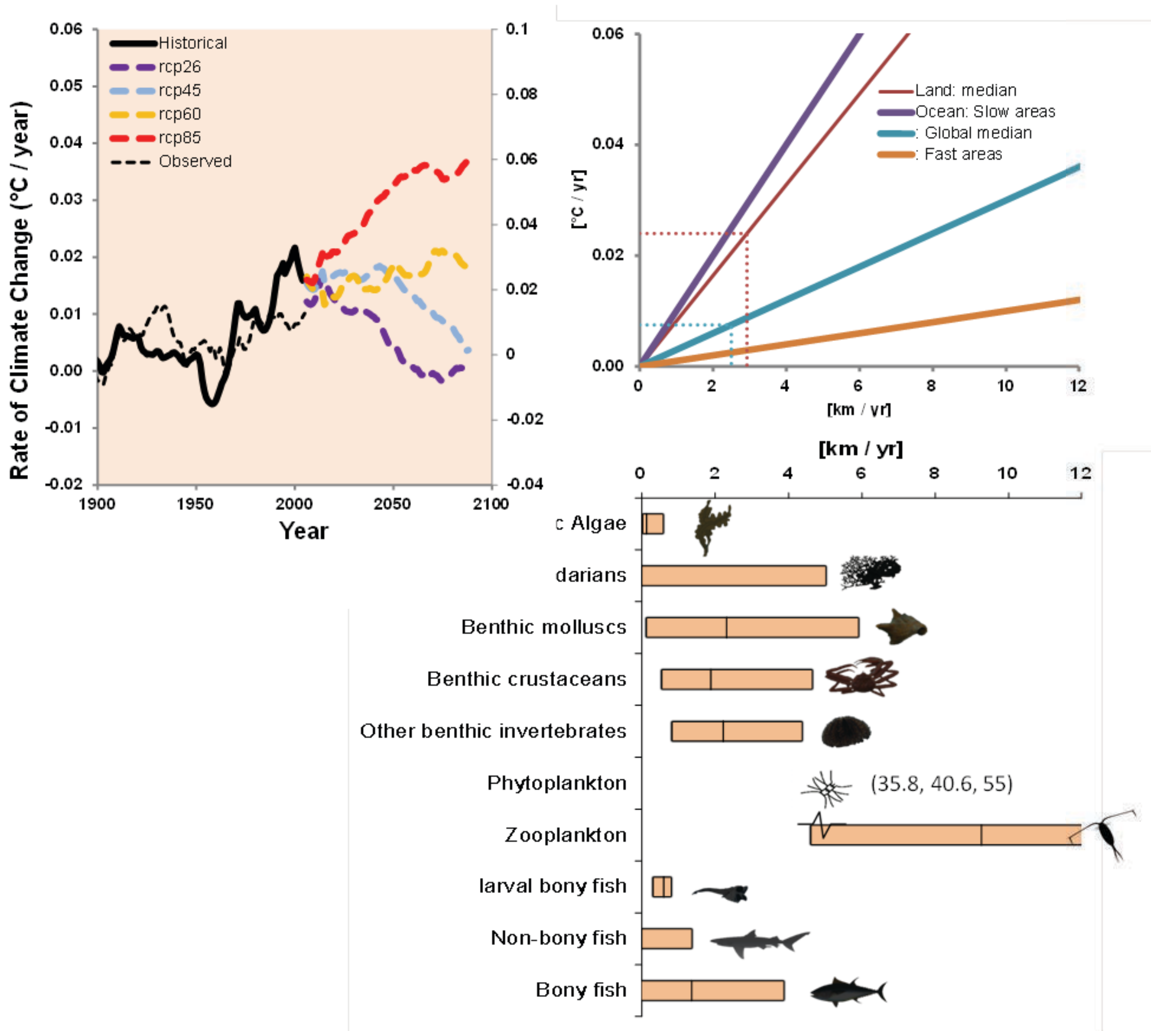

Figure MB-3. A. Rate of climate change for the Ocean (sea surface temperature (SST) °C); B. corresponding climate velocities for the Ocean and median velocity from land (adapted from Burrows et al., 2011); and C. observed rates of displacement of marine taxonomic groups over several decades until 2010. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.008 °C yr^{-1} correspond to ca. 2.4 km yr^{-1}median climate velocity in the Ocean. When compared to observed rates of displacement, many marine taxonomic groups have been able to track these velocities, except phyto- and zooplankton where rates of displacement greatly exceed climate velocity. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (A) Observed rates of climate change for Ocean SST (Black dotted line) are derived from HadISST1.1 data set, all other rates are calculated based on the average of the CMIP5 climate model ensembles (Table S30-3) for the historical period and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window. (B) Median climate velocity calculated from HadISST1.1 dataset over 1960–2010 using the methods of Burrows et al., 2011. The three axes represent estimated median climate velocities are representative of areas of slow velocities such as Pacific subtropical gyre (STG) system (Purple line), the global Ocean surface (excluding polar seas, Blue line), and areas of high velocities such as the Coral Triangle and North Sea (Orange line). Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2010. The Red line corresponds to the median rate over global land surface calculated using historical surface temperatures from the CMIP5 model ensemble (Table S30-3). (C) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. 2013 using published studies (Figure MB-2 Black data set). Note the displacement rates for phytoplankton exceed the axis, so values are given. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

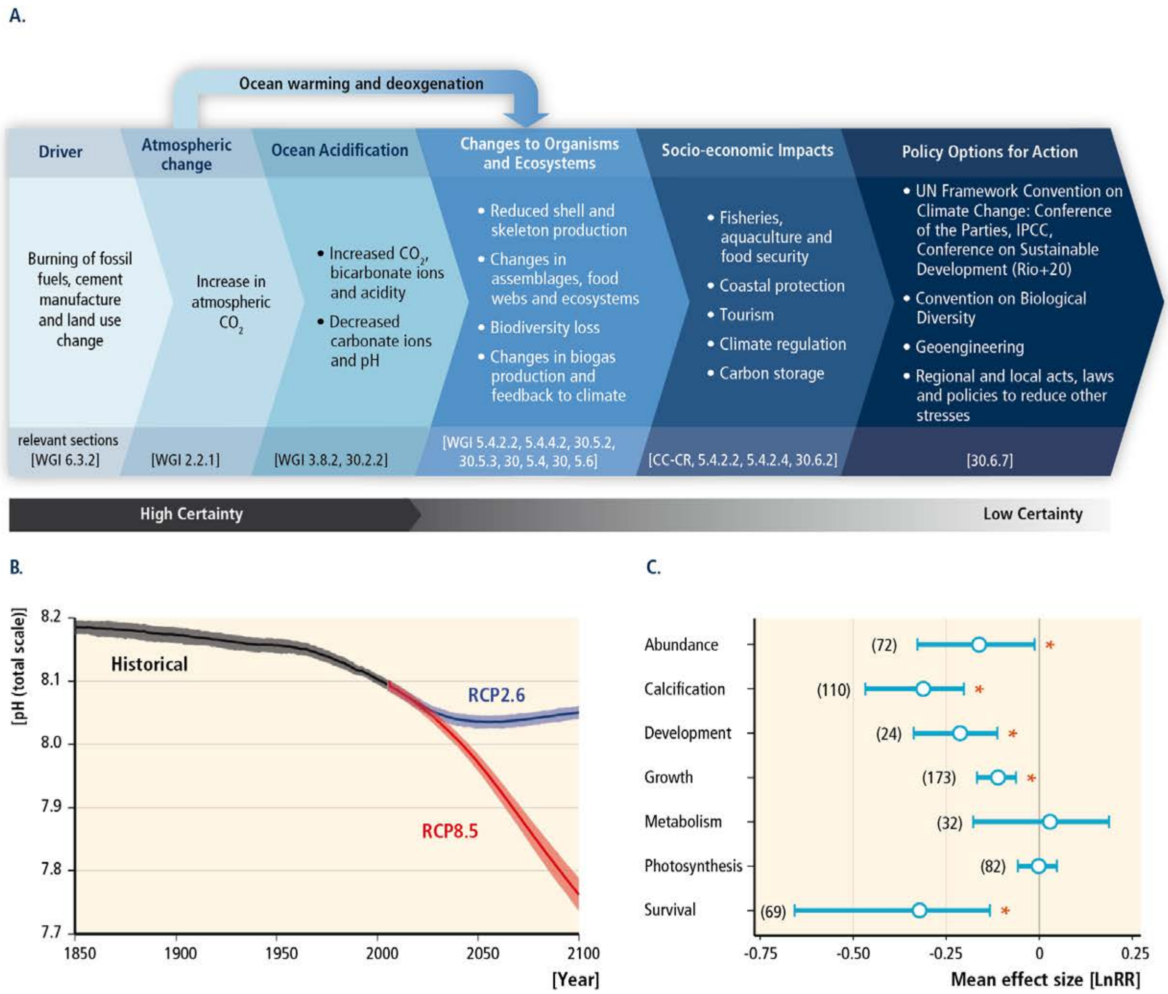

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.

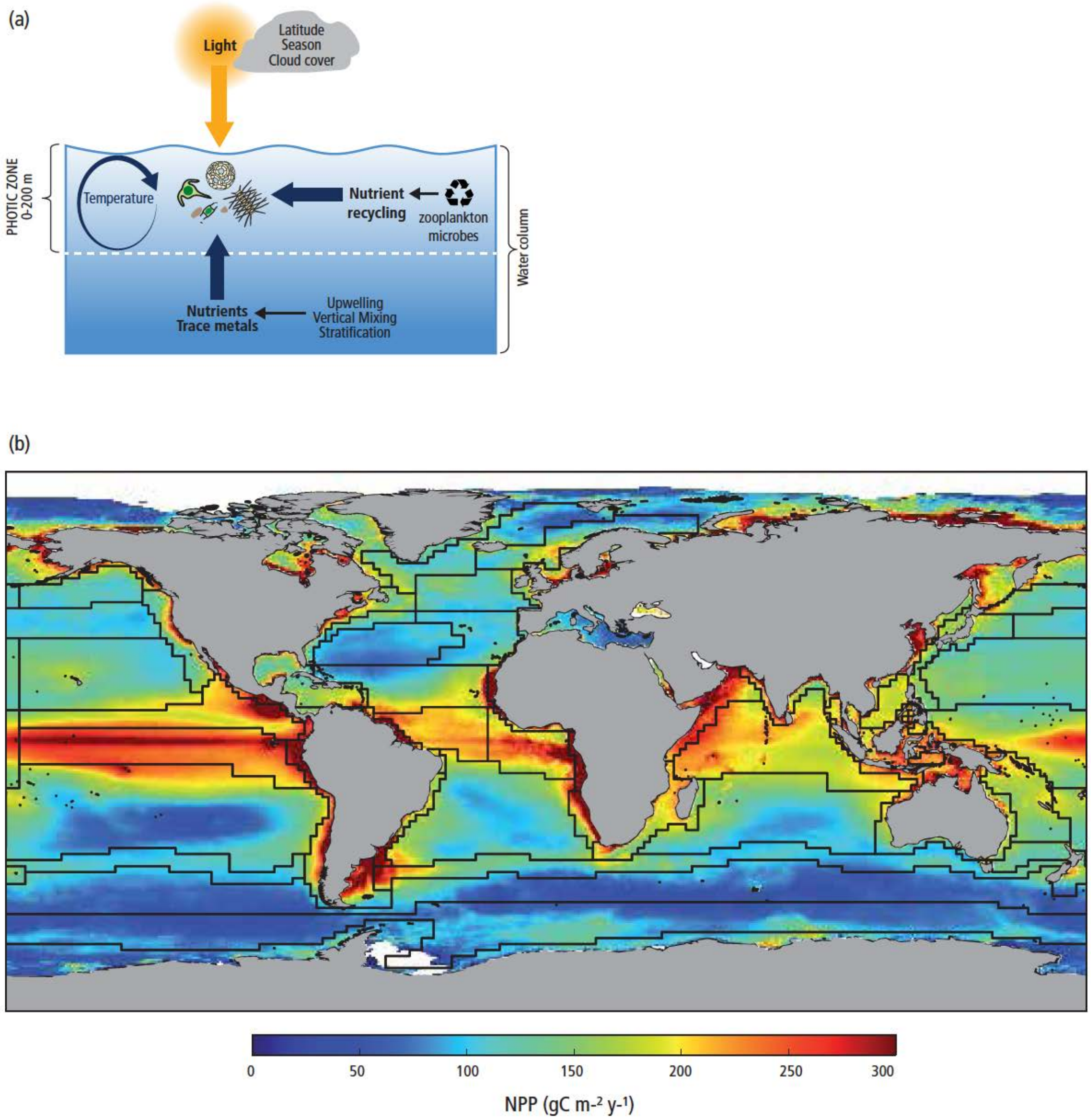

Figure PP-1: A) Environmental factors controlling Net Primary Production (NPP). NPP is mainly controlled by three basic processes: 1) Light conditions in the surface ocean, i.e. the photic zone where photosynthesis occurs, 2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, 3) Regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. B) Annual composite map of global areal NPP rates (derived from MODIS Aqua satellite climatology from 2003-2012; NPP was calculated with the Carbon-based Production Model (CbPM, Westberry *et al*., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.
[Illustration to be redrawn to conform to IPCC publication specifications.]

A.

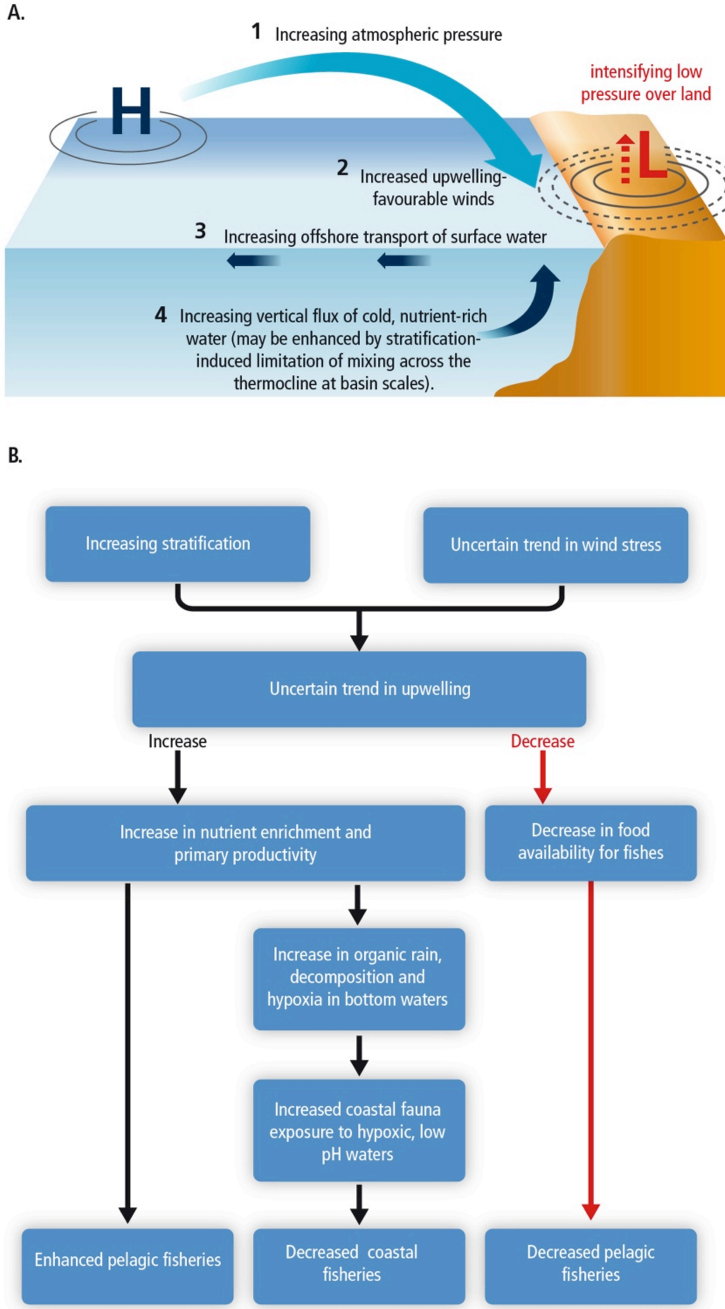

Figure UP-1: Upper panel: Schematic hypothetic mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decreased coastal fisheries due to an augmented exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.

Chapter 7. Food Security and Food Production Systems

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Contents

Executive Summary

The effects of climate change on crop and food production are evident in several regions of the world (*high confidence*). Negative impacts of climate trends have been more common than positive ones. [Figures 7-2, 7-7] Positive trends are evident in some high latitude regions (*high confidence*). Since AR4, there have been several periods of rapid food and cereal price increases following climate extremes in key producing regions, indicating a sensitivity of current markets to climate extremes among other factors. [Figure 7-3, Table 18-4] Several of these climate extremes were made more likely as the result of anthropogenic emissions (*medium confidence*). [Table 18-4]

Climate trends are affecting the abundance and distribution of harvested aquatic species, both freshwater and marine, and aquaculture production systems in different parts of the world. [7.2.1.2, 7.3.2.4, 7.4.2] These are expected to continue with negative impacts on nutrition and food security for especially vulnerable people, particularly in some tropical developing countries [7.3.3.2], but with benefits in other regions which become more favourable for aquatic food production (*medium confidence*). [7.5.1.1.3]

Studies have documented a large negative sensitivity of crop yields to extreme daytime temperatures around 30°C. [Chapter 5 AR4, 7.3.2.1.1] These sensitivities have been identified for several crops and regions and exist throughout the growing season (*high confidence*). Several studies report that temperature trends are important for determining both past and future impacts of climate change on crop yields at sub-continental to global scales (*medium confidence*). [7.3.2, Box 7-1] At scales of individual countries or smaller, precipitation projections remain important but uncertain factors for assessing future impacts (*high confidence*). [7.3.2, Box 7-1]

Evidence since AR4 confirms the stimulatory effects of CO_2 in most cases and the damaging effects of elevated tropospheric ozone on crop yields (*high confidence*). Experimental and modelling evidence indicate that interactions between CO_2 and ozone, mean temperature, extremes, water and nitrogen are non-linear and difficult to predict (*medium confidence*). [7.3.2.1.2, Figure 7-2]

Changes in climate and CO_2 concentration will enhance the distribution and increase the competiveness of agronomically important and invasive weeds (*medium confidence*). Rising CO_2 may reduce the effectiveness of some herbicides (*low confidence*). The effects of climate change on disease pressure on food crops is uncertain, with evidence pointing to changed geographical ranges of pests and diseases but less certain changes in disease intensity (*low confidence*). [7.3.2.3]

All aspects of food security are potentially affected by climate change, including food access, utilization, and price stability (*high confidence*). [7.3.3.1, Table 7-1] There remains limited quantitative understanding of how non-production elements of food security will be affected, and of the adaptation possibilities in these domains. Nutritional quality of food and fodder, including protein and micronutrients, is negatively affected by elevated CO_2, but these effects may be counteracted by effects of other aspects of climate change (*medium confidence*). [7.3.2.5] Climate change will increase progressively the inter-annual variability of crop yields in many regions (*medium confidence*). [Figure 7-6]

Without adaptation, local temperature increases in excess of about 1°C above pre-industrial is projected to have negative effects on yields for the major crops (wheat, rice and maize) in both tropical and temperate regions, although individual locations may benefit (*medium confidence*). [7.4, Figures 7-4,7-5,7-7] With or without adaptation, negative impacts on average yields become *likely* from the 2030s [Figure 7-5] with median yield impacts of 0 to -2% per decade projected for the rest of the century [Figure 7-7], and after 2050 the risk of more severe impacts increases (*medium confidence*). [Figure 7-5] These impacts will occur in the context of rising crop demand, which is projected to increase by about 14% per decade until 2050. [Figure 7-7] Regional chapters 22 (Africa), 23 (Europe), 24 (Asia), 27 (Central and South America) and Box 7-1 show crop production to be consistently and negatively affected by climate change in the future in low latitude countries, while climate change may have positive or negative effects in northern latitudes (*high confidence*).

Changes in temperature and precipitation, without considering effects of CO_2 will contribute to increased global food prices by 2050, with estimated increases ranging from 3-84% (*medium confidence*). Projections that include the effects of CO_2 changes, but ignore ozone and pest and disease impacts, indicate that global price increases are about as likely as not, with a range of projected impacts from -30% to +45% by 2050. [7.4.4]

Under scenarios of high levels of warming, leading to local mean temperature increases of 3-4 °C or higher, models based on current agricultural systems suggest large negative impacts on agricultural productivity and substantial risks to global food production and security (*medium confidence*). Such risks will be greatest for tropical countries, given the larger impacts in these regions, which are beyond projected adaptive capacity, and higher poverty rates compared to temperate regions. [7.4.1, Figures 7-4, 7-7]

The average benefit, as yield difference between the adapted and non-adapted cases, of adapting crop management is equivalent to about 15 to 18% of current yields. [Figure 7-8, Table 7-2] This response is, however, extremely variable, ranging from negligible benefit from adaptation and even potential dis-benefit to very substantial (*medium confidence*). [7.5.1.1.1] Projected benefits of adaptation are greater for crops in temperate, rather than tropical regions [7.5.1.1.1, Figures 7-4, 7-7] (*medium confidence*), with some adaptation options more effective than others [Table 7-2] (*medium confidence*) and wheat-based systems more adaptable than other crops [Figure 7-4] (*low confidence*). Positive and negative yield impacts associated with local temperature increases of about 2°C above pre-industrial maintain possibilities for effective adaptation in crop production [Figures 7-4,7-5,7-8]; local warming of about 4°C and higher above pre-industrial is projected to result in differences between crop production and its population-driven demand becoming increasingly large in many regions (*high confidence*), thus posing very significant risks and challenges to food security (*high confidence*). [Figure 7-7, Table 7-3]

Adaptation in fisheries, aquaculture and livestock production will potentially be strengthened by adoption of multi-level adaptive strategies to minimise negative impacts. Key adaptations for fisheries and aquaculture include policy and management to maintain ecosystems in a state that is resilient to change, enabling occupational flexibility and developing early warning systems for extreme events (*medium confidence*). [7.5.1.1.2] Adaptations for livestock systems centre on adjusting management to the available resources, using breeds better adapted to the prevailing climate and removing barriers to adaptation such as improving credit access (*medium confidence).* [7.5.1.1.3]

A range of potential adaptation options exist across all food system activities, not just in food production, but benefits from potential innovations in food processing, packaging, transport, storage and trade are insufficiently researched. [7.1, 7.5, 7.6, Figures 7-1, 7-7, 7-8] More observational evidence is needed on the effectiveness of adaptations at all levels of the food system. [7.6]

7.1. Introduction and Context

Many definitions of food security exist and these have been the subject of much debate. As early as 1992, Maxwell and Smith (1992) reviewed over 180 items discussing concepts and definitions, and more definitions have been formulated since (Defra, 2006). While many earlier definitions centred on food production, more recent definitions highlight access to food, in keeping with the 1996 World Food Summit definition (FAO, 1996) that food security is met when 'all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life'. World-wide attention on food access was given impetus by the food 'price spike' in 2007-08, triggered by a complex set of long- and short-term factors (von Braun and Torero, 2009). FAO's provisional estimates show that, in 2007, 75 million more people were added to the total number of undernourished relative to 2003–2005 (FAO, 2008); other studies report a lower number (Headey and Fan, 2010). More than enough food is currently produced *per capita* to feed the global population, yet about 870 million people remained hungry in 2012 (FAO *et al.*, 2012). The questions for this chapter are how far climate and its change affect current food production systems and food security and the extent that they will do so in the future (Figure 7-1).

7.1.1. Food Systems

A food system is all processes and infrastructure involved in satisfying a population's food security, i.e. the gathering/catching, growing, harvesting (production aspects), storing, processing, packaging, transporting, marketing, consuming food, and disposing of food waste (non-production aspects) It includes food security outcomes of these activities related to availability and utilization of, and access to, food as well as other socioeconomic and environmental factors (Ericksen, 2008; Ericksen *et al.*, 2010; Ingram 2011). This chapter synthesises and evaluates evidence for the impacts of climate on both production and non-production elements and their adaptation to climate change (Figure 7-1).

[INSERT FIGURE 7-1 HERE
Figure 7-1: Main issues of the chapter. Drivers are divided into climate and non-climate elements, affecting production and non-production elements of food systems, thereafter combining to provide food security. The thickness of the red lines is indicative of the relative availability of refereed publications on the two elements.]

The impacts of climate change on food systems are expected to be widespread, complex, geographically and temporally variable, and profoundly influenced by socio-economic conditions (Vermeulen *et al.*, 2012). Changes in food system drivers give rise to changes in food security outcomes, *(medium evidence, high agreement)* but often researchers only consider the impacts on the food production element of food security (Figure 7-1). Efforts to increase food production are nevertheless increasingly important as 60% more food will be needed by 2050 given current food consumption trends and assuming no significant reduction in food waste (FAO *et al.*, 2012).

7.1.2. The Current State of Food Security

Most people on the planet currently have enough food to eat. The vast majority of undernourished people live in developing countries *(medium evidence, medium agreement)*, when estimated based on aggregate national calorie availability and assumptions about food distribution and nutritional requirements. More precise estimates are possible with detailed household surveys, which often show higher incidence of food insecurity than estimated by FAO. Using food energy deficit as the measure of food insecurity, Smith et al. (2006) estimated average rates of food insecurity of 59% for 12 African countries, compared to a 39% estimate from FAO for the same period (Smith et al., 2006). While there is *medium evidence, medium agreement* on absolute numbers, there is *robust evidence, high agreement* that Sub-Saharan Africa has the highest proportion of food insecure people, with an estimated regional average of 26.8% of the population undernourished in 2010-2012, and where rates over 50% can be found (FAO et al., 2012). The largest numbers of food insecure are found in South Asia, which has roughly 300 million undernourished (FAO *et al.*, 2012. In addition to common measures of calorie availability, food security can be broadened to include nutritional aspects based on the diversity of diet including not only staple foods but also vegetables, fruits, meat, milk, eggs, and fortified foods (FAO, 2011). There is *robust evidence* and *high agreement* that lack of essential micronutrients such as zinc and vitamin A affect hundreds of millions of additional (Lopez *et al.*, 2006; Pinstrup-Andersen, 2009).

Food insecurity is closely tied to poverty; globally about 25 to 30 percent of poor people, measured using a $1 to $2 per day standard, live in urban areas (Ravallion *et al.*, 2007; IFAD, 2010). Most poor countries have a larger fraction of people living in rural areas and poverty rates tend to be higher in rural settings (by slight margins in South Asia and Africa, and by large margins in China). In Latin America, poverty is more skewed to urban areas, with roughly two-thirds of the poor in urban areas, a proportion that has been growing in the past decade *(medium evidence, medium agreement)*. Rural areas will continue to have the majority of poor people for at least the next few decades, even as population growth is higher in urban areas *(medium evidence, medium agreement)* (Ravallion *et al.*, 2007; IFAD, 2010).

The effects of price volatility are distinct from the effects of gradual price rises, for two main reasons. First, rapid shifts make it difficult for the poor to adjust their activities to favour producing higher value items. Second, increased volatility leads to greater uncertainty about the future, and can dampen willingness to invest scarce resources into productivity enhancing assets, such as fertilizer purchases in the case of farmers or rural infrastructure in the case of governments. Several factors have been found to contribute to increased price volatility: poorly articulated local markets, increased incidence of adverse weather events and greater reliance on production areas with high exposure to such risks, biofuel mandates, and increased links between energy and agricultural markets (World Bank, 2012). Vulnerability to food price volatility depends on the degree to which households and countries are net food purchasers, the level of integration into global, regional and local markets and their relative degree of volatility, which in turn is conditional upon their respective governance (HLPE, 2011; World Bank, 2012) with *robust evidence* and *medium agreement*.

7.1.3. Summary from AR4

Food systems as integrated drivers, activities and outcomes for food security did not feature strongly in AR4. Summary points from AR4 were that, with *medium confidence*, in mid- to high-latitude regions moderate warming will raise crop and pasture yields. Sight warming will decrease yields in low-latitude regions. Extreme climate and weather events will, with *high confidence*, reduce food production. The benefits of adaptation in crops enable avoidance of a 10-15% reduction in yield, corresponding to 1-2°C local temperature increase. Adaptive capacity is projected to be exceeded in low-latitude areas with temperature increases of more than 3°C. Local extinctions of particular fish species are expected with *high confidence* at the edges of their ranges and have serious negative impacts on fisheries with a *medium confidence* level.

7.2. Observed Impacts, with Detection and Attribution

7.2.1. Food Production Systems

Formal detection of impacts requires that observed changes be compared to a clearly specified baseline that characterizes behaviour in the absence of climate change (Chapter 18). For food production systems, the number and strength of non-climate drivers, such as cultivar improvement or increased use of irrigation and fertilizers in the case of crops, make defining a clear baseline extremely difficult. Most non-climatic factors are not very well characterized in terms of spatial and temporal distributions, and the relationships between these factors and specific outcomes of interest (e.g., crop or fish production) are often difficult to quantify.

Attribution of any observed changes to climate trends are further complicated by the fact that models linking climate and agriculture must, implicitly or explicitly, make assumptions about farmer behaviour. In most cases, models implicitly assume that farming practices or technologies did not adjust in response to climate over the period of interest. This assumption can be defended in some cases based on ancillary data on practices, or based on small differences between using models with and without adaptation (Schlenker and Roberts, 2009). However, in some instances the relationship between climate conditions and crop production has been shown to change over time because of management changes, such as introduction of irrigation or changes in crop varieties Zhang *et al,* 2008; Liu *et al.*,2009; Sakurai *et al.,* 2012).

7.2.1.1. Crop Production

Many studies of cropping systems have estimated impacts of observed climate changes on crop yields over the past half century, although they typically do not attempt to compare observed yields to a counterfactual baseline, and thus are not formal detection and attribution studies. These studies employ both mechanistic and statistical approaches (7.3.1), and estimate impacts by running the models with observed historical climate and then computing trends in modelled outcomes. Based on these studies, there is *medium confidence* that climate trends have negatively affected wheat and maize production for many regions (Figure 7-2) (*medium evidence, high agreement*). Since many of these regional studies are for major producers, and a global study (Lobell et al. 2011) estimated negative impacts on these crops, there is also *medium confidence* for negative impacts on global aggregate production of wheat and maize. Effects on rice and soybean yields have been small in major production regions and globally (Figure 7-2) (*medium evidence, high agreement*). There is also *high confidence* that warming has benefitted crop production in some high-latitude regions, such as Northeast China or the United Kingdom Jaggard *et al.*, 2007, Supit *et al.*, 2010; Chen *et al.,* 2010; Gregory and Marshall, 2012).

[INSERT FIGURE 7-2 HERE
Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends (7.3.2.1.2) but most did not. (a) shows number of estimates with different level of impact (% yield per decade), (b) shows boxplot of estimates separated by temperate vs. tropical regions, modelling approach (process-based vs. statistical), whether CO_2 effects were included, and crop. Boxplots indicate the median (vertical line), 25th-75th percentiles (box), and 10th-90th percentiles (whiskers) for estimated impacts in each category, and n indicates the number of estimates. Studies were for China (Tao *et al.*, 2006; Tao *et al.,* 2008; Wang *et al.*, 2008; You *et al.,* 2009; Chen *et al.*, 2010; Tao *et al.*, 2012), India (Pathak *et al.*,2003; Auffhammer *et al.,* 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell *et al.,* 2005), France (Brisson *et al.*, 2010; Licker *et al.*, 2013) Scotland (Gregory and Marshall, 2012), Australia (Ludwig *et al.*, 2009), Russia (Licker *et al.,* 2013), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al.,* 2010; Lobell *et al.,* 2011). Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate.]

More difficult to quantify with models is the impact of very extreme events on cropping systems, since by definition these occur very rarely and models cannot be adequately calibrated and tested. Table 18-4 lists some notable extremes over the past decade, and the impacts on cropping systems. Despite the difficulty of modeling the impacts of these events, they clearly have sizable impacts that are apparent immediately or soon after the event, and therefore not easily confused with effects of more slowly moving factors. For a subset of these events, climate research has evaluated whether anthropogenic activity has increased or decreased their likelihood (Table 18-4).

A sizable fraction of crop modelling studies were concerned with production for individual sites or provinces, spatial scales below which the changes in climate conditions are attributable to anthropogenic activity (AR5 WG1 Chapter 10). Similarly, most crop studies have focused on the past few decades, a time scale shorter than most attribution studies for climate. However, some focused on continental or global scales (Lobell and Field, 2007; You *et al.,* 2009; Lobell *et al.,* 2011), at which trends in several climatic variables, including average summer temperatures, have been attributed to anthropogenic activity. In particular, global temperature trends over the past few decades are attributable to human activity (AR5 WG1 Chapter 10), and the studies discussed above indicate that this warming has had significant impacts on global yield trends of some crops.

In general, little work in food production or food security research has focused on determining whether climate trends affecting agriculture can be attributed to anthropogenic influence on the climate system. However, as the field of climate detection and attribution proceeds to finer spatial and temporal scales, and as agricultural modelling studies expand to broader scales, there should be many opportunities to link climate and crop studies in the next few years. Importantly, climate attribution is increasingly documented not only for measures of average conditions over growing seasons, but also for extremes. For instance, Min *et al.*, (2011) attributed changes in rainfall extremes for 1951-99 to anthropogenic activity, and these are widely acknowledged as important to cropping systems (Rosenzweig *et al.,* 2002). Frost damage is an important constraint on crop growth in many crops, including for various high-value crops, and significant reductions in frost occurrence since 1961 have been observed and attributed to greenhouse gas emissions in nearly every region of the world (Zwiers *et al.,* 2011; IPCC, 2012).

Increased frequency of unusually hot nights since 1961 are also attributable to human activity in most regions (AR5 WG1 Chapter 10). These events are damaging to most crops, an effect that has been observed most commonly for rice yields (Peng *et al.*, 2004; Wassmann *et al.*, 2009; Welch *et al.*,2010) as well as rice quality (Okada *et al.*, 2011). Extremely high daytime temperatures are also damaging and occasionally lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009), and trends at the global scale in annual maximum daytime temperatures since 1961 have been attributed to greenhouse gas emissions (Zwiers *et al.*, 2011). At regional and local scales, however, trends in daytime maximum are harder to attribute to greenhouse gas emissions because of the prominent role of soil moisture and clouds in driving these trends (Christidis *et al.,* 2005; Zwiers *et al.,* 2011).

In addition to effects of changes in climatic conditions, there are clear effects of changes in atmospheric composition on crops. Increase of atmospheric CO_2 by over 100 ppm since pre-industrial times has *virtually certainly* enhanced water use efficiency and yields, especially for C_3 crops such as wheat and rice, although these benefits played a minor role in driving overall yield trends (Amthor, 2001; McGrath and Lobell, 2011).

Emissions of CO_2 often are accompanied by ozone (O_3) precursors that have driven a rise in tropospheric O_3 that harms crop yields (Morgan *et al.*, 2006; Mills *et al.*, 2007; 7.3.2.1.2). Elevated O_3 since pre-industrial times has *very likely* suppressed global production of major crops compared to what they would have been without O_3 increases, with estimated losses of roughly 10% for wheat and soybean and 3-5% for maize and rice (Van Dingenen *et al.*, 2009). Impacts are most severe over India and China (Van Dingenen *et al.*, 2009, Avnery et al. 2011), but are also evident for soybean and maize in the United States (Fishman *et al.*, 2010).

7.2.1.2. Fisheries Production

The global average consumption of fish and other products from fisheries and aquaculture in 2010 was 18.6 kg per person per year, derived from a total production of 148.5 million tonnes, of which 86% was used for direct human consumption. The total production arose from contributions of 77.4 and 11.2 million tonnes respectively from marine and inland capture fisheries, and 18.1 and 41.7 million tonnes respectively from marine and freshwater aquaculture (FAO, 2012). Fisheries make particular contributions to food security and more than 90% of the people engaged in the sector are employed in small-scale fisheries, many of whom are found in the poorer countries of the world (Cochrane et al., 2011). The detection and attribution of impacts are as confounded in inland and marine fisheries as in terrestrial food production systems. Overfishing, habitat modification, pollution and inter-annual to decadal climate variability can all have impacts that are difficult to separate from those directly attributable to climate change.

One of the best studied areas is the North East Atlantic, where the temperature has increased rapidly in recent decades, associated with a poleward shift in distribution of fish (Perry *et al.*, 2005; Brander, 2007; Cheung *et al.*, 2010). There is *high confidence* in observations of increasing abundance of fish species in the northern extent of their ranges while decreases in abundance have occurred in the southern part (Chapter 30.5.1.1.1.1). These trends will have mixed implications for fisheries and aquaculture with some commercial species negatively and others positively affected (Cook and Heath, 2005). There is a similar well-documented example in the oceans off SE Australia with large warming trends associated with more southward incursion of the Eastern Australian Current, resulting in southward migration of marine species into the oceans around eastern Tasmania (Last *et al.*, 2011); *robust evidence, high agreement*). As a further example, coral reef ecosystems provide food and other resources to more than 500 million people and with an annual value of US$5 billion or more (Hoegh-Guldberg, 2011; Munday et al., 2008). More than 60% of coral reefs are considered to be under immediate threat of damage from a range of local threats, of which overfishing is the most serious (Burke *et al.*, 2011; Box CC-CR. Coral Reefs) and the percentage under threat rises to approximately 75% when the effect of rising ocean temperatures is added to these local impacts (Burke *et al.*, 2011). Wilson *et al.* (2006) demonstrated that declines in coral reef cover typically led to declines in abundance of the majority of fish species associated with coral reefs. There is *high confidence* that the availability of fish and invertebrate species associated with coral reefs that are important in many tropical coastal fisheries is *very likely* to be reduced (Chapter 30.6.2.1.2). Other examples around the world are described in Chapter 30.5.1.1.1.

These changes are impacting marine fisheries: a recent study that examined the composition of global fisheries catches according to the inferred temperature preferences of the species caught in fisheries found that there had been changes in the species composition of marine capture fisheries catches and that these were significantly related to changes in ocean temperatures (Cheung et al. 2013; Chapter 6.4.1.1). These authors noted that the relative contribution to catches by warmer water species had increased at higher latitudes while the contributions of subtropical species had decreased in the tropics. These changes have negative implications for coastal fisheries in tropical developing countries which tend to be particularly vulnerable to climate change (Cheung et al. 2013; Chapter 6.4.3; 7.5.1.1.3).

There is considerably less information available on climate change impacts on fisheries and fishery resources in freshwater systems and aquaculture. Considerable attention has been given to the impacts of climate change in some African lakes but with mixed interpretations (Chapter 22.3.3.1.4.). There is evidence that increasing temperature has reduced the primary productivity of Lake Tanganyika in East Africa and a study by O'Reilly et al. (2003) estimated that this would have led to a decrease of approximately 30% in fish yields. However, Sarvala et al. (2006) disagreed and concluded that observed decreases in the fish catches could be explained by changed fishery practices. There has been a similar difference of opinion for Lake Kariba where Ndebele-Murisa et al., (2011) argued that a reduction in fisheries productivity had been caused by climate change while Marshall (2012) argued that the declines in fish catches can only have been caused by fishing. There is *medium confidence* that in India, changes in a number of climate variables including an increase in air temperature, regional monsoon variation and a regional increase in incidence of severe storms have led to changes in species composition in the River Ganga and to have reduced the availability of fish spawn for aquaculture in the river Ganga while having positive impacts on aquaculture on the plains through bringing forward and extending the breeding period of the majors carps (Vass et al. 2009).

7.2.1.3. Livestock Production

In comparison to crop and fish production, considerably less work has been published on observed impacts for other food production systems, such as livestock or aquaculture, and to our knowledge nothing has been published for hunting or collection of wild foods other than for capture fisheries. The relative lack of evidence reflects a lack of study in this topic, but not necessarily a lack of real-world impacts of observed climate trends. A study of blue-tongue virus, an important ruminant disease, evaluated the effects of past and future climate trends on transmission risk, and concluded that climate changes have facilitated the recent and rapid spread of the virus into Europe (Guis *et al.*, 2012). Ticks that carry zoonotic diseases have also *likely* changed distribution as a consequence of past climate trends (Chapter 23.4.2).

7.2.2. Food Security and Food Prices

Food production is an important aspect of food security (7.1), and the evidence that climate change has affected food production implies some effect on food security. Yet quantifying this effect is an extremely difficult task, requiring assumptions about the many non-climate factors that interact with climate to determine food security. There is thus limited direct evidence that unambiguously links climate change to impacts on food security.

One important aspect of food security is the prices of internationally traded food commodities (7.1.3). These prices reflect the overall balance of supply and demand, and the accessability of food for consumers integrated with regional to global markets. Although food prices gradually declined for most of the 20th century (FAO, 2009) since AR4 there have been several periods of rapid increases in international food prices (Figure 7-3). A major factor in recent price changes has been increased crop demand, notably via increased use in biofuel production related both to energy policy mandates and oil price fluctuations (Roberts and Schlenker, 2010; Wright, 2011; Mueller *et al.*, 2011; Abbott *et al.*, 2011). Yet fluctuations and trends in food production are also widely believed to have played a role in recent price changes, with recent price spikes often following climate extremes in major producers (Figure 7-3). Moreover, some of these extreme events have become more likely as a result of climate trends (Table 18-4). Domestic policy reactions can also amplify international price responses to weather events, as was the case with export bans announced by several countries since 2007 (FAO, 2008). In a study of global production responses to climate trends (Lobell, Schlenker, Costas-Roberts, 2011) estimated a price increase of 19% due to the impacts of temperature and precipitation trends on supply, or an increase of 6% once the beneficial yield effects of increased CO_2 over the study period were considered. Since the price models were developed for a period ending in 2003, these estimates do not account for the policy responses witnessed in recent years which have amplified the price responses to weather.

[INSERT FIGURE 7-3 HERE
Figure 7-3: Since the AR4 report, international food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index (composite measures of food prices), with vertical lines indicating events when a top 5 producer of a crop had yields 25% below trend line (indicative of a seasonal climate extreme). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years. At the same time, food prices are increasingly associated with the price of crude oil (blue line), making attribution of price changes to climate difficult. Thus, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002-2004 averages. Food price and crop yield data from FAO (http://www.fao.org/worldfoodsituation/foodpricesindex and http://faostat.fao.org/) and oil price data from http://www.eia.gov.]

7.3. Assessing Impacts, Vulnerabilities, and Risks

7.3.1. Methods and Associated Uncertainties

7.3.1.1. Assessing Impacts

Methods developed or extended since AR4 have resulted in more robust statements on climate impacts, both in the literature and in 7.3.2. Two particular areas, which are explored below, are improved quantification and presentation of uncertainty; and greater use of historical empirical evidence of the relationship between climate and food production.

The methods used for field and controlled environment experiments remain similar to those at the time of AR4. There has been a greater use of remote sensing and geographic information systems for assessing temporal and spatial changes in land use particularly in agricultural land use for assessment of food security status (Goswami et al., 2012; Fishman et al., 2010; Thenkabail, 2009). There has also been an increase in the number of Free Air

Concentration Enrichment (FACE) studies that examine ozone instead of, or in addition to, CO_2. In agriculture, FACE experiments have been used for assessing impacts of atmospheric CO_2 on grain yield, quality characteristics of important crops (Erbs et al., 2010), elemental composition (Fernando et al., 2012) and diseases (Eastburn et al., 2011; Chakraborty et al., 2011). A number of meta-analyses of experimental studies, in particular FACE studies have been made since AR4. However, debate continues on the disparities between results from FACE experiments and non-FACE experiments, such as in open-top chambers or greenhouses. As reported in AR4, FACE studies tend to show lower elevated CO_2 responses than non-FACE studies. Although some authors have claimed that the results of the two are statistically indistinct, others have argued that the results are only similar when the FACE experiments are grown under considerably more water stress than non-FACE experiments (Kimball, 2010; Ainsworth et al., 2008). Hence comparisons between different methodologies must take care to control for differences in water availability and microclimate. Another reason for differences between experiments may be differences in the temporal variance of CO_2 – i.e. whether concentrations are fluctuating or constant (Bunce, 2012). Unfortunately, the FACE experiments are carried out mostly in the USA and in China, thus limited to specific environmental conditions, which do not fully reflect tropical or sub-tropical conditions, where CO_2 and soil nutrient interactions could lead to large differences in photosynthesis rate, water use and yield. Also, the number of FACE studies are still quite low, which limits statistical power when evaluating the average yield effects of elevated CO_2 or interactions with temperature and moisture (7.3.2).

Numerical simulation models can be used to investigate a larger number of possible environmental and management conditions than physical experiments. This, in turn, enables a broader range of statements regarding the possible response of food production systems to climate variability and change. Previous assessment reports have documented new knowledge resulting from numerical simulation of the response of food production to climate change. AR4 noted the increasing number of regional studies, which is a trend that has continued to date (Zhu et al., 2013; Craufurd et al., 2013). Since AR4, crop models have been used to examine a large number of management and environmental conditions, such as interactions among various components of food production systems (Lenz-Wiedemann et al., 2010), determination of optimum crop management practices (Soltani and Hoogenboom, 2007), vulnerability and adaptability assessments (Sultana et al., 2009), evaluation of water consumption and water use efficiency (Mo et al., 2009; Kang et al., 2009) and fostering communication between scientists, managers, policymakers and planners.

The trend towards quantification of uncertainty in both climate and its impacts has continued since AR4. Novel developments include methodologies to assess the impact of climate model error on projected agricultural output, particularly for crops (Ramirez-Villegas et al., 2013, Watson and Challinor, 2013). Models that integrate crop growth models as part of broader land surface and earth systems models (Bondeau et al., 2007; Osborne et al., 2007) are also increasingly common. Ensemble techniques for climate impacts, which were in their infancy at AR4, now include the use of Bayesian methods to constrain crop model parameters (Iizumi et al., 2009; Tao et al., 2009a). It is also increasingly common to assess both bio-physical and socio-economic drivers of crop productivity within the same study (Fraser et al., 2008; Reidsma et al., 2009; Tao et al., 2009b; Challinor et al., 2010). Finally, an important recent development is the systematic comparison of results from different modelling and experimental approaches for providing insights into model uncertainties as well as to develop risk management (Challinor and Wheeler, 2008; Kang et al., 2009; Schlenker and Lobell, 2010; Rosenzweig et al., 2013).

Increased quantification of uncertainty can lead to clear statements regarding climate impacts. Studies with different methods have been shown to produce convergent results for some crops and locations (Challinor et al., 2009; *medium evidence, medium agreement*). The methods used to describe uncertainty have also improved since AR4. The projected range of global and local temperature changes can be described by quantifying uncertainty in the temporal dimension, rather than that in temperature itself (Joshi et al., 2011), and a similar approach can be used for crop yield (Figure 7-5). Descriptions of uncertainty that present key processes and trade-offs, rather than ranges of outcome variables, have also proved to be useful tools for understanding future impacts (Thornton et al., 2009; Hawkins et al., 2012; Ruane et al., 2013). Section 7.3.2 reviews the results of such studies.
A considerable body of work since AR4 has used extensive datasets of country- regional- and farm- level crop yield together with observed and/or simulated weather time series in order to assess the sensitivity of food production to weather and climate. These statistical models offer a complement to more process-based model approaches, some of which require many assumptions about soil and management practices. Process-based models, which extrapolate

based on measured interactions and mechanisms, can be used to develop a causal understanding of the empirically determined relationships in statistical models (cf Shlenker and Roberts, 2010; Lobell et al., 2013b). Although statistical models forfeit some of the process knowledge embedded in other approaches, they can often reproduce the behaviour of other models (Iglesias et al., 2000; Lobell and Burke, 2010) and can leverage within one study a growing availability of crop and weather data (Welch et al., 2010; Lobell et al., 2011). However, statistical models usually exclude the direct impact of elevated CO_2, making multi-decadal prediction problematic. In determining future trends, crop models of all types can only extrapolate based on historically-determined relationships. Agro-climatic indices provide an alternative to crop models that avoid various assumptions by developing metrics, rather than providing yield predictions *per se* (Trnka et al., 2011). However, correlations between climate, or associated indices, and yield are not always statistically significant.

The robustness of crop model results depends on data quality, model skill prediction and model complexity (Bellocchi et al., 2010). Modelling and experiments are each subject to their own uncertainties. Measurement uncertainty is a feature of field and controlled environment experiments. For example, interactions between CO_2 fertilisation, temperature, soil nutrients, ozone, pests and weeds is not well understood (Soussana *et al.*, 2010) and therefore most crop models do not include all these effects, nor broader issues of water availability, such as competition for water between industry and households (Piao et al., 2010). There are also uncertainties associated with generalizing the results of field experiments, since each one has been conducted relatively few times under a relatively small range of environmental and management conditions, and for a limited number of genotypes. This limits breadth of applicability both through limited sample size and limited representation of the diversity of genotypic responses to environment (Craufurd et al., 2013). For example, yield increases normalised by increase in CO_2 have been found to vary between zero and over 30% among crop varieties (Tausz et al., 2011).

The uncertainty in climate simulation is generally larger than, or sometimes comparable to, the uncertainty in crop simulation using a single model (Iizumi et al., 2011), but can be less than crop model uncertainty when multiple crop models are used (Koehler et al, 2013). There is significant uncertainty in agricultural simulation arising from climate model error. Since AR4 the choice of method for GCM bias correction has been identified as a significant source of uncertainty (Hawkins et al., 2012). There is also a contribution to uncertainty in crop model output from yield measurement error, through the calibration procedure. Yield measurements rarely have associated error bars to give an indication of accuracy. Greater access to accurate regional-scale crop yield data can lead to decreased uncertainty in projected yields (Watson and Challinor, 2013)

The use of multiple crop models in impacts studies is relatively rare. Field-scale historical model intercomparisons have shown variations in yield and biomass of more than 100% (Palosuo et al., 2011). Early results from impacts studies with multiple crop models suggest that the crop model uncertainty can be larger than that caused by GCMs, due in particular to high temperature and temperature-by-CO_2 interactions (Asseng et al., 2013). However, in contrast to absolute values, yield changes can be consistent across crop models (Oleson et al 2007). Given these different strengths and weaknesses, and associated dependencies, it is critical that both experimental and modelling lines of evidence, and their uncertainties, are examined carefully when drawing conclusions regarding impacts, vulnerabilities and risks. This approach to assessment is applied to each of the topics described in the rest of the chapter.

The methods used for assessing impacts, vulnerabilities and risks in fisheries and aquaculture face the constraint that meaningful controlled experiments are usually not practical for fisheries in large rivers, lakes and marine environments because of the typical open and connected nature of these ecosystems. Experimentation has been used to examine responses to impacts at the scale of individual species, for example, to demonstrate the impacts of high atmospheric carbon dioxide in reducing coral calcification and growth (Hoegh-Guldberg et al. 2007) and to study the temperature tolerances of different cultured species (Ficke et al., 2007; De Silva and Soto, 2009). The far more common approach, however, is the empirical analysis of data collected in the field. This has been used to examine the effect of climate related factors on recruitment to a population, growth and population production of specific species, for example (Brander, 2010; Chapters 6 and 30). Different modelling approaches have also been used to integrate available information and assess the impacts of climate change on ecosystems and fish production at scales from national to global (Cheung et al., 2010; Fulton, 2011; Merino et al. 2012 et al.; Chapter 6.5). Efforts to assess the vulnerability of those dependent on fisheries and aquaculture have increased in recent years and range from studies that use available information on exposure, sensitivity and adaptive capacity to provide an index of vulnerability (Allison et al., 2009; Cinner at al., 2011) to more detailed social and economic studies focused on particular communities or localities (Daw et al. 2009).

7.3.1.2. Treatment of Adaptation in Impacts Studies

Adaptation occurs on a range of timescales and by a range of actors. Incremental adaptation, such as a change in crop management, can occur relatively autonomously within farming systems. It is the type of adaptation most commonly assessed in the impacts literature, and it is the only form of adaptation discussed in sections 7.3 and 7.4. Systemic and transformational adaptations are discussed in section 7.5. Methods exist to examine impacts and adaptation together in the context of non-climatic drivers (Mandryk et al., 2012), but conclusions are difficult to generalise.

7.3.2. Sensitivity of Food Production to Weather and Climate

7.3.2.1. Cereals and Oilseeds

7.3.2.1.1. Mean and extremes of temperature and precipitation

Both statistical and process-based models have widely been used since AR4 to assess the response of crop yield to temperature. Model results confirm the importance of known key physiological processes, such as the shortening of the time to maturity of a crop with increasing mean temperature (Iqbal et al., 2009), decline in grain set when high temperatures occur during flowering (Moriondo et al., 2011), and increased water stress at high temperatures throughout the growing cycle (Lobell et al., 2013b). Temperature responses are generally well-understood for temperatures up to the optimum temperature for crop development. The impacts of prolonged periods of temperatures beyond the optimum for development are not as well understood (Craufurd and Wheeler, 2009). For example, temperatures above 34 °C after flowering appear to rapidly speed senescence in wheat (Lobell et al., 2012; Asseng et al., 2011), but many crop models do not represent this process. Crop models can be used to quantify abiotic stresses such as these, although only by hypothesizing that the functional responses to weather derived from experiments are valid at regional scales. Thus, whilst many fundamental bio-physical processes are understood at the plant or field scale, it remains difficult to quantify the extent to which these mechanisms are responsible for the observed regional-scale relationships between crop yield and weather. Despite these particular areas where specific understanding is lacking, the evidence from regional-scale statistical analyses (Schlenker and Roberts, 2009) and process-based models shows clear negative impacts of temperatures above 30-34°C on crop yields (depending on the crop and region) (*high evidence, high agreement*).

The overall relationship between weather and yields is often crop and region specific, depending on differences in baseline climate, management and soil, and the duration and timing of crop exposure to various conditions. For example, rice yields in China have been found to be positively correlated with temperature in some regions and negatively correlated in others (Zhang et al., 2010). The trade-offs that occur in determining yield are therefore region-specific. This difference may be due to positive correlation between temperature and solar radiation in the former case, and negative correlation between temperature and water stress in the latter case. Similarly, although studies consistently show spikelet sterility in rice for daytime temperatures exceeding 33°C (Jadadish et al., 2007; Wassmann et al., 2009), some statistical studies find a positive effect of daytime warming on yields because these extremes are not reached frequently enough to affect yields (Welch et al., 2010). Responses to temperature may vary according whether yields are limited by low or high temperatures. However, there is evidence that high temperatures will limit future yields even in cool environments (Semenov et al., 2012; Teixeira et al., 2013).

The relative importance of temperature and water stress for crop productivity can be assessed using models, and can vary according to the criteria used for assessment (Challinor et al., 2010). There are also some cases where the sign of a correlation depends on the direction of the change. For example, Thornton et al. (2009) found that the response of crop yields to climate change in the drylands of East Africa is insensitive to increases in rainfall, since wetter climates are associated with warmer temperatures that act to reduce yields. Since precipitation exhibits more spatial variability than temperature, temporal variations in the spatial average of precipitation tend to diminish as the spatial domain widens. As a result, precipitation becomes less important as a predictor of crop yields at broad scales (Lobell and Field, 2007; Li et al., 2010). Similarly, projected changes in precipitation from climate models tend to be more spatially variable than temperature, leading to the greater importance of projected temperatures as the spatial scale of analysis grows wider (Lobell and Burke, 2008). There is also evidence that where irrigation increases over time the influence of temperature on yields starts to dominate over that of precipitation (Hawkins et al., 2012). The impact of drought on crop yield is a more common topic of research than the impact of floods.

Analysis of 66 yield impact studies for major cereals, including both pre- and post- AR4 contributions, gives broadly similar results to AR4 (Figure 7-4). Figure 7-4 shows that yields of maize and wheat begin to decline with 1-2^{o}C of local warming in the tropics. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with warming of 3-5^{o}C. These data confirm AR4 findings that even slight warming will decrease yields in low-latitude regions (*medium evidence, high agreement*). However, whilst AR4 had few indications of yield reductions at less than 2^{o}C of local warming, the new analysis has, in the absence of incremental adaptation, more yield decreases than increases at all temperatures. Hence, whilst AR4 concluded with *medium confidence* that in mid- to high-latitude regions moderate warming will raise crop yields, new knowledge suggests that temperate wheat yield decreases are *about as likely as not* for moderate warming. A recent global crop model intercomparison for rice, wheat and maize shows similar results to those presented here, although with less impacts on temperate rice yields (Rosenzweig et al, 2013). That study also showed that crop models without explicit nitrogen stress fail to capture the expected response. Quantitative assessments of yield changes can be found in section 7.4. Across the globe, regional variability, which has not been summarised in meta-analyses except in contributing to the spread of data (Figure 7-4), will be important in determining how climate change affects particular agricultural systems.

[INSERT FIGURE 7-4 HERE
Figure 7-4: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Dots indicate where a known change in atmospheric CO_2 was used in the study; remaining data are indicated by x. Note that differences in yield value between these symbols do not measure the CO_2 fertilisation effect, since changes in other factors such as precipitation may be different between studies. Non-parameteric regressions (LOESS, span=1 and degree=1) of subsets of these data were made 500 times. These bootstrap samples are indicated by shaded bands at the 95% confidence interval. Regressions are separated according to the presence (blue) or absence (red) of simple agronomic adaptation (Table 7-2). In the case of tropical maize the central regression for absence of adaptation is slightly higher than that with adaptation. This is due to asymmetry in the data – not all studies compare adaptated and non-adapted crops. Figure 7-8 presents a pair-wise adaptation comparison. Note that four of the 1048 datapoints across all six panels are outside the yield change range shown. These were omitted for clarity. Some of the studies have associated temporal baselines, with centre-points typically between 1970 and 2005. Note that local warming in cropping regions generally exceeds global mean warming (Figure 21-3). Data are taken from a review of literature: Abou-Hadid (2006); Abraha & Savage (2006); Aggarwal & Mall (2002); Alexandrov (1999); Alexandrov & Hoogenboom (2000); Alexandrov et al. (2002); Arndt et al. (2011); Brassard & Singh 2008); Brassard & Singh (2007); Butt et al. (2005); Byjesh et al. (2010); Chhetri et al. (2010); Chipanshi et al. (2003); Corobov (2002); Izaurralde et al. (2001); DeJong et al. (2001); Deryng et al. (2011); Droogers (2004); Easterling et al. (2003); El Maayar et al. (2009); El-Shaher et al. (1997); Ewert et al. (2005); Gbetibouo & Hassan (2005); Howden & Jones (2004); Iqbal et al. (2011); Izaurralde et al (2005); Jones & Thornton (2003); Kaiser (1999); Kapetanaki & Rosenweig (1997); Karim et al. (1996); Krishnan et al. (2007); Lal (2011); Lal et al. (1998); Li et al. (2011); Erda et al. (2005); Liu et al. (2010); Lobell & Ortiz-Monasterio (2007); Luo et al. (2003); Matthews & Wasmann (2003); Moya et al. (1998); Osborne et al. (2013); Piao et al. (2010); Porter & Semenov (2005); Reyenga et al. (1999); Rosenzweig et al. (1994); Rowhani et al. (2011); Sands & Edmond (2005); Schlenker & Roberts (2009); Shuang-He et al. (2011); Southworth et al. (2000); Tan et al. (2010); Tao & Zhang (2010); Tao & Zhang (2011); Tubiello et al. (2000); Thomson et al. (2005); Thornton et al. (2009); Thornton et al. (2011); Thornton et al. (2010); Tingem & Rivington (2009); Tingem et al. (2008); Walker & Schulze (2008); Winters et al. (1998); Xiao et al. (2005); Xiong et al. (2007); Yates & Strzepek (1998); Zhang & Liu (2005); Zhao et al. (2005).]

7.3.2.1.2. Impact of carbon dioxide and ozone

There is further observational evidence since AR4 that response to a change in CO_2 depends on plant type; C_3 or C_4 (DaMatta et al., 2010). The effect of increase in CO_2 concentration tends to be higher in C_3 plants (wheat, rice, cotton, soybean, sugar beets, and potatoes) than in C_4 plants (corn, sorghum, sugarcane), because photosynthesis rates in C_4 crops are less responsive to increases in ambient CO_2 (Leakey, 2009). The highest fertilization responses have been observed in tuber crops, which have large capacity to store extra carbohydrates in belowground organs (Fleisher et al., 2008; Högy and Fangmeier, 2009). There is observational evidence, new since AR4, that the response of crops to CO_2 is genotype-specific (Ziska et al. 2012). For example, yield enhancment at 200 ppm additional CO_2 ranged from 3 to 36 % among rice cultivars (Hasegawa et al., 2013).

FACE studies have shown that the impact of elevated CO_2 varies according to temperature and availability of water and nutrients, although the strong geographical bias of FACE studies towards temperate zones limits the strength of this evidence. FACE studies have shown that CO_2 enhancment is limited under both low (Shimono et al., 2008) (Hasegawa et al., 2013) and high temperature. Theory suggests that water-stressed crops will respond more strongly to elevated CO_2 than well-watered crops, because of CO_2 induced increases in stomatal resistance. This suggests that rain-fed cropping systems will benefit more from elevated CO_2 than irrigated systems. Thus both TAR and AR4 cited the expectation that rain-fed systems benefit more from elevated CO_2 than systems under wetter conditions. New evidence based on historical observations supports this notion by demonstrating that the rate of yield gains in rain-fed systems is higher in dry years than in wet years (McGrath and Lobell, 2011). However, this response is not seen consistently across models and FACE meta-analyses and there is some suggestion that the relationship between water stress and assimilation may vary with spatial scale, with canopy analyses showing a reversal of the expected leaf-level dry *vs* wet signal (Challinor and Wheeler, 2008).

Ozone in the stratosphere provides protection from lethal short-wave solar ultraviolet radiation, but in the troposphere it is a phytotoxic air pollutant. The global background concentration of ozone has increased since pre-industrial era due to anthropogenic emission of its precursors (carbon monoxide, volatile organic compounds and oxides of nitrogen), by vehicles, power plants, biomass burning and other sources of combustion. Like CO_2, O_3 is taken up by green leaves through stomata during photosynthesis but unlike CO_2, its concentration is significantly variable depending on geographic location, elevation and extent of anthropogenic sources. Being a powerful oxidant, ozone and its secondary by-products damage vegetation by reducing photosynthesis and other important physiological functions (Mills et al., 2009; Ainsworth and McGrath, 2010). This results in stunted crop plants, inferior crop quality and decreased yields (Booker et al., 2009; Fuhrer, 2009; Vandermeiren et al., 2009; Pleijel and Uddling, 2012) and posing a growing threat to global food security (*robust evidence, high agreement*).

The literature published since AR4 further corroborates the negative impacts of increasing concentrations of surface ozone on yield at global (Van Dingenen et al., 2009; Teixeira et al., 2011; Avnery et al., 2011a; Avnery et al., 2011b) and regional scales (Northern Hemisphere: Hollaway et al, (2011); USA: (Emberson et al., 2009; Fuhrer, 2009; Fishman et al., 2010); India (Roy et al., 2009; Rai et al., 2010; Sarkar and Agrawal, 2010); China: (Wang et al., 2007; Piao et al., 2010); Bangladesh: (Akhtar et al., 2010); Europe: (Hayes et al., 2007; Vandermeiren *et al.*, 2009; Fuhrer, 2009). Global estimates of yield losses due to increased ozone in soybean, wheat and maize in 2000 ranged from 8.5-14%, 3.9-15% and 2.2-5.5% respectively, amounting to economic losses of $11-18 billion (Avnery et al., 2011a). Ozone may have direct effect on reproductive process, leading to reduced seed and fruit development and abortion of developing fruit (Royal Society, 2008; *robust evidence, high agreement*).

The interactive effects of ozone with other environmental factors such as CO_2, temperature, moisture and light, are important but not well understood. Generally, the ambient and increasing concentrations of O_3 and CO_2 individually exert counteractive effects on C_3 plants (Tianhong et al., 2005; Ainsworth, 2008; Gillespie et al., 2012); but their interactive effect may compensate for each other (Ainsworth, 2008; Taub et al., 2008; Gillespie et al., 2012). However, the losses might be greater when elevated O_3 combines with high temperature (Long, 2012) particularly during grain filling of wheat, when elevated ozone causes premature leaf senescence (Feng et al., 2008; Feng et al., 2011). Periods of abundant radiation and adequate water supply are favourable for both agricultural production and the formation of surface ozone; thus the effects of ozone on crops, can be difficult to detect (Long, 2012).

7.3.2.2. Other Crops

Earlier flowering and maturity have been observed *(robust evidence, high agreement*) worldwide in grapes (García-Mozo et al., 2010; Duchêne et al., 2010; Jorquera-Fontena and Orrego-Verdugo, 2010; Sadras and Petrie, 2011; Webb et al., 2011), apples (Fujisawa and Koyabashi, 2010; Grab and Craparo, 2011) and other perennial horticultural crops (Glenn et al., 2013). Cassava (also known as manioc) is an important source of food for many people in Africa and Latin America and recent studies suggest (*medium evidence, medium agreement*) that future climate should benefit its productivity as this crop is characterized by elevated optimum temperature for photosynthesis and growth, and a positive response to CO_2 increases (Jarvis *et al.*, 2012; Rosenthal and Ort, 2012; El-Sharkawy, 2012).

7.3.2.3. Pests, Weeds, Diseases

As a world-wide average, yield loss in major crop species due to animal pests and (non-virus) pathogens, in the absence of any physical, biological or chemical crop protection, has been estimated at 18% and 16%, respectively (Oerke, 2006). Climate change will alter potential losses to many pests and diseases. Changes in temperature can result in geographic shifts through changes in seasonal extremes, and thus, for example, overwintering and summer survival. CO_2 and ozone can either increase or decrease plant disease, and can exhibit important interactions (Chakraborty and Newton, 2011; Garrett et al., 2011), suggesting the need for system-specific risk assessment (Chakraborty et al., 2008; Eastburn et al., 2011). Interactions with landscape effects may be particularly important in forests and grasslands (Pautasso et al., 2010).

The rarity of long-term studies of plant diseases and pests is a problem for the evaluation of climate change effects, but there are some examples of the potential for such analyses. On-going wheat experiments at Rothamsted Research Station UK, maintained for over 160 years, have revealed shifts in foliar wheat pathogens linked to rainfall, temperature, and SO_2 emissions (Bearchell et al., 2005; Shaw et al., 2008). Wheat rust risk has been observed to respond to ENSO (Scherm and Yang, 1995). Over almost seven decades, earlier and more frequent epidemics of potato late blight, and more frequent pesticide use, were observed in Finland, associated with changing climate conditions and lack of crop rotation (Hannukkala et al., 2007).

Changes in climate are expected to affect the geographic range of specific species of insects and diseases for a given crop growing region. For example, Cannon (1998) has suggested that migratory insects could colonize crops over a larger range in response to temperature increases, with subsequent reductions in yield. Climate change may also be a factor in extending the northward migration of agronomic and invasive weeds in North America (Ziska et al., 2011). Weed species also possess characteristics that are associated with long-distance seed dispersal, and it has been suggested (Hellman et al. 2008) that they may migrate rapidly with increasing surface temperatures. Predator and insect herbivores respond differently to increasing temperature, leading to possible reductions in insect predation and thus greater insect numbers. However, ecosystems are complex and insect and disease occurrence can go down as well as up. Overall, our ability to predict CO_2/climate change impacts on pathogen biology and subsequent changes on yield is limited because, with few exceptions (Savary et al., 2011), experimental data are not available and analyses focus on individual diseases rather than the complete set of important diseases (*medium evidence, medium agreement*).

Elevated CO_2 can reduce yield losses due to weeds for C_3 crops (soybean, wheat and rice), since many agricultural weeds are C_4 species; and the C_3 pathway, in general, shows a stronger response to rising carbon dioxide levels. However, both C_3 and C_4 weed species occur in agriculture, and there is a wide range of responses among these species to recent and projected CO_2 levels (Ziska 2010). For example, in the United States, every crop, on average, competes with an assemblage of 8-10 weed species (Bridges, 1992). CO_2 and climate can also affect weed demographics. For example, with field grown soybean, elevated CO_2 *per se* appeared to be a factor in increasing the relative proportion of C_3 to C_4 weedy species with subsequent reductions in soybean yields (Ziska and Goins, 2006). For rice and barnyard grass (C_4), increasing CO_2 favoured rice, but if both temperature and CO_2 increased simultaneously, the C_4 weed was favoured, primarily because higher temperatures resulted in increased seed yield loss for rice. For weeds that share physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species, (often among the "worst" weeds in agronomic situations, e.g. rice and red rice) the decrease in seed yield from weeds may, be greater under elevated CO_2 (Ziska, 2010).

With respect to control, a number of studies have, to date, indicated a decline in herbicide efficacy in response to elevated CO_2 and/or temperature for some weed species, both C_3 and C_4 (Archambault, 2007; Manea et al., 2011). Some of the mechanisms for this are understood, for example for the invasive plant species Canada thistle (Cirsium arvense), elevated CO_2 results in a greater root biomass, thus diluting the active ingredient of the herbicide used and reducing chemical control (Ziska 2010). To date, studies on physical, cultural or biological weed control are lacking.

7.3.2.4. Fisheries and Aquaculture

The natural and human processes in fisheries and aquaculture differ from mainstream agriculture and are characterized by distinct impacts and interactions related to climate change. Capture fisheries in particular, comprising the largest remaining example of harvesting natural, wild resources, are strongly influenced by global ecosystem processes. The social, economic and nutritional requirements of the growing human population are already driving heavy exploitation of capture fisheries and rapid development of aquaculture (Chapter 6.4.1.1). This trend will continue over the next 20 to 30 years at least: (Merino et al., 2012) forecast that in addition to a predicted small increase in marine fisheries production, between 71 and 117 million tonnes (MT) of fish will need to be produced by aquaculture to maintain current average *per capita* consumption of fish. The impacts of climate change add to and compound these threats to the sustainability of capture fisheries and aquaculture development (FAO, 2009). Expected changes in the intensity, frequency and seasonality of climate patterns and extreme events, sea level rise, glacier melting, ocean acidification and changes in precipitation with associated changes in groundwater and river flows are expected to result in significant changes across a wide range of aquatic ecosystem types and regions with consequences for fisheries and aquaculture in many places (Chapter 30.5.1.1; FAO, 2009). Ocean acidification will also have negative impacts on the culture of calcifying organisms (Chapter 30.6.2.1.4), including mollusc species of which 14.2 MT were produced by aquaculture in 2010, equivalent to 23.6% of global aquaculture production (FAO, 2012). There are also concerns that that climate change could lead to the spread of pathogens with impacts on wild and cultured aquatic resources (De Silva and Soto, 2009).

Given the proximity of fishing and aquaculture sites to oceans, seas and riparian environments, extreme events can be expected to have impacts on fisheries and aquaculture with those located in low-lying areas at particular risk. The consequences of sea level rise and the expected increased frequency and intensity of storms include increased risks of loss of homes and infrastructure, increased safety risks while fishing and the loss of days at sea because of bad weather (Daw et al., 2009). In areas that experience water stress and competition for water resources, aquaculture operations and inland fisheries production will be at risk.

Food production from fisheries and aquaculture will be affected by the sensitivity of the caught and cultured species to climate change and both positive and negative outcomes can be expected. Changes in marine and freshwater mean temperatures, ocean acidification, hypoxia and other climate-related changes will influence the distribution and productivity of fished and farmed aquatic species (Chapter 6.4.3; 7.2.1.2; Chapter 30.6.2). Changes in temperature extremes are also likely to have impacts. Many aquatic species are routinely subjected to large daily and seasonal fluctuations in temperature and are able to cope with them: for example, temperatures in shallow coastal habitats in the tropical Pacific can vary by more than 14^{o}C diurnally (Pratchett et al., 2011). Nevertheless, distribution and productivity of aquatic species and communities are sensitive to changes in temperature extremes. A study on salmon populations in Washington State, USA (Mantua et al., 2010) demonstrated important impacts of seasonal variations and extremes. The study concluded that warming in winter and spring would have some positive impacts while increased summertime stream temperatures, seasonal low flows and changes in the peak and base flows would have negative impacts on the populations. Coral reefs are particularly susceptible to extremes in temperature: temperatures 1 or 2^{o}C in excess of normal maximums for 3 to 4 weeks are sufficient to disrupt the essential relationship between endosymbiotic dino-flagellates and their coral hosts leading to coral bleaching. Large scale bleaching of coral reefs has increased in recent decades both in intensity and frequency (Hoegh-Guldberg et al., 2007).

The impacts of climate change on the fisheries and aquaculture sector will have implications for the four dimensions of food security i.e. availability of aquatic foods, stability of supply, access to aquatic foods, and utilization of aquatic products (FAO, 2009). Where climate-driven ecological changes are significant, countries and communities will need to adapt through, for example, changes in fishing and aquaculture practices and operations (7.5.1.1.2.).

7.3.2.5. Food and Fodder Quality and Human Health

Food quality is any characteristic other than yield that is valuable to the producer or consumer. Examples include wheat protein and starch concentrations, which affect dough quality; amylose content in rice, which affects taste; and mineral concentrations, which affects nutrient intake of consumers. Climate change will have some adverse impacts on food quality through both biotic and abiotic stresses (Ceccarelli et al., 2010). These changes may affect crop quality by altering carbon and nutrient uptake and biochemical processes that produce secondary compounds or redistribute and store compounds during grain development and maturation. This in turn could impact human and livestock health by altering nutritional intake and/or affect economic value by altering traits valuable to processers or the consumers.

Change in nitrogen concentration, a proxy for protein concentration, is the most examined quality trait and since AR4 studies have been extended to almost all the major food crops. Cereals grown in elevated CO_2 show a decrease in protein (Piikki *et al.*, 2007; Hogy *et al.*, 2009; Erbs *et al.*, 2010; Ainsworth and McGrath, 2010; DaMatta *et al.*, 2010; Erda et al., 2010; Fernando *et al.*, 2012). Meta-analysis of 228 experimental observations finds decreases between 10 to 14 % in edible portions of wheat, rice, barley and potato, but only 1.5 % in soybeans, a nitrogen-fixing legume, when grown in elevated CO_2 (Taub et al., 2008).

Mineral concentration of edible plant tissues are affected by growth in elevated CO_2 in a similar manner to nitrogen. Although there are numerous studies measuring mineral concentration, there are relatively few measurements for any given mineral relevant to human health. Although there were several studies published before the release of AR4, this topic was not covered in any depth in AR4. Meta-analysis of studies prior to 2002 finds that P, Ca, S, Mg, Fe, Zn, Mn and Cu decline by 2.5 - 20 % in wheat grain and leaves of numerous species in elevated CO_2, but K increases insignificantly in wheat grain (Loladze, 2002; Hogy et al., 2009; Fernando et al., 2012). Since 2002, studies generally find decreases in Zn, S, P, Mg and Fe in wheat and barley grain, increase in Cu, Mo and Pb (from a limited number of studies) and mixed results for Ca and K (Hogy et al., 2009; Erbs et al., 2010; Fernando et al., 2012). Changes in mineral concentration due to elevated CO_2 are determined by several factors including crop species, soil type, tissue (tubers, leaves or grain) and water status.

Elevated CO_2 can lower the nutritional quality of flour produced from grain cereals (Hogy et al., 2009; Erbs et al., 2010) and of cassava (Gleadow et al., 2009). When coupled with increased crop and pathogen biomass, elevated CO_2 can result in increased severity of the *Fusarium pseudograminearum* pathogen, leading to shriveled grains with low market value (Melloy et al., 2010). Extreme temperatures and elevated CO_2 concentrations reduce milling quality of rice by increasing chalkiness, but can improve taste, through, for example, reduced amylase concentration (Yang et al., 2007). Cultivars vary in their susceptibility to these processes (Ambardekar et al., 2011; Lanning et al., 2011). Overall, there is *robust evidence* and *high agreement* that elevated CO_2 on its own likely results in decreased nitrogen concentrations. Combining knowledge of nitrogen and mineral studies, there is *medium evidence* and *medium agreement* that mineral concentrations will decline. The majority of these data are from wheat, with comparatively little information from key crops such as maize, rice, potato and cassava; thus magnitudes are uncertain for the species.

Elevated O_3 concentrations appear to have the opposite effect as elevated CO_2. Meta-analysis of about 50 wheat experiments found that elevated O_3 increased grain protein concentration by decreasing yield (Pleijel and Uddling, 2012). For other species, studies find both increases and decreases of N and several minerals (Taub et al., 2008), and as such no firm conclusions can be drawn, but they mostly respond similarly. Similarly, experiments examining the effect of drought on mineral concentrations find both decreases and increases in mineral concentrations (Ghorbanian et al., 2011; Sun et al., 2011).

Confidence in the impact of climate, CO_2 and O_3 on food quality does not imply confidence in changes regarding human health for several reasons. Post-processing of food affects nutrient concentrations, when the nutrient-rich outer layers of rice are removed, leaving the starch dense endosperm. Also, elevated CO_2 can increase crop yield, thus increasing the overall yield minerals (Duval et al., 2011) and permitting greater mineral consumption. Furthermore, since calorie intake is the primary concern in many food insecure populations, even if intake of minerals is decreased, those negative effects could be outweighed by increased calorie intake. In assessing impacts on health, current diets must be considered. Decreased mineral intake will matter for those who currently do not meet, or just barley meet, requirements, but will not affect those who already exceed requirements. Little is known about combined effects of climate change factors on food quality or the economic and behavioral changes that will occur. Thus, there is little confidence regarding effects of climate change on human health through changes in nutrient composition.

7.3.2.6. Pastures and Livestock

Pastures response to climate change is complex because, in addition to the direct major atmospheric and climatic drivers (CO_2 concentration, temperature, and precipitation), there are important indirect interations such as plant competition, perennial growth habits, seasonal productivity, and plant-animal interactions. Projected increases in temperature and the lengthening of the growing season should extend forage production into late fall and early spring, thereby decreasing the need for accumulation of forage reserves during the winter season in USA (Izaurralde et al., 2011). In addition, water availability may play a major role in the response of pasturelands to climate change although there are differences in species response (Izaurralde et al., 2011). There is general consensus that increases in CO_2 will benefit C_3 species; however, warmer temperatures and drier conditions will tend to favour C_4 species (Izaurralde et al., 2011; Hatfield et al., 2011; AR5 WG2 Chapter 4). While elevated atmospheric CO_2 concentrations reduce sensitivity to lower precipitation in grassland ecosystems and can reduce mortality and increase recovery during severe water stress events, it is still unclear how general this result is (Soussana et al., 2010).

Temperature is an important limiting factor for livestock. As productivity increases, be it increasing milk yield in dairy cattle or higher growth rates and leanness in pigs or poultry, so metabolic heat production increases and the capacity to tolerate elevated temperatures decreases (Zumbach *et al.*, 2008; Dikmen and Hansen, 2009). Over the long term, single-trait selection for productivity will tend to result in animals with lower heat tolerance (Hoffmann, 2010). Recent work adds to previous understanding (AR4 WG2 Chapter 5) and indicates that heat stress *(medium evidence, high agreement,*) in dairy cows can be responsible for the increase in mortality and economic losses (Vitali *et al.*, 2009); it affects a wide range of parameters in broilers (Feng et al, 2008); it impairs embryonic development and reproductive efficiency in pigs (Barati *et al.*, 2008); and affects ovarian follicle development and ovulation in horses (Mortensen *et al.*, 2009). Water stess also limits livestock systems. Climate change will affect the water resources available for livestock via impacts on runoff and groundwater (AR5 WG2 Chapter 3). Populated river basins may experience changes in river discharge, and large human and livestock populations may experience water stress such that proactive or reactive management interventions will almost certainly be required (Palmer *et al.*, 2008). Problems of water supply for increasing livestock populations will be exacerbated by climate change in many places in sub-Saharan Africa and South Asia.

7.3.3. Sensitivity of Food Security to Weather and Climate

7.3.3.1. Non-Production Food Security Elements

As indicated in the discussion in section 7.1.1 and Figure 7-1, food security is dependent on access and consumption patterns, food utilization and nutrition, and overall stability of the system as much as food production and availability. The overall impact of climate change on food security is considerably more complex and potentially greater than projected impacts on agricultural productivity alone. Figure 7-1 indicates the main components of food security and their key elements. All of these will be affected by climate change to some extent. For example, climate change effects on water, sanitation and energy availability have major implications for food access and utilization as well as availability. Likewise, changes in the frequency and severity of climate extremes can affect stability of food availability and prices, with consequent impacts on access to food.

7.3.3.2. Accessibility, Utilization, and Stability

7.3.2.2.1. Climate change impacts on access

As noted in the discussion in section 7.1.3, change in the levels and volatility of food prices is a key determinant of food access. Given the hypothesis that climate change will be a contributing factor to food price increases, and hence its affordability, the vulnerability of households to reduced food access depends on their channel of food access (*medium evidence, medium agreement).* Table 7-1 divides households into five main categories of food access, indicating their relative impacts of food price increases.

[INSERT TABLE 7-1 HERE
Table 7-1: Households divided into five categories of food access, indicating the impacts for them of food price increases.]

Concern about the impact of increased food prices on poverty and food security arises due to the high share of income that poor consumers spend on food, thus generating a disproportionately negative effect of price increases on this group (FAO, 2011). A study by the World Bank estimated a net increase of 44 million people in extreme poverty in low and middle income countries as a result of food price increases since June 2010 (Ivanic et al., 2011).

Tthe distribution of net food buyers and net food sellers varies considerably across countries and can be expected to change with the process of economic development (Zezza et al., 2008; Aksoy et al., 2010; FAO, 2011). Changing consumption patterns associated with dietary transitions that accompany income growth, urbanization, market development, and trade liberalization determine the rate and nature of food demand growth and nutritional levels, and thus is a key determinant of global and local food security (Kearney, 2010). However the evidence base on potential climate change impacts on consumption patterns, or on other non-production elements of food security is thin, particularly when compared with the literature on climate change impacts on food production and availability.

Current and future variation in the distribution and vulnerability to loss of food access across household types makes impacts assessment complex and difficult. Nonetheless, there are reasons for concern about food access due to the current high rates of food insecurity in many low income countries. Agricultural producers who are net food buyers are particularly vulnerable. Similarly, low income agricultural dependent economies that are net food importers, which are those that already have high rates of food insecurity, could experience significant losses in food access through a double negative effect on reduced domestic agricultural production and increased food prices on global markets.

7.3.2.2.2. Climate change impacts on stability

There is increasing evidence of and confidence in the effect of climate change on increasing the incidence and frequency of some types of climate extreme events (IPCC, 2012), and this will have significant impacts on food security (*medium evidence; medium agreement*). Recent experience of global climate patterns affecting food security indicate the potential nature and magnitude of increased variability. An impact assessment of the 2010 Pakistan floods surveyed 1800 households 6 months after the floods and found that 88% of the households reported income losses of up to 50%, with significantly higher rates in rural than urban areas (Kirsch et al., 2012). The same study indicated that loss of key services such as electricity, sanitation and clean water resulted in lower standards of living even in the wake of significant relief attempts, again with significantly heavier effects on rural populations (Kirsch et al., 2012). The Russian heat wave of 2010 and subsequent export ban contributed to the more than doubling of global wheat prices by the end of the year. The degree to which these price increases affected domestic consumers and poverty depended on national responses in importing countries, although a significant net negative effect on poverty was found (Ivanic et al., 2011).

Increased incidence of climate extremes reduces incentives to invest in agricultural production, potentially offsetting positive impacts from increasing food price trends. This is particularly true for poor smallholders with limited or no access to credit and insurance. Greater exposure to climate risk, in the absence of well-functioning insurance markets, leads to: 1) greater emphasis on low-return but low-risk subsistence crops (Roe and Graham-Tomasi, 1986; Fafchamps, 1992; Heltberg and Tarp, 2002), 2) a lower likelihood of applying purchased inputs such as fertilizer (Kassie et al., 2008; Dercon and Christiansen, 2011), 3) a lower likelihood of adopting new technologies (Feder *et al.*, 1985; Antle and Crissman., 1990), and 4) lower investments (Skees et al., 1999). All of these responses generally lead to both lower current and future farm profits *(robust evidence, high agreement*) (Rosenzweig and Binswanger, 1993; Hurley, 2010).

It is also well documented that in many rural areas, smallholders in particular do not have the capacity to smooth consumption in the face of climate shocks, particularly generalized shocks that affect a majority of households in the same location (Dercon, 2004; Skoufias and Quisumbing, 2005; Dercon, 2006; Fafchamps, 2009; Prakash, 2011). Any increases in climate extremes will exacerbate the vulnerability of all food insecure people, including smallholders (*robust evidence, high agreement*). Currently, smallholders rely to a large extent on increasing labor off-farm where possible (Fafchamps, 1999; Kazianga and Udry, 2006), but also by decreasing both food consumption and non-food expenditures, such as those on education and healthcare (Skoufias and Quisumbing, 2005) (*medium evidence, high agreement*). Furthermore, some evidence also suggests that poorer households are more likely to reduce consumption, while wealthier households liquidate assets to cover current deficits (*limited evidence, medium agreement*) (Kazianga and Udry, 2006; Carter and Lybbert, 2012). Reductions in food consumption, sales of productive assets, education and healthcare can lead to long-term losses in terms of income-generation and thus to future food security (*limited evidence, medium agreement*) (Hoddinot and Maluccio, 2008; Skoufias and Quisumbing, 2005). Increased uncertainty of future climate conditions and increases in climate extremes will increase food insecurity unless these significant barriers to consumption and asset smoothing can be addressed (*medium evidence, medium agreement*).

7.3.3.2.3. Climate change impacts on utilization

Climate change impacts on utilization may come about through changes in consumption patterns in response to shocks, as well as changes in nutrient content of food as well as food safety (*medium evidence; medium agreement*). Rationing consumption to prioritize calorie-rich, but nutrient poor foods is another common response (Bloem et al., 2010). The effects are a decrease in dietary quality as well as quantity, which are magnified by pre-existing vulnerabilities – and lead to long term loss of health, productivity capacity and low incomes (*medium evidence; medium agreement*) (Bloem et al., 2010; Alderman, 2010; Brinkman et al., 2010; Campbell et al., 2010; Sari et al., 2010). The biological effects of climate change on nutrient content of foods is one of main pathways for effects on utilization. A summary of recent literature on the impacts of climate change on the composition of nutrients in food items is given in HLPE (2012). Research on grains generally shows lowering of protein content with elevated temperature and CO_2 levels (Ainsworth and McGrath, 2010; Erda et al., 2005; Hatfield et al., 2011). There is good agreement that for plant-derived foods, mycotoxins are considered the key issue for food safety under climate change (Miraglia et al., 2009). The impacts of climate change on mycotoxins in the longer term are complex and region-specific; temperatures may increase sufficiently to eliminate certain mycotoxin-producing species from parts of the tropics, but in colder tropical regions and temperate zones, infections may increase (Cotty and Jaime-Garcia, 2007).

7.3.4. Sensitivity of Land Use to Weather and Climate

As noted in the AR4, changes in land use, for example adjusting the location of crop production, are a potential adaptation response to climate change. Studies since the AR4 have confirmed that high latitude locations will, in general, become more suitable for crops (Iqbal et al., 2009). Trnka et al. (2011), for example, examined projections of eleven agro-climatic indices across Europe, and found that declines in frost occurrence will lead to longer growing seasons, although temperature and moisture stress will often lead to greater inter-annual variability in crop suitability. The potential influence of pests and diseases is commonly beyond the scope of such studies (Gregory et al., 2009).

For tropical systems where moisture availability or extreme heat rather than frost limits the length of the growing season, there is a likelihood that the length of the growing season and overall suitability for crops will decline (*medium evidence, medium agreement*) (Jones and Thornton, 2009; Zhang and Cai, 2011). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat stressed by the 2050s, whilst temperate wheat environments will expand northwards as climate changes (Ortiz et al., 2008). Similarly, by 2050, the majority of African countries will experience climates over at least half of their current crop area that lie outside the range currently experienced within the country (Burke et al., 2009). The majority of these novel climates have analogues in other African countries. In mountainous regions, where temperature varies significantly across topography, changes in crop suitability can be inferred from the variation of temperature across topography. The resulting vertical zones of increasing, decreasing and unchanging suitability can be relatively robust in the face of uncertainty in future climate (Schroth et al., 2009).

The interaction between water resources and agriculture is expected to become increasingly important as climate changes. For example, whilst projected changes in crop productivity in China are uncertain, even within a single emissions scenario, irrigation has significant adaptation potential (Piao et al., 2010). However, limitations to availability of water will affect this potential. Changes in water use, including increased water diversion and development to meet increasing water demand, and increased dam building will also have implications for inland fisheries and aquaculture, and therefore for the people dependent on them (Ficke et al., 2007; FAO, 2009). In the case of the Mekong River basin, a large proportion of the 60 million inhabitants are dependent in some way on fisheries and aquaculture which will be seriously impacted by human population growth, flood mitigation, increased offtake of water, changes in land use and overfishing, as well as by climate change (Brander, 2007). Ficke et al. (2007) reported that at that time there were 46 large dams planned or already under construction in the Yangtze River basin, the completion of which would have detrimental effects on those dependent on fish for subsistence and recreation.

The models used in projections of land suitability and cropland expansion discussed above rely on assumptions about non-climatic constraints on crop productivity, such as soil quality and access to markets. These assumptions are increasingly amenable to testing as the climate system shifts, by comparing observed changes in cropland area with model predictions. The location of the margin between cropping land and extensive grazing in southern Australia has varied with decadal climate conditions and is projected to shift towards the coast with hotter and drier conditions, notwithstanding the positive impacts of elevated CO_2 (Nidumolu et al., 2011). Recent trends in climate have seen reductions in cropping activity consistent with these projections (Nidumolu et al., 2011).

7.4. Projected Integrated Climate Change Impacts

7.4.1. Projected Impacts on Cropping Systems

Crop yields remain the most well studied aspect of food security impacts from climate change, with many projections published since AR4. These newer studies confirm many of the patterns identified in AR4, such as negative yield impacts for all crops past 3°C of local warming without adaptation, even with benefits of higher CO_2 and rainfall (Figure 7-4).

Figure 7-5 shows projected impacts on mean crop yield in twenty-year bins, including cases with no adaptation and a range of incremental adaptations. The data indicate that negative impacts on average yields become *likely* from the 2030s. Negative impacts of more than 5% are *more likely than not* beyond 2050 and *likely* by the end of the century. Some important differences by emission scenario and region are masked in Figure 7-5. From the 2080s onwards, negative yield impacts in the tropics are *very likely,* regardless of adaptation or emission scenario. This is consistent with the meta-analysis of Knox et al. (2012), and a recent model intercomparison of global gridded crop models (Rosenzweig et al., 2013).

[INSERT FIGURE 7-5 HERE
Figure 7-5: Projected changes in crop yield as a function of time. The y-axis indicates percentage of studies and the colours denote percentage change in crop yield. The sum of absolute bar heights in each time period equals 100%. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Data taken from Abraha & Savage, 2006; Alexandrov & Hoogenboom, 2000; Arndt et al., 2011; Berg et al., 2012; Brassard & Singh, 2008; Brassard & Singh, 2007; Butt et al., 2005; Calzadilla et al., 2009; Chhetri et al., 2010; Ciscar et al., 2011; Deryng et al., 2011; Giannakopoulos et al., 2009; Hermans et al., 2010; Iqbal et al., 2011; Izaurralde et al, 2005; Kim et al., 2010; Lal, 2011; Li et al., 2011; Lobell et al., 2008; Moriondo et al., 2010; Muller et al., 2010; Osborne et al., 2013; Peltonen-Sainio et al., 2011; Piao et al., 2010; Ringler et al., 2010; Rowhani et al., 2011; Schlenker & Roberts, 2009 ;Shuang-He et al., 2011; Southworth et al., 2000; Tan et al., 2010; Tao & Zhang, 2010; Tao & Zhang, 2011; Tao et al., 2009; Thornton et al., 2009; Thornton et al., 2011; Thornton et al., 2010; Tingem & Rivington, 2009 Tingem et al., 2008; Walker & Schulze, 2008; Wang et al., 2011; Xiong et al., 2009; Xiong et al., 2007.]

A few studies have explicitly compared projections for different regions or crops to identify areas at most risk. Lobell et al. (2008) used a statistical crop model with 20 GCMs and identified South Asia and Southern Africa as two regions that, in the absence of adaptation, would suffer the most negative impacts on several important crops. Yields changes have also been assessed by regional meta-analyses: Knox et al. (2012) synthesized projections from 52 studies and estimated an expected 8% negative yield impact in both Africa and South Asia by 2050 averaged over crops, with wheat, maize, sorghum, and millets more affected than rice, cassava, and sugarcane.

Changes in the interannual variability of yields could potentially affect stability of food availability and access. Figure 7-6 shows projected changes in the coefficient of variation (CV) of yield from some of the few studies that publish this information. The data shown are consistent with reports of CV elsewhere: Müller et al. (2013) conducted gridded simulations across the globe and reported an increase of more than 5% in CV in 64% grid cells, and a decrease of more than 5% in 29% of cases. Increases in CV can be due to reductions in mean yields and/or increases in standard deviation of yields, and often simulated changes are a combination of the two. Overall, climate change will increase crop yield variability in many regions (*medium evidence, medium agreement*).

[INSERT FIGURE 7-6 HERE
Figure 7-6: Projected percentage change in coefficient of variation (CV) of yield for wheat (gold), maize (green), rice (blue) and C_4 crops (red) taken from C2010 (Challinor et al., 2010), B2013 (Berg et al., 2013), T2009 (Tao et al., 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban et al., 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. 81 datapoints are plotted in the figure, although the underlying data consist of many thousands of crop model simulations. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2013 is a global study of the tropics, U2012 is for US maize, and the remaining studies are for China.]

Estimated impacts of both historical and future climate changes on mean yields are summarized along with projected impacts on yield variability in Figure 7-7, with all impacts expressed as the average percentage impact per decade. This comparison illustrates that future impacts are expected to be consistent with the trajectory of past impacts, with the majority of locations experiencing negative impacts while some locations benefit. Each additional decade of climate change is expected to reduce mean yields by roughly 1%, which is a small but nontrivial fraction of the antipicated roughly 14% increase in productivity per decade needed to keep pace with demand. For future projections, enough studies are available to assess differences by region and adaptation scenario, with significant adaptation effects apparent mainly in temperate systems (7.5).

[INSERT FIGURE 7-7 HERE
Figure 7-7: Boxplot summary of studies that quantify impact of climate and CO_2 changes on crop yields, including historical and projected impacts, mean and variability of yields, and for all available crops in temperate and tropical regions. All impacts are expressed as average impact per decade (a 10% total impact from a 50 year period of climate change would be represented as 2% per decade). References for historical impacts are given in Figure 7-2, for projected mean yields in Figure 7-5, and for yield variability in Figure 7-6. N indicates the number of estimates, with some studies providing multiple estimates. In general, decreases in mean yields and increases in yield variability are considered negative outcomes for food security. Also indicated on figure is the expected increase in crop demand of 14% per decade (Alexandratos and Bruinsma, 2012), which represents a target for productivity improvements to keep pace with demand.]

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4^oC or more. An analysis for sub-Saharan Africa predicted overall decreases of 19% for maize yields, 68% decrease for bean yields and a small increase for fodder grass (*Brachiaria decumbens*) given 5^oC global average warming (Thornton et al., 2011). Rötter et al. (2011) conclude that positive effects of modest warming and increased CO_2 levels on crop yields in Finland will be reversed at global temperatures increases of 4^oC, leading to negative yield impacts in excess of 20% in relation to current conditions.

For perennial crops, winter chill accumulation that is important to many fruit and nut trees is projected to continue its decline, with for instance a 40 h per decade reduction projected for California for the period up to 2100 (Baldocchi and Wong, 2008). Averaging over three GCMs, annual winter chill loss by 2050 compared to 1970 would amount 17.7 % to 22.6 % in Egypt (Farag et al., 2010). Several studies have projected negative yield impacts of climate trends for perennial trees, including apples eastern Washington (Stöckle et al., 2010) and cherries in California (Lobell and Field, 2011), although CO_2 increases may offset some or all of these losses. Reductions in suitability for grapevine are expected in most of the wine producing regions (Hall and Jones, 2009; White et al., 2009; Jones et al., 2010). Wine grape production and quality will be affected in Europe, US, Australia (Jones et al., 2005; Wolfe et al., 2008; Cozzolino et al., 2010; AR5 WG2 Chapter 25), although it could be a benefit in Portugal (Santos et al., 2011) and British Columbia in Canada (Rayne et al., 2009). Important crops in Brazil like sugarcane and coffee are expected to migrate towards more favorable zones in the South (Pinto, 2007; Pinto et al., 2008; AR5 WG2 Chapter 27). Sugarcane fresh stalk mass is generally expected to gain from both warming and elevated CO_2 in Brazil (Marin et al., 2013). The suitability for coffee crops in Costa Rica, Nicaragua and El Salvador will be reduced by more than 40% (Glenn et al., 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops towards higher altitudes by mid-century (Ramirez-Villegas et al., 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne, et al., 2007).

Consideration of pest, weed, and disease impacts are omitted from most yield projections, yet other studies have focused on projecting impacts of these biotic stressors. For pests and diseases, range expansion has been predicted for the destructive *Phytophthora cinnamomi* in Europe (Bergot et al., 2004) and for phoma stem canker on oilseed rape in the UK (Evans et al., 2008). Increased generations under climate change for the coffee nematode have been predicted for the coffee nematode in Brazil (Ghini et al., 2008). Walnut pests in California are predicted to experience increased numbers of generations under climate change scenarios (Luedeling et al., 2011). Luck (2011) summarized the mixed results for the qualitative effects of climate change on pathogens that cause disease of four major food crops - wheat, rice, soybean and potato - where some diseases increased in risk while others decreased under climate change scenarios. In syntheses, there is a tendency for risk of insect damage to plants to increase (Deutsch et al., 2008; Paulson et al., 2009). Typical scenario analyses are limited by simplistic assumptions, and work remains to evaluate how conclusions will change as more complete scenarios, such as those including migration and invasion patterns and other types of global change, are considered (Savary et al., 2005; Garrett et al., 2011). Effects on soil communities represent an area that needs more attention (Pritchard, 2011). Mycotoxins and pesticide residues in food are an important concern for food safety in many parts of the world, and identified as an important issue for climate change effects in Europe (Miraglia et al., 2009).

Weed populations and demographics are expected to change (*medium confidence*), with an overall poleward migration in response to warming (Ziska et al., 2011a). An overview of crop and weed competitive studies indicate that weeds could limit crop yields to a greater extent with rising levels of carbon dioxide per se (Ziska, 2010). This may be related to the greater degree of phenotypic and genotypic plasticity associated with weedy species relative to the uniformity inherent in large cropping systems (Chapter 4.2.4.6). Chemical control of weeds, which is the preferred management method for large-scale farms, may become less effective (*limited evidence, medium agreement*), with increasing economic and environmental costs (7.3.2.3).

Climate change effects on productivity will alter land use patterns, both in terms of total area sown to crops and the geographic distribution of that area. For example, the suitability for potato crops is expected to increase in very high latitudes and high tropical altitudes towards 2100 (Schaefleitner et al., 2011). Given expected trends in population, incomes, bioenergy demand, and agricultural technology, global arable area is projected to increase from 2007 to 2050, with projected increases over this period of +9% (Bruinsma, 2009), +8% (Fischer et al., 2009), +10-20% (Smith et al., 2010), +18-23% (Lobell et al. 2013) (*medium evidence, medium agreement*). Not all such studies included the effects of global warming. Where this is the case, estimates range from a 20% increase in cropping area to a decline of 9% (Zhang and Cai, 2011), but with large regional differences (*limited evidence, low agreement*). Countries at northern latitudes and under the current constraint of low temperature may increase cultivated area (*limited evidence, low agreement*). The generally lower nutrient quality of soils and the lack of necessary infrastructure required to convert virgin land into productive arable land make estimates of cropping area increases highly uncertain.

7.4.2. Projected Impacts on Fisheries and Aquaculture

Many studies have projected impacts of climate change on capture fisheries (Chapters 6 and 30) and only a subset of the more indicative studies at different ecological and geographical scales is included here. Overall, there is *high confidence* that climate change will impact on fisheries production with significant negative impacts particularly for developing countries in tropical areas, while more northerly, developed countries may experience benefits (Chapter 6.4.3).

Simulation studies on skipjack and bigeye tuna in the Pacific under both the B1 and A2 scenarios indicate that catches of skipjack in the region as a whole are likely to increase by approximately 19% in 2035 compared to recent catch levels while catches of bigeye are projected to increase by 0.33%. By 2100, under the B1 scenario, catches of skipjack are projected to be 12.4% higher than recent levels but 7.5% lower under the A2 scenario, while catches of bigeye will be 8.8% and 26.7% lower under the B1 and A2 scenarios respectively. The models indicate important regional differences, with a general trend that catches of both species will decrease in the Western Pacific and increase in the Eastern Pacific (Lehodey et al, 2011; Chapters 6.5.3 and 30.6.2.1.1). These changes have important implications for the future of national fishing fleets and canneries in the western Pacific (Bell et al. 2011a) . Climate change is expected to impact directly on the productivity of coastal fisheries in the Pacific island countries and territories through increased sea surface temperature and ocean acidification and indirectly through climate-driven damage to coral reefs, mangroves, sea-grasses and intertidal flats (Pratchett et al., 2011). Extreme events such as increased severity of tropical cyclones could also impact on some species. Under both B1 and A2 emissions scenarios, the vulnerability of coastal fisheries as a whole in 2035 (as estimated through the framework described in Bell et al. (2011a)) is considered to be low. Extended to 2100, the projected impacts under the A2 emissions scenario are more severe, with reductions in coastal fisheries production by 20-35% in the west and 10-30% in the east (Pratchett et al., 2011).

Brown et al. (2010) project that, under the A2 emissions scenario, primary production in the ocean around Australia will increase over the 50-year period from 2000-2050 as a result of small increases in nutrient availability from changes in ocean stratification and temperature, although the authors acknowledge considerable model uncertainty. This increase is forecast, in general, to benefit fisheries catch and value. In a complementary study, Fulton (2011) used available end-to-end models to forecast the impacts of climate change under the A2 scenario across approximately two-thirds of Australia's exclusive economic zone. The results indicated that by 2060, the large-scale commercial fisheries, aided by their adaptive flexibility, would experience an overall increase of more than 90% in the value of their operations, although differing across sectors .The change in returns for the small-scale sector varied regionally from a decrease of 30-51% to a potential increase of 9-14% in another.

At the global scale, projections based on a dynamic bioclimate envelope model under the SRES A1B scenario suggested that climate change could lead to an average 30–70% increase in fisheries yield from high-latitude regions (>50° N in the northern hemisphere), but a decrease of up to 40% in the tropics by 2055 compared to yields obtained in 2005 (Cheung et al., 2010). Another study used a suite of models linking physical, ecological, fisheries, and bioeconomic processes projected that, under the A1B scenario, the global yield from 'large' fish could increase by 6% and that of the 'small fish' used in fishmeal production by approximately 3.6%, assuming that marine fisheries and fish resources would be managed sustainably (Merino et al., 2012).

There is limited information available on projected impacts on food production in inland fisheries. Xenopoulus et al. (2005) investigated the effect of climate change and water withdrawal on freshwater fish extinctions under the assumptions of two scenarios consistent with scenarios A2 and B2. They forecast that discharge would increase in between 65 and 70% of river basins in the world but it would decrease by as much as 80% in 133 rivers for which fish species data were available. In the latter group, by 2070 up to 75% of the local fish biodiversity would be 'headed toward extinction' because of changes in climate and water consumption, with the highest rates of extinction forecast mainly in tropical and subtropical areas. These results are not directly translatable into changes in fishery production but do give cause for concern for the likely affected areas (*limited evidence; low agreement*).

Information on future impacts on aquaculture is equally limited. Huppert et al. (2009) considered the impacts on the coast of Washington State, USA. They concluded that inundation of low-lying coastal areas from sea level rise, flooding from major storm events, and increased ocean temperatures and acidification would create significant challenges for the important shellfish aquaculture industry in the state. Inundation of existing shellfish habitats from sea level rise and increased incidence of harmful algal blooms were also contributory factors. Using a structured vulnerability framework and considering the B1 and A2 emission scenarios to project impacts on aquaculture in the tropical Pacific to 2035 and 2100, Pickering et al..(2011) concluded that production of freshwater species such as tilapia, carp and milkfish will probably benefit from the expected climate changes, while coastal enterprises are expected to encounter problems in the same time horizons, varying according to species. Aquaculture production of calcifying organisms such as molluscs will experience loss of suitable habitats through ocean acidification. This will be particularly pronounced at and in the vicinity of eastern boundary upwelling systems (Chapter 30.6.2.1.4).

The food security consequences of the different impacts on capture fisheries and aquaculture are more difficult to estimate than the biological and ecological consequences. A preliminary study by Allison et al., (2009) examined the vulnerability of the economies of 132 countries to climate change impacts on fisheries in 2050 under the A1FI and B2 scenarios. Vulnerability was considered as a composite of three components: exposure to the physical effects of climate change; the sensitivity of the country to impacts on fisheries; and adaptive capacity within the country. This analysis suggested that under both scenarios several of the least developed countries were also amongst the most vulnerable to climate change impacts on their fisheries. They included countries in central and western Africa, Peru and Columbia in South America and four tropical Asian countries.

7.4.3. Projected impacts on Livestock

Climate change impacts on livestock will include effects on forage and feed, direct impacts of changes in temperature and water availability on animals, and indirect effects via livestock diseases. Many of the relevant processes and projected impacts for rangelands are discussed in Chapter 4.3.3.2, as well as in chapters for regions with prominent livestock sectors (Chapters 22.3.4.2, 23.4.2, 25.7.2.1). In North American cattle systems, warming is expected to lengthen forage groing season but decrease forage quality, with important variations due to rainfall changes (Craine et al., 2010; Izaurralde et al., 2011, Hatfield et al., 2011). Simulations for French grasslands (Graux et al., 2013) and sown pastures in Tasmania (Perring et al., 2010) also project negative impacts on forage quality. Similarly, legume content of grasslands in most of southern Australia is projected to increase to the 2070s for SRES A2, with larger increases in wetter locations (Moore and Ghahramani, 2013).

There is *high confidence* that high temperatures tend to reduce animal feeding and growth rates (Andre et al., 2011; Renandeau et al. 2011). The impacts of a changing UK climate on dairy cow production were analysed by (Wall *et al.*, 2010), who showed that in some regions, milk yields will be reduced and mortality increased because of heat stress throughout the current century, with annual production and mortality losses amounting to some £40 million by the 2080s under a medium-high greenhouse gas emission scenario.

Existing challenges of supplying water for an increasing livestock population will be exacerbated by climate change in many places (*limited evidence, high agreement)*. For example, Masike and Urich (2008) project that warming under A1 SRES emission scenario will cause an annual increase of more than 20% in cattle water demand by 2050 for Kgatleng District, Botswana. At the same time, there is ample scope to improve livestock water productivity considerably (Molden et al., 2010); for example, in mixed crop-livestock systems of sub-Saharan Africa via feed, water and animal management (Descheemaeker et al., 2010).
Host and pathogen systems in livestock will change their ranges because of climate change (*high confidence)*. Species diversity of some pathogens may decrease in lowland tropical areas as temperatures increase (Mills et al., 2010). The temperate regions may become more suitable for tropical vector-borne diseases such as Rift Valley fever and malaria, which are highly sensitive to climatic conditions (Rocque et al., 2008). Vector-borne diseases of livestock such as African horse sickness and bluetongue may expand their range northwards in the northern hemisphere because rising temperatures increase the development rate and winter survival of vectors and pathogens (Lancelot et al., 2008). Diseases such as West Nile virus and schistosomiasis are projected to expand into new areas (Rosenthal, 2009). The distribution, composition and migration of wild bird populations that harbour the genetic pool of Avian Influenza viruses will all be affected by climate change, although in ways that are somewhat unpredictable (Gilbert et al., 2008). The changing frequency of extreme weather events, particularly flooding, will affect diseases too. For example, outbreaks of Rift Valley fever in East Africa are associated with increased rainfall and flooding due to El Niño-Southern Oscillation events (Gummow, 2010; Pfeffer and Dobler, 2010). In general, the impacts of climate change on livestock diseases remain difficult to predict and highly uncertain (Mills et al., 2010; Tabachnick, 2010).

Box 7-1 summarises impacts on a regional basis for crops and livestock. Developing countries rely heavily on climate-dependent agriculture and especially in conjunction with poverty and rapid increase in population they are vulnerable to climate change. While food insecurity is concentrated mostly in developing countries situated in the tropics (Berg et al. 2013; Ericksen et al, 2011; St. Clair and Lynch, 2010) global food supply may also be affected by heat stress in both temperate and subtropical regions (Teixeira et al. 2013). Chapter 22 identifies Africa as one of the regions most vulnerable to food insecurity. Climate change will also affect crop yields, food security and local economies in Central America, northeast Brazil and parts of the Andean region (Chapter 27) as well as in South Asia (Iqbal et al. 2009, Chapter 24). As shown in Box 7-1, in spite of uncertainties in responses at regional/national and sub-national level, there is high confidence that most developing countries will be negatively affected by climate change in the future, although climate change may have positive effects in some regions. In high latitudes (such as Russia, northern Europe, Canada, South America) global warming may increase yields and expand the growing season and acreage of agricultural crops, although yields may be low due to poor soil fertility and water shortages in some regions (Kiselev et al., 2013; Chapters 23, 24, 26, 27). Although there is slim evidence, some studies do indicate a significant increase in crops yields in some parts of China, Africa and India. Like crops, livestock is also negatively affected by climate change in almost all the continents, as evidenced by the regional chapters of Working Group 2. The dairy, meat and wool systems primarily rely on fodders, grasslands and rangelands. Climate change can impact the amount and quality of produce, profitability and reliability of production (Chapter 23, 25). Higher temperature would lead to decline in dairy production, reduced animal weight gain, stress on reproduction, increased cost of production and lower food conversion efficiency in warm regions. Disease incidence among livestock is expected to be exacerbated by climate change as most of the diseases are transmitted by vectors such as ticks and flies (Chapter 23) whose proliferation depends on climatic parameters of temperature and humidity.

_____ START BOX 7-1 HERE _____

Box 7-1. Projected Impacts for Crops and Livestock in Global Regions and Sub-Regions under Future Scenarios

Crop yield impacts in () correspond to () in the scenario column. - CO_2, without CO_2 effects; + CO_2, with CO_2 effects; I, irrigated; R, rainfed. In Europe: Atl., Atlantic; Cont., continental; Med., Mediterranean. pp, precipitation. N, north; E, east; W, west; S, south; C, central. [NB: See tables file for box content.]

_____ END BOX 7-1 HERE _____

7.4.4. Projected Impacts on Food Prices and Food Security

AR4 presented a summary of food price projections based on five studies that used projected yield impacts as inputs to general or partial equilibrium models of commodity trade. Many additional projections of this type have been made since AR4, expanding the number of trade models used, the diversity of yield projections considered, and the disaggregation of prices by commodity (Hertel et al., 2010; Baldos and Hertel, 2013; Calzadilla et al. 2013; Lobell et al., 2013; Nelson et al., 2013). Many of the studies did not include CO_2 effects, which is sometimes justified on the grounds that studies are concerned with “worst-case” scenarios, or that the bias from omitting positive CO_2 effects balances the known bias from omitting negative effects of elevated O_3 and increased weed and pest damage. Studies also typically ignore potential changes in yield variability (Figure 7-6) and policy responses such as export bans which have important international price effects (7.2.2).

Based on the studies cited above, it is *very likely* that changes in temperature and precipitation, without considering effects of CO_2, will lead to increased food prices by 2050, with estimated increases ranging from 3-84%. The combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices, with a range of projected impacts from -30% to +45% by 2050. One lesson from recent model intercomparison experiments (Nelson *et al.*, 2013) is that the choice of economic model matters at least as much as the climate or crop model for determining price response to climate change, indicating the critical role of economic uncertainties for projecting the magnitude of price impacts.

The AR4 concluded that climate changes are expected to result in higher real prices for food past 2050. This conclusion remains intact with *medium confidence*, albeit with a relative lack of new studies exploring price changes to 2100 or beyond. Of course, international prices are only one indicator of global food security, with the pathways by which price changes can affect food security outlined in section 7.3.3. A limited number of studies have estimated the effects of price changes on food security and related health outcomes. Nelson et al. (2009) project that, without accelerated investment in planned adaptations, climate change by 2050 would increase the number of undernourished children under the age of 5 by 20-25 million (or 17-22%), with the range including projections with and without CO_2 fertilization. Lloyd et al. (2011) used the projected changes in undernourishment from Nelson (2009) to project the impact of climate change on human nutrition, estimating a relative increase in moderate stunting of 1–29% in 2050 compared with a future without climate change. Severe stunting was projected to increase by 23% (central Africa) to 62% (South Asia). Baldos and Hertel (2013) estimate that, compared to a baseline scenario, climate change impacts result in an increase in global malnourished population by 49 million (11%) in 2050, but that the combined effects of climate change and CO_2, which result in yield increases in their study, reduces the number of malnourished.

In summary, if global yields are negatively impacted by climate change, an increase in both international food prices and the global headcount of food insecure people is expected (*limited evidence, high agreement*). However, it is only *about as likely as not* that the net effect of climate and CO_2 changes on global yields will be negative by 2050, but *likely* that such changes will occur later in the 21st century. At the same time, it is *likely* that socio-economic and technological trends, including changes in institutions and policies, will remain a relatively stronger driver of food security over the next few decades than climate change (Goklany, 2007; Parry et al., 2009). Importantly, all of the studies that project price impacts assume some level of on-farm agronomic adaptation, often by optimizing agronomic practices within the model. Most, but not all, also prescribe income growth rates as exogenous factors, despite the fact that incomes are heavily dependent on agriculture in many poor countries. One study that accounted for income effects found that, in countries such as Indonesia that had both a large share of poverty in agriculturally dependent households and yield impacts that were small relative to other regions, poverty was reduced by the effects of climate change (Hertel et al., 2010). However, in most countries the positive income effects of higher prices could not outweigh the costs of reduced productivity and higher food prices.

Recent work has also highlighted that productivity in many sectors besides agriculture are significantly influenced by warming, with generally negative effects of warming on economic output in tropical countries (Hsiang, 2010; Dell et al., 2012). Given the importance of incomes to food access, incorporating these effects into future estimates of food security impacts will be important. Conflict is also known to be an important factor in food security (FAO, 2010a), and evidence of climate variability effects on conflict risk (Hsiang et al., 2011) indicates a need to also consider this dimension in future work (Chapter 12).

Since the impacts of climate change on food production and food security depends on multiple interacting drivers, the timing of extreme events, which are expected to become more frequent (IPCC, 2012), is critical. Extremes contribute to variability in productivity (Figure 7-6) and can form part of compound events that are driven by common external forcing (e.g. El Niño), climate system feedbacks, or causally unrelated events (IPCC, 2012). Such compound events, where extremes have simultaneous impacts in different regions, may have negative impacts on food security, particularly against the backdrop of increased food price volatility (Figure 7-3). There are very few projections of compound extreme events and interactions between multiple drivers are difficult to predict. Effective monitoring and prediction, and building resilience into food systems, are likely to be two key tools in avoiding the negative impacts resulting from these interactions (Misselhorn et al., 2010).

7.5. Adaptation and Managing Risks in Agriculture and Other Food System Activities

7.5.1. Adaptation Needs and Gaps based on Assessed Impacts and Vulnerabilities

7.5.1.1. Methods of Treating Impacts in Adaptation Studies – Incremental to Transformational

The pervasiveness of climate impacts on food security and production (7.2), the commitment to future climate change from past greenhouse gas emissions (WGI SPM) and the very high likelihood of additional and likely greater climate changes from future greenhouse gas emissions (WGI SPM) means that some level of adaptation of food systems to climate change will be necessary. Here we take adaptation to mean reductions in risk and vulnerability through the actions of adjusting practices, processes and capital in response to the actuality or threat of climate change. This often involves changes in the decision environment, such as social and institutional structures, and altered technical options that can affect the potential or capacity for these actions to be realized. Adaptation can also enhance opportunities from climate change (AR4 WG2 Chapter 5; Chapter 17.2.3). These adaptations will need to be taken in the context of a range of other pressures on food security such as increasing demand as a result of population growth and increasing per capita consumption (7.1).

Following the AR4, the literature on adaptation and food production has increased substantially, although there has been less focus on adaptations to food systems and on value chains: the linked sets of activities that progressively add value as inputs are converted into products the market demands. Many adaptation frameworks or approaches have been published, informing the approach in the AR4 which addressed both autonomous and planned adaptations. Autonomous adaptations are incremental changes in the existing system including through the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced. They include coping responses and are reactive in nature. Planned adaptations are proactive and can either adjust the broader system or transform it (Howden *et al.*, 2010). Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that whilst many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favourable for effective adaptation including investment in new technologies, infrastructure, information and engagement processes (Chapters 14.3, 14.4, 15.2.4). Building adaptive capacity by decision-makers at all scales (Nelson *et al.*, 2008) is an increasingly important part of the adaptation discourse which has also further addressed costs, benefits, barriers and limits of adaptation (Adger *et al.*, 2009). The sector-specific nature of many adaptations means that sectors will initially be addressed separately below.

7.5.1.1.1. Cropping

Effective adaptation of cropping could be critical in enhancing food security and sustainable livelihoods, especially in developing countries (AR4 WG2 Chapter 5, Chapter 9.4.3.1). There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times, crop cultivars and species) and marketing arrangements (Chapter 9.4.3.1, Fujisawa and Koyabashi; 2010, Olesen *et al.*, 2011) although this response is not ubiquitous (Bryan *et al.*, 2009). There are a large number of potential adaptations for cropping systems and for the food systems of which they are part, many of them enhancements of existing climate risk management and all of which need to be embedded in the wider farm systems and community contexts.

The possibility of extended growing seasons because of higher temperatures increasing growth in cooler months means that changing planting dates is a frequently identified option for cereals and oilseeds provided there is not an increase in drought at the end of the growing season (Krishnan *et al.*, 2007; Magrin *et al.*, 2009; Travasso *et al.*, 2009; Deressa *et al.*, 2009; Mary and Majule, 2009; Meza and Silva, 2009; Tingem and Rivington, 2009; Laux *et al.*, 2010; Stöckle *et al.*, 2010; Shimono *et al.*, 2010; Van de Geisen *et al.*, 2010; Tao and Zhang, 2010; Olesen *et al.*, 2011; Cho *et al.*, 2012). Aggregated across studies, changing planting dates may increase yields by a median of 3-17% but with substantial variation (Table 7-2). Early sowing is being facilitated by improvements in machinery and by the use of techniques such as dry sowing (Passioura and Angus, 2010), seedling transplanting and seed priming and these adaptations can be integrated with varieties with greater thermal time requirements so as to maximize production benefits and to avoid late spring frosts (Tingem and Rivington, 2009; Cho et al., 2012). There can however, be practical constraints to early sowing such as seedbed condition (van Oort et al. 2012). In some situations early sowing may allow double cropping or intercropping where currently only a single crop is feasible. For example, this could occur for irrigated maize in central Chile (Meza et al., 2008) and the double crop wheat/soybean in the southern pampas of Argentina (Monzon et. al., 2007), increasing productivity per unit land although increasing nitrogen and water demand at the same time. However, in Mediterranean climates, early sowing of cereals is dependent on adequate planting rains in autumn and climate projections indicate that this may decrease in many regions (WGI SPM), limiting the effectiveness of this adaptation and possibly resulting in later sowings than are currently practiced. In such circumstances, use of short duration cultivars could be desirable so as to reduce exposure to end of season droughts and high temperature events (Orlandini et al., 2008; Walter et al., 2010). There is *medium confidence* that optimisation of crop varieties and planting schedules appears to be effective adaptations, increasing yields by up to 23% compared with current managementwhen aggregated across studies (Table 7-2) (*medium evidence, high agreement*). This flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Meza et al., 2008; Deressa et al., 2009) and especially in dealing with projections of increased climate variability (Figure 7-6). Approaches that integrate climate forecasts at a range of scales in some cases are able to better inform crop risk management (Cooper et al., 2009; Sultan et al., 2010; Baethgen, 2010, Li et al. 2010) although such forecasts are not always useable or useful (Chapter 9.4.4; Lemos and Rood, 2010; Dilling and Lemos 2011)

[INSERT TABLE 7-2 HERE
Table 7-2: The simulated median benefit (difference between the yield change from baseline for the adapted and non-adapted cases) for different crop management adaptations: cultivar adjustment; planting date adjustment; adjusting planting date in combination with cultivar adjustment; adjusting planting date in combination with other adaptations; irrigation optimization; fertilizer optimization; other management adaptations. The numbers in parentheses are the 25th and 75th percentile. Data points where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Only studies with both a 'no adaptation' and an 'adaptation' assessment are used. Data taken from Abraha & Savage, 2006; Aggarwal & Mall, 2002; Alexandrov, 1999; Alexandrov et al., 2002; Butt et al., 2005; Challinor et al., 2009; Corobov, 2002; DeJong et al., 2001; Deryng et al., 2011; Droogers, 2004; Easterling et al., 2003; El-Shaher et al., 1997; Ewert et al., 2005; Gbetibouo & Hassan, 2005; Howden & Jones, 2004; Kaiser, 1999; Karim et al., 1996; Lal, 2011; Lal et al., 1998; Erda et al., 2005; Matthews & Wasmann, 2003; Moya et al., 1998; Reyenga et al., 1999; Rosenzweig et al., 1994; Southworth et al., 2000; Tao & Zhang, 2011; Tubiello et al., 2000; Thornton et al., 2010; Tingem & Rivington, 2009; Xiao et al., 2005; Yates & Strzepek, 1998; Zhang & Liu, 2005.]

Warmer conditions may also allow range expansion of cropping activities polewards in regions where low temperature has been a past limitation (*limited evidence, medium agreement*) provided varieties with suitable daylength response are available and soil and other conditions suitable. This may particularly occur in Russia, Canada and the Scandinavian nations although the potential may be less than earlier analyses indicated due to increased climate extremes, water limitations and various institutional barriers (Alcamo et al., 2007; Dronin and Kirilenko, 2011; Kulshreshtha, 2011; Kvalvik et al., 2011; Tchebakova et al., 2011; Bindi and Olesen, 2011). In many of these cases, the northerly range expansion may only offset the reduction in southerly cropping areas and yields due to lower rainfall, water shortages and high temperatures (*limited evidence, high agreement,*).

Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and environments worldwide as high temperatures are known to reduce both yield and quality (Krishnan et al., 2007; Challinor et al., 2009; Wassmann et al., 2009; Luo et al., 2009; Shimono et al., 2010; Stöckle et al., 2010) noting that a new cultivar usually takes between eight and 20 years to deliver and so it is important to be selecting cultivars for expected future climate and atmospheric conditions (Ziska et al. 2012). Improving gene conservation and access to extensive gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (Mercer et al., 2008; Wassmann et al., 2009) as well as to take advantage of increasing atmospheric CO_2 concentrations (Ziska et al., 2012) and respond to changing pest, disease and weed threats with these developments needing **t**o be integrated with *in situ* conservation of local varieties (IAASTD, 2009).

Similarly, the prospect of increasing drought conditions in many cropping regions of the world (Olesen et al., 2011) raises the need for breeding additional drought-tolerant crop varieties (Naylor et al., 2007; Mutekwa, 2009; Tao and Zhang, 2011), for enhanced storage and access to irrigation water, more efficient water delivery systems, improved irrigation technologies such as deficit irrigation, more effective water harvesting, agronomy that increases soil water retention through practices such as minimum tillage and canopy management, agroforestry, increase in soil carbon and more effective decision support (Verchot et al. 2007; Luo et al., 2009; Lioubimtseva and et al., 2009; Falloon and Betts, 2010; Piao et al., 2010; Olesen et al., 2011) amongst many other possible adaptations (Chapter 22.4.3.7.1). There is *medium confidence* (*limited evidence, high agreement*) that crop adaptations can lead to moderate yield benefits (mean of 10 to 20%) under persistently drier conditions (Deryng et al. 2011) and that irrigation optimisation for changed climate can increase yields by a median of 3.2% (Table 7-2) as well as having a range of other beneficial effects (Chapter 3.7).

Diversification of activities is another climate adaptation option for cropping systems (Lioubimtseva et al., 2009; Thornton et al., 2010). For example, Reidsma and Ewert (2008) found that regional farm diversity reduces the risk that is currently associated with unfavourable climate conditions in Europe. Diversification of activities often incorporates higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008) or to reduce risk (Seo 2010). In some cases, increased diversification outside of agriculture may be favoured (Coulthard, 2008; Mary and Majule, 2009; Mertz et al., 2009a).

The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate change and increase the benefit of positive changes as found in AR4 WG2 Chapter 5 (*medium evidence, high agreement,*). To quantify the benefits of adaptation, a meta-analysis of recent crop adaptation studies has been undertaken for wheat, rice and maize (see Figure 7-4). This meta-analysis adds more recent studies to that undertaken in the AR4 WG2 Chapter 5. It indicates that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management is equivalent to about 15 to 18% of current yields (Figure 7-8). This response is, however, extremely variable, ranging from negligible benefit from adaptation (even potential dis-benefit) to very substantial. The responses are dissimilar between wheat, maize and rice (Figure 7-4) with temperate wheat and tropical rice showing greater benefits of adaptation. The responses also differ markedly between adaptation management options (Table 7-2). For example, when aggregated over studies, cultivar adaptation (23%) and altering planting date in combination with other adaptations (3 to 17%) provide on average more benefit than optimizing irrigation (3.2%) or fertilisation (1%) to the new climatic conditions. These limits to yield improvements from agronomic adaptation and the increasingly overall negative crop yield impact with ongoing climate change (Figures 7-4 and 7-5) mean a substantial challenge in ensuring increases in crop production of 14% per decade given a population of nine billion people in 2050. This could be especially so for tropical wheat and maize where impacts from increases in temperature of more than 3ºC may more than offset benefits from agronomic adaptations (*limited evidence, medium agreement,*).

[INSERT FIGURE 7-8 HERE
Figure 7-8: Simulated yield benefit from adaptation calculated as the difference between the yield change from baseline (%) for paired non-adapted and adapted cases as affected by temperature and aggregated across all crops. The shaded bands at the 95% confidence interval are calculated as for Figure 7-4. Data points (n=31) where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Data sources are the same as for Table 7-2 and only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used so as to avoid the issues arising from un-paired studies documented in Figure 7-4 for tropical maize.]

Potential increased variability of crop production means that other climate-affected aspects of food systems such as food reserve, storage and distribution policies and systems may need to be enhanced (IAASTD, 2009, Stathers et al. 2013) (*medium evidence, high agreement*) along with a range of broader, value-chain issues such as provision of effective insurance markets, clarity in property rights, building adaptive capacity and developing effective participatory research cultures (Chapter 9, AR4 WG2 Chapter 5).

It is notable that most of the above adaptations raised above and used in this analysis are essentially either incremental changes to existing agricultural systems or are systemic changes which integrate new aspects into current systems. Few could be considered to be transformative changes. Consequently, the potential adaptation benefits could be understated (*limited evidence, medium agreement*) (Rickards and Howden 2012).

7.5.1.1.2. Fisheries

Many of the resources for capture fisheries are already fully or overexploited with an estimated 30% of stocks overexploited in 2009 and 57% fully exploited (FAO, 2012). Comparable global statistics are not available for inland fisheries but the status of those stocks may not be any better. Overfishing is widely regarded as the primary pressure on marine fishery resources but other human activities including coastal and offshore mining, oil and gas extraction, coastal zone development, land-based pollution and other activities are also negatively impacting stock status and production (Rosenberg and Macleod, 2005; Cochrane *et al.,* 2009). In inland fisheries, overfishing is also widespread, coupled with many other impacts from other human activities (Allan et al., 2005). Climate change adds another compounding influence in both cases.

Adaptive responses to reduce the vulnerability of fisheries and fishing communities could include: management approaches and policies that strengthen the livelihood asset base; improved understanding of the existing response mechanisms to climate variability to assist in adaptation planning; recognising and responding to new opportunities brought about by climate change; monitoring biophysical, social and economic indicators linked to management and policy responses; and adoption of multi-sector adaptive strategies to minimise negative impacts (Allison *et al.,* 2009; Badjeck *et al.,* 2010; MacNeil *et al.,* 2010). Complementary adaptive responses include occupational flexibility, changing target species and fishing operations, protecting key functional groups and the establishment of insurance schemes (Coulthard, 2008; FAO, 2009; McNeil *et al.,* 2010; Koehn *et al.,* 2011; Daw *et al.,* 2009). Fishers and fish farmers will be vulnerable to extreme events such as flooding and storm surges which will require a range of adaptations including developing early warning systems for extreme events, provision of hard defences against flooding and surges, ensuring infrastructure such as ports and landing sites are protected, effective disaster response mechanisms and others (Daw *et al.,* 2009).

Governance and management of fisheries will need to follow an ecosystem approach to maximise resilience of the ecosystem, and to be adaptive and flexible to allow for rapid responses to climate induced change (Chapter 6.4.2; FAO, 2009; Daw *et al.,* 2009). Within an ecosystem approach, habitat restoration will frequently be a desirable adaptation option, particularly in freshwater and coastal environments (Koehn et al., 2011). A wide range of management tools and strategies have been developed to manage fisheries. These are all necessary but not sufficient for adaptation to climate change in fisheries (Grafton, 2010). Grafton argued that the standard tools for fisheries management were developed to control fishing mortality and to maintain adequate levels of recruitment to fishery stocks but without necessarily addressing the needs for resilience to change or to be able to function under changing climates. He therefore proposed that these conventional management tools must be used within processes that i) have a core objective to encourage ecosystems that are resilient to change and ii) that explicitly take into account uncertainties about future conditions and the effect of adaptation, and make use of models to explore the implications of these (Grafton, 2010). There are also opportunities for fisheries to contribute to mitigation efforts (FAO, 2009; Grafton, 2010).

Aquaculture is the fastest-growing animal-food-producing sector with per capita consumption of products increasing at an average rate of 7.1% p.a. between 1980 and 2010 (FAO, 2012). Adaptive responses in aquaculture include use of improved feeds and selective breeding for higher temperature tolerance strains to cope with increasing temperatures (De Silva and Soto, 2009) and shifting to more tolerant strains of molluscs to cope with increased acidification (Huppert *et al.*, 2009). Better planning and improved site selection to adapt to expected changes in water availability and quality; integrated water use planning that takes into account the water requirements and human benefits of fisheries and aquaculture in addition to other sectors; and improving the efficiency of water use in aquaculture operations are some of the other adaptation options (De Silva and Soto, 2009). Integrated water use planning will require making trade-offs between different land and water uses in the watershed (Mantua *et al.*, 2010). Insurance schemes accessible to small-scale producers would help to increase their resilience (De Silva and Soto, 2009). In some near-shore locations there may be a need to shift property lines as the mean high water mark is displaced landwards by rising sea level (Huppert *et al.*, 2009).

There are no simple, generic recipes for fisheries adaptation with Bell et al. (2011b) suggesting a list of 25 separate but inter-related actions, together with supporting policies to adapt fisheries and aquaculture in the tropical Pacific to climate change (Chapter 30.6.2.1.1). These actions fall into three categories according to the primary objective: economic development and government revenue; maintaining the contribution of fish to food security; and maximising sustainable livelihoods. Actions and policies for adaptation in fisheries and aquaculture must complement those for other sectors. Similar case-by-case, integrated planning will be required in all other regions and at scales from community to regional to achieve clearly defined adaptation goals.

7.5.1.1.3. Livestock

Extensive livestock systems occur over a huge range of biophysical and socio-ecological systems, with a consequent large range of potential adaptations. In many cases, these livestock systems are highly adapted to past climate risk, and there is *high confidence* that this provides a sound starting point for climate change adaptation (*medium evidence, high agreement*) (Thornton et al. 2009). These adaptations include matching stocking rates with pasture production, adjusting herd and water point management to altered seasonal and spatial patterns of forage production, managing diet quality (using diet supplements, legumes, choice of introduced pasture species and pasture fertility management), more effective use of silage, pasture spelling and rotation, fire management to control woody thickening, using more suitable livestock breeds or species, migratory pastoralist activities and a wide range of biosecurity activities to monitor and manage the spread of pests, weeds and diseases (Fitzgerald et al., 2008; Howden et al., 2008; Nardone et al., 2010; Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). Combining adaptations can result in substantial increases in benefits in terms of production and profit when compared with single adaptations (Ghahramani and Moore, 2013; Moore and Ghahramani, 2013). In some regions, these activities can in part be informed by climate forecasts at differing time-scales to enhance opportunities and reduce risks including soil degradation (McKeon et al., 2009). Many livestock systems are integrated with or compete for land with cropping systems and one climate adaptation may be to change these relationships. For example, with increased precipitation, farmers in Africa may need to reduce their livestock holdings in favour of crops, but with rising temperatures, they may need to substitute small ruminants in place of cattle with small temperature increases or reduce stocking rates with larger temperature rises (Kabubo-Mariara, 2009; Thornton et al., 2010). As with other food systems there is a range of barriers to adaptation which could be addressed on-farm and off-farm by changes in infrastructure, establishment of functioning markets, improved access to credit, improved access to water and water management technologies, enhanced animal health services and enhanced knowledge adoption and information systems (Howden et al., 2008; Kabubo-Mariara, 2009; Mertz et al., 2009b, Silvestri et al. 2012).

Heat stress is an existing issue for livestock in some regions (*robust evidence, high agreement*), especially in higher productivity systems (7.3.2.6). For example, some graziers in Africa are already making changes to stock holdings in response to shorter term variations in temperatures (Chapter 9.4.3.1; Thornton et al. 2009). Breeding livestock with increased heat stress resistance is an adaptation often identified but there are usually trade-offs with productivity as well as benefits including animal welfare and so this option needs careful evaluation (Nardone et al., 2010) . Increased shade provision through trees or cost-effective structures can substantially reduce the incidence of high heat stress days, reduce animal stress and increase productivity, with spraying a less effective option (Gaughan et al. 2010; Nidumolu et al., 2011). In cooler climates, warming may be advantageous due to lesser need for winter housing and feed stocks.

7.5.1.1.4. Indigenous knowledge

Indigenous Knowledge (IK) has developed to cope with climate hazards contributing to food security in many parts of the world. Examples in the Americas include Alaska, where the Inuit knowledge of climate variability assured the source of food to hunters and reduced various risks (Ford 2009; Alessa et al., 2008; Weatherhead et al., 2010) down to the southern Andes where the Inca traditions of crop diversification, genetic diversity, raised bed cultivation, agroforestry, weather forecasting and water harvesting are still used in agriculture (Chapters 9.4.3.1, 27.3.4.2; Goodman-Elgar, 2008; Renard, 2011; McDowell and Hess, 2012). In Africa, weather forecasting, diversity of crops and agropastoralism strategies have been useful in the Sahel (Nyong et al., 2007). Rainwater harvesting has been a common practice in Sub-Saharan Africa (Biazin et al., 2012) to cope with dry spells and improve crop productivity, while strategies from agropastoralists in Kenya are related to drought forecasting based on the fauna, flora, moon, winds and other factors (Speranza et al., 2010). In South Africa, farmer's early warming indicators of wet or dry periods in Namibia based on animals, plants and climate observations contributed to deal with climatic variability (Newsham and Thomas, 2011). In the same way, in Asia and Australia IK plays an important role to assure food security of certain groups (Salick and Ross, 2009; Marin, 2010; Speranza et al., 2010; Green et al., 2010; Kalanda et al., 2011; Pareek and Trivedi, 2011; Biazin et al., 2012), although IK and the opportunities to implement it can differ according to gender and age in some communities (Chapter 9.3.5; Rengalakshmi, 2007; Turner and Clifton, 2009; Kalanda et al., 2011) leading to distinct adaptive capacities and options.

In addition to changes already occurring in climate (seasonal changes, changes in extreme events: IPCC 2012) projected changes beyond historical conditions could reduce the reliance on IK (Speranza et al., 2010; Kalanda et al., 2011; McDowell and Hess, 2012) affecting the adaptive capacity of a number of peoples globally (*medium evidence, medium agreement*). Moreover, there is *medium confidence* that some policies and regulations leading to limit the access to territories, promoting sedentarization, the substitution of traditional livelihoods, reduced genetic diversity and harvesting opportunities as well as loss of transmission of IK, may contribute to limit the adaptation to climate change in many regions (Nakashina et al., 2012) (*medium evidence, medium agreement*).

7.5.1.2. Practical Regional Experiences of Adaptation, including Lessons Learned

Given the early stages of climate change, there are relatively few unequivocal examples of adaptation (7.5.2) additional to existing climate risk management. Where there have been management changes these have often been in response to several driving variables of which climate is only one (Chapter 9.4.3.1; Smit and Wandel, 2006; Mertz et al., 2009a; Chen et al., 2011; Odgaard and et al., 2011. The preparedness to consider adaptation even within an industry varies regionally (Battaglini et al., 2009) and in some regions there already appears to be adaptation to climate change occurring (Chapter 9.4.3.1; Fujisawa and Koyabashi, 2010; Olesen et al., 2011; Bohensky et al., 2012). Activities to build adaptive capacity to better manage climate change are more widespread (Twomlow et al., 2008) but there remain questions as to how this capacity will evolve and be maintained (Nelson et al., 2009). Crucial in this will be devolution of the decision-making process so as to integrate local, contextual information into adaptation decision-making (Nelson et al., 2008).

7.5.1.3. Observed and Expected Barriers and Limits to Adaptation

Adaptation is strongly influenced by factors including institutional, technological, informational and economic and there can be barriers (restrictions that can be addressed) and limits in all these factors (Chapters 14, 15 and 16: *robust evidence, high agreement*). Several barriers to adaptation of food systems have been raised including inadequate information on the climate, climate impacts and on the risks and benefits of the adaptation options, lack of adaptive capacity, inadequate extension, institutional inertia, cultural acceptability, financial constraints including access to credit, insufficient fertile land, infrastructure, lack of functioning markets and insurance systems (Chapter 16; Bryan et al., 2009; Deressa et al., 2009; Kabubo-Mariara, 2009; De Bruin and Dellink, 2011, Silvestri et al. 2012). Limits to adaptation can occur for example where crop yields drop below the level required to sustain critical infrastructure such as sugar or rice mills (Park et al., 2012). In some cases, these can be effectively irreversible. Some studies have shown that access to climate information is not the principal limitation to improving decision making and it can result in perverse outcomes, increasing inequities and widening gender gaps (Coles and Scott, 2009). Incomplete adoption of adaptations may also occur.

Lack of technical options can also be a barrier to adaptation. New varieties of crops or breeds of livestock provide possible core adaptations of production systems (*medium evidence, high agreement;* Mercer et al., 2008; Tingem and Rivington, 2009) however, there is substantial investment needed to develop these along with delays before they are available, both of which can act as adaptation barriers. This may be addressed in part by investments to improve local crop varieties or livestock breeds that are easily adopted (IAASTD, 2009). There also can be physiological limits to performance such as upper temperature limits for heat tolerance (AR4 WG2 Chapter 5).

7.5.1.4. Facilitating Adaptation and Avoiding Maladaptation

Adaptation actions would usually be expected to provide benefits to farmers, the food industry along the value chain or perhaps to a broader community. However, there are possible maladaptations that arise from adapting too early or too late, by changing the incorrect elements of the food system or changing them by the incorrect amount (Chapter 14.7). A key maladaptation would be one which increased emissions of greenhouse gases, this making the underlying problem worse (Smith and Olesen, 2010); AR4 WG3 Chapter 11, *robust evidence, high agreement*). A recent review of agricultural climate change adaptation options found they tend to reduce greenhouse gas emissions (Smith and Olesen, 2010; Falloon and Betts, 2010) (*medium evidence, medium agreement*). These adaptations include measures that reduce soil erosion and loss of nutrients such as nitrogen and phosphorus, for increasing soil carbon, measures for conserving soil moisture and reducing temperature extremes by increasing vegetative cover.

There is a strong focus on incremental adaptation of existing food systems in the literature since AR4 (see above) however, and this may result in large opportunity costs that could arise from not considering more systemic adaptation or more transformative change (Howden et al., 2010; Kates et al., 2012) (*limited evidence, medium agreement*). For example, in the USA, changes in farming systems (i.e. the combination of crops) have been assessed as providing significant adaptation benefit in terms of net farm income (Prato et al., 2010) although in other regions this might be minor (Mandryk *et al*. 2012). There is a need to also engage farmers, policymakers and other stakeholders in evaluating transformative, pro-active, planned adaptations such as structural changes (Mäder et al., 2006; McCrum, 2009; Olesen et al., 2011). This could involve changes in land allocation and farming systems, breeding of functionally-different crop varieties, new land management techniques and new classes of service from lands such as ecosystem services (Rickards and Howden 2012). In Australia, industries including the wine, rice and peanut industries are already attempting transformative changes such as change in location so as to be early adopters of what are perceived as opportunities arising from change (Park et al., 2012).

There is substantial commonality in adaptation actions within different agricultural systems. For example, changing varieties and planting times are incremental adaptations found in studies of many different cropping systems as evidenced by the sample size in the meta-analysis in this chapter. Collating information on the array of adaptation options available for farmers, their relative cost and benefit and their broad applicability could be a way of initiating engagement with decision-makers. In the climate mitigation domain, this has been attempted using marginal abatement cost curves which identify mitigation options, their relative cost and the potential size of emission-reductions (AR4 WG3 Chapter 11). These curves can be used in setting investment priorities and informing policy discussions. The local nature of many adaptation decisions, their interactions with other highly contextual driving factors and the time and climate change-sensitive nature of adaptation decisions mean however, that global, time-independent curves are not feasible. The studies aggregated in Table 7-2 indicate that there are some options which may be more relevant and useful to consider than others. These results illustrate the potential scope and benefit of developing effective adaptation options if implemented in an adaptive management approach.

7.5.2. Food System Case Studies of Adaptation – Examples of Successful and Unsuccessful Adaptation

Incremental, systemic and transformational adaptation to climate change is beginning to be documented, though the peer-reviewed literature largely covers vulnerability assessments and intentions to act, not adaptation actions (Berrang-Ford et al., 2010).

Case 1: Incremental adaptation in the Sahel
Much of the literature covers incremental, reactive adaptation, but given actors are constantly adapting to changing social and economic conditions, incremental adaptation to climate change is difficult to distinguish from other actions (Berrang-Ford et al., 2010; Speranza, 2010), and in fact is usually a response to a complex of factors. This case, of the zaï soil management practice in the Sahel region, is an example where a complex of factors drives local actions, and factors such as growing land scarcity and new market opportunities, rather than climate, may be the primary factors (Barbier et al., 2009; Mertz, 2009b). Inherent poor soil quality and human activities have resulted in soil degradation – crusting, sealing, erosion by water and wind, and hardpan formation (Fatondji et al., 2009; Zougmoré et al., 2010). Zaï, a traditional integrated soil and water management practice, can combat land degradation and improve yield and decrease yield variability by concentrating runoff water and organic matter in small pits (20-40 cm in diameter and 10-15 cm deep) dug manually during the dry season and combined with contour stone bunds to slow runoff. A handful of animal manure or compost is placed in each pit. By breaking the soil crust, the pits facilitate greater water infiltration, while the applied organic matter improves soil nutrient status and attracts termites, which have a positive effect on soil structure. The zaï technique is very labour intensive requiring some 60 days of labour per hectare. Innovations to the system, involving animal-drawn implements, can reduce labour substantially.

Case 2: Mixed farming systems in Tanzania
In Morogoro, Tanzania, farming households have adapted in many ways to climatic and other stresses (Paavola, 2008). They have extended cultivation through forest clearance or reducing the length of the fallow period. Intensification is under way, through change in crop choices, increased fertiliser use and irrigation, and especially greater labour inputs. Livelihood diversification has been the main adaptation strategy – this has involved more non-farm income-generating activities, tapping into natural resources for subsistence and cash income (e.g. charcoal production), and has included artisanal gold and gemstone mining. Households have also altered their cropping systems, for example, by changing planting times. Migration is another frequently used strategy – with farmers moving to gain land, access markets or get employment. Parents also send children to cities to work for upkeep and cash income to reduce the household numbers that need to be supported by uncertain agricultural income. While many of these strategies help in terms of the short-term needs, in the longer term they may be reducing the capacity of households to cope. For instance, land cover change interacting with climate changes has negative impacts on current and future water supplies for irrigation (Natkhin *et al.*, 2013), and deforestation and forest degradation means faltering forest-based income sources. This will be particularly problematic to the more vulnerable groups in the community, including women and children.

7.5.3. Key Findings from Adaptations – Confidence Limits, Agreement, and Level of Evidence

There have been many studies of crop adaptation since the AR4. In aggregate these show that adaptations to changed temperature and precipitation will bring substantial benefit, (*robust evidence, high agreement*) with some adaptations (e.g. cultivar adaptation and planting date adjustment) assessed as on average being more effective than others (e.g. irrigation optimisation; 7.5.1.1.1). Most studies have assessed key farm-level adaptations such as changing planting dates and associated decisions to match evolving growing seasons and improving cultivar tolerance to high temperature, drought conditions and elevated CO_2 levels. Limits to adaptation will increasing emerge for such incremental adaptations as the climate further changes, raising the need for more systemic or transformational changes (*limited evidence, medium agreement,*; 7.5.1, 7.5.1.1). An example of transformational change is latitudinal expansion of cold-climate cropping zones polewards but this may be largely offset by reductions in cropping production in the mid-latitudes due to rainfall reduction and temperature increase (*medium confidence, limited evidence;* 7.5.1.1.1*).* Adaptations to food systems additional to the production phase have been identified and sometimes implemented but the benefits of these have largely not been quantified.

Livestock and fisheries systems also have available a large range of possible adaptations often tailored to local conditions but there is not adequate information to aggregate the possible value of these adaptations although there is *high confidence* (*medium evidence, high agreement*) that they will bring substantial benefit, particularly if implemented in combination (7.5.1.1.2, 7.5.1.1.3). Key livestock adaptations include matching stocking rates with pasture availability, water management, monitoring and managing the spread of pests, weeds and diseases, livestock breeding and adjusting to changed frequencies of heat stress and cold conditions (7.5.1.1.2). Fishery adaptations include management approaches and policies that strengthen the livelihood asset base, take a risk-based ecosystem approach to managing the resource and adoption of multi-sector adaptive strategies to minimise negative impacts. Importantly, there is an emerging recognition that existing fishery management tools and strategies are necessary but not sufficient for adaptation to climate (7.5.1.1.2).

Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. Climate changes may be reducing reliance on indigenous knowledge in some locations but also some policies and regulation may be limiting the contribution that indigenous knowledge can make to effective climate adaptation (*medium evidence, medium agreement*; 7.5.1.1.4).

The focus on incremental adaptations and few studies on more systemic and transformational adaptation or adaptation across the food system mean that there may be underestimation of adaptation opportunities and benefits (*limited evidence, medium agreement;* 7.5.1.1). In addition to this, there is a range of limits and barriers to adaptation and many of these could be addressed by devolution of the decision-making process so as to integrate local, contextual information into adaptation decision-making. A schematic summary of these issues is given in Table 7-3.

[INSERT TABLE 7-3 HERE
Table 7-3: Schematic key risks for food security and the potentials for adaptation in the near- and long-term for high and low levels of warming.]

7.6. Research and Data Gaps – Food Security as a Cross-Sectoral Activity

Research and data gaps reflect that most work since AR4 has continued to concentrate on food production and has not included other aspects of the food system that connect climate change to food security. Features such as food processing, distribution, access and consumption have recently become areas of research interest in their own right but only tangentially attached to climate change.

Many studies either do not examine yield variability or do not report it. Closer attention should be paid to yield variability in the quantity and quality of food production, especially given observed price fluctuations associated with climate events. We expect environmental thresholds and tipping points, such as high temperatures, droughts and floods, to become more important in the future. Specific recommendations are for food production experiments in which changes in variability reflect predicted changes for given warming scenarios. Including thresholds in impact models, for especially high levels of global warming (i.e. 4-5 ^{o}C above pre-industrial), are highly likely to result in lower projections of yield, given changes in climate variability and increasing mean temperatures. Important gaps in knowledge continue to be studies of weeds, pests, and diseases, including animal diseases, in response to climate change and how related adaptation activities can be robustly incorporated into food security assessments. Yield and other agronomic data, at a range of spatial scales, are crucial to the development, evaluation and improvement of models. Model development is currently limited by lack of data.

Adaptation studies for cropping systems typically assess relatively minor agronomic management changes under future climate conditions only. Forthcoming studies should examine the impact of proposed adaptations when employed in the current climate. In this way management changes that are beneficial in a range of environments can be separated from management changes that are specificly targeted at climate change. Further, studies should be inclusive of the broader range of systemic and transformational adaptation options open to agriculture.

Current forecasts of changes in distribution and productivity of marine fish species and communities are typically at global or regional scale and include adaptations to only a limited extent. Increasing the resolution to forecast impacts and changes at the national and local ecosystem scale would provide valuable information to governments and stakeholders and enable them to prepare more effectively for expected impacts on food production and security offered by fisheries.

Possibilities for agronomic and breeding adaptations of food production to global warming are possible up to high levels of climate change. However, food security studies are urgently required to estimate the actual range of adaptations open to farmers and other actors in the food system and the implementation paths for these especially when possible changes in climate variability are included.

Frequently Asked Questions

FAQ 7.1: What factors determine food security and does low food production necessarily lead to food insecurity?
[to be placed in Section 7.2]
Observed data and many studies indicate that a warming climate has a negative effect to crop production, generally reduce yields of staple cereals such as wheat, rice and maize, which, however, differs between regions and latitudes. Elevated CO_2 could benefit crops yields in short term by increasing photosynthesis rates, however, there is big uncertainty in the magnitude of the CO_2 effect and that interactions with other factors. Climate change will affect fisheries and aquaculture through gradual warming, ocean acidification and through changes in the frequency, intensity and location of extreme events. Other aspects of the food chain are also sensitive to climate but such impacts are much less well known. Climate-related disasters are among the main drivers of food insecurity, both in the aftermath of a disaster and in the long run. Drought is a major driver of food insecurity, and contributes to a negative impact on nutrition. Floods and tropical storms also affect food security by destroying livelihood assets. The relationship between climate change and food production depends to a large degree on when and which adaptation actions are taken. Other links in the food chain from production to consumption are sensitive to climate but such impacts are much less well known.

FAQ 7.2: How could climate change interact with change in fish stocks, ocean acidification?
[to be placed in Section 7.4]
Millions of people rely on fish and aquatic invertebrates for their food security and as an important source of protein and some micronutrients. However, climate change will affect fish stocks and other aquatic species. For example, increasing temperatures will lead to increased production of important fishery resources in some areas but decreased production in others while increases in acidification will have negative impacts on important invertebrate species, including species responsible for building coral reefs which provide essential habitat for many fished species in these areas. The poorest fishers and others dependent on fisheries and subsistence aquaculture will be the most vulnerable to these changes, including those in small-island developing States, central and western African countries, Peru and Columbia in South America and some tropical Asian countries.

FAQ 7.3: How could adaptation actions enhance food security and nutrition? *[to be placed in Section 7.5]*
Over 70 per cent of agriculture is rain-fed. This suggests that agriculture, food security and nutrition are all highly sensitive to changes in rainfall associated with climate change. Adaptation outcomes focusing on ensuring food security under a changing climate could have the most direct benefits on livelihoods, which have multiple benefits

for food security, including: enhancing food production, access to markets and resources, and reduced disaster risk. Effective adaptation of cropping can help ensure food production and thereby contributing to food security and sustainable livelihoods in developing countries, by enhancing current climate risk management. There is increasing evidence that farmers in some regions are already adapting to observed climate changes in particular altering cultivation and sowing times and crop cultivars and species. Adaptive responses to climate change in fisheries could include: management approaches and policies that maximize resilience of the exploited ecosystems, ensuring fishing and aquaculture communities have the opportunity and capacity to respond to new opportunities brought about by climate change, and the use of multi-sector adaptive strategies to reduce the consequence of negative impacts in any particular sector. However, these adaptations will not necessarily reduce all of the negative impacts of climate change, and the effectiveness of adaptations could diminish at the higher end of warming projections.

Cross-Chapter Boxes

Box CC-HS. Heat Stress and Heat Waves

[Lennart Olsson (Sweden), Dave Chadee (Trinidad and Tobago), Ove Hoegh-Guldberg (Australia), John Porter (Denmark), Hans-O. Pörtner (Germany), Kirk Smith (USA), Maria Isabel Travasso (Argentina), Petra Tschakert (USA)]

Heat waves are periods of abnormally and uncomfortably hot weather during which the risk of heat stress on people and ecosystems is high. The number and intensity of hot days have increased markedly in the last three decades (Coumou et al., 2013) (*high confidence*). According to WG I, it is *likely* that the occurrence of heat waves has more than doubled in some locations due to human influence and it is *virtually certain* that there will be more frequent hot extremes over most land areas in the latter half of the 21st century. Coumou et al. (2013) predicted that, under a medium warming scenario, the number of monthly heat records will be over 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +10C or more, the habitability of large parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and they may act as triggers for tipping points (Hughes et al., 2013). Consequently, heat waves play an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society [Ch 10, 11, 12, 13]

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012). In LICs and MICs, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health [Ch 11]

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro *et al.*, 2011; Rahmstorf and Coumou, 2011; Nitschke et al., 2011; Diboulo et al., 2012; Hansen et al., 2012). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, Jan C et al., 2008).

Increase in ozone concentrations due to high temperatures affects health (Smith et al., 2010), leading to premature mortality, e.g. cardiopulmonary mortality (Smith et al., 2010). High temperatures are also associated with an increase in air-borne allergens acting as a trigger for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems [Ch 4, 5, 6, 30]

Tree mortality is increasing globally (Williams et al., 2012) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult due to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013), Box 4.2.

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (Hoegh-Guldberg et al., 2007), Figure 6-5, (*medium confidence*) [Ch 6.3.1, 6.3.5; 30.4; 30.5; CC-MB]

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*). [Ch 5, 6, 30.4-30.5, CC-CR, CC-MB]

Agriculture [Ch 7]

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2011). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and suitability for crops (*medium evidence, medium agreement*) (Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the U.S., current economic losses due to heat stress of livestock are estimated at several billion USD annually (St-Pierre et al., 2003).

Box CC-HS References

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Box CC-OA. Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Fig. CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30.8, 30.9). Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several metaanalyses (6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea-floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves and gastropods reducing the competitiveness with non-calcifiers (5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; 6.1.2).

Projections of ocean acidification effects at ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (5.4.2.2).

Due to an incomplete understanding of species-specific responses and trophic interactions the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, 5.4.2.4) and the goods and services that they provide such as fisheries, tourism and coastal protection (*limited evidence, high agreement*; Box CC-CR, 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially-exploited shelled mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global GDP, it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e. reduce anthropogenic emissions of CO_2), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (6.4.2.1).

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

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between countries, regions and production systems. Energy technologies (e.g. biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber 2008; McMahon and Price, 2011; Macknick *et al*., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Asano et al., 2006; Khan and Hanjra, 2009; USEPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012) *(robust evidence, high agreement)*. Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Sung et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Sections 10.2.2 10.3.4, 25.7.4; van Vliet et al., 2012; Davies et al., 2013) *(robust evidence, high agreement)*. Water for biofuels, for example, under the IEA Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (WEC, 2010; Sattler et al., 2012) *(medium evidence, high agreement)*. Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) *(robust evidence, high agreement)*.

Water may require significant amounts of energy for lifting, transport and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly– electricity use (kWhr/m^3 of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (Smit and Nasr, 1992; Jimenez, 1996; Wichelns et al., 2007; Raschid-Sally and Jayakody, 2008) *(medium confidence)*. More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita et al, 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) *(high confidence)*.

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) *(robust evidence, high agreement)*. Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (Sections 25.4.3 and 25.6.2, Box 25-10) *(medium evidence, high agreement)*. Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity and other factors (see Figure WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this report.

The interconnectivity of food/fiber, water, land use, energy and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel-food-land use-water-GHG mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type and use requirements, energy requirements and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use and climate change is increasingly recognized as critical to effective climate resilient pathway decision making *(medium evidence, high agreement)*, although tools to support local- and regional-scale assessments and decision-support remain very limited.

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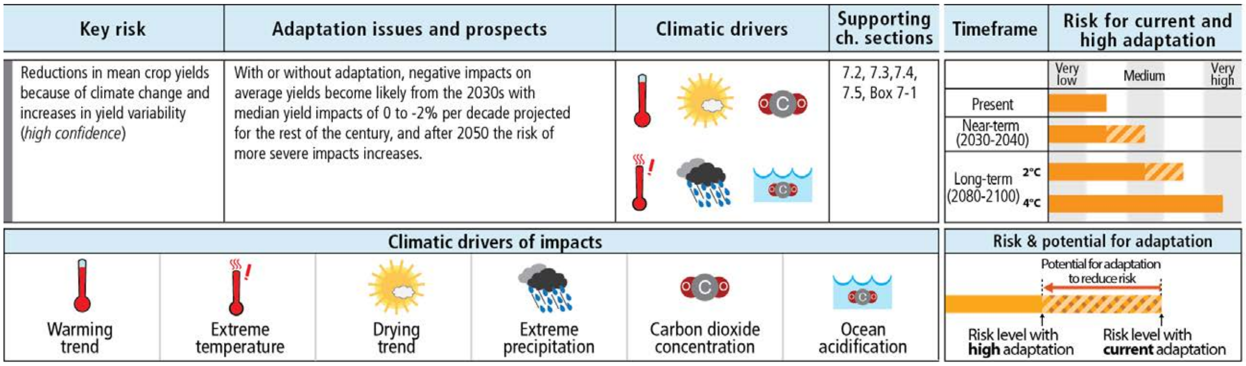
Table 7-1: Households divided into five categories of food access, indicating the impacts of food price increases.

Food Access Category	**Characteristics**	**Impacts of food price increase on food access**
Primarily subsistence (autarkic)	Subsistence farmers, herders, fishers and forest dependent populations; generally low share of population (Karfakis et. al. 2011)	Limited impact.
Food producers: net sellers	Generally lower share of population compared with net buyers (Aksoy and Sid-Dimelik; 2008; Zezza et al. 2008; FAO 2011)	Positive impact through increased income effect. Major beneficiaries are those with greatest surplus (e.g. larger, more commercialized farms) (FAO 2011)
Food producers: net buyers	Majority of poor rural households (IFAD, 2010; FAO, 2011)	Ambiguous: depends on relative size of income and price effects, but generally expected to be negative due to high share of income spent on food (Ivanic and Martin 2008; FAO, 2011; Ivanic et. al., 2011)
Rural non-farming households	Rural landless: characterized by high rates of food insecurity; average share of population for 15 low income countries was 22% (Aksoy et. al.)	Negative impact due to high share of income spent on food; however some limited evidence that wage increases may accompany price increases in which case overall effects are ambiguous. (FAO 2011; Aksoy and Sid-Dikmelik 2008).
Urban consumers	Growing share of population in most countries (IFAD 2010)	Negative impact by reducing food affordability. Especially vulnerable to changes in global food prices, as they are more likely to consume staple foods derived from tradable commodities (FAO, 2008a; Ivanic et al. 2011).

Table 7-2: The simulated median benefit (difference between the yield change from baseline for the adapted and non-adapted cases) for different crop management adaptations: cultivar adjustment; planting date adjustment; adjusting planting date in combination with cultivar adjustment; adjusting planting date in combination with other adaptations; irrigation optimization; fertilizer optimization; other management adaptations. The numbers in parentheses are the 25th and 75th percentile. Data points where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Only studies with both a 'no adaptation' and an 'adaptation' assessment are used. Data taken from Abraha & Savage, 2006; Aggarwal & Mall, 2002; Alexandrov, 1999; Alexandrov et al., 2002; Butt et al., 2005; Challinor et al., 2009; Corobov, 2002; DeJong et al., 2001; Deryng et al., 2011; Droogers, 2004; Easterling et al., 2003; El-Shaher et al., 1997; Ewert et al., 2005; Gbetibouo & Hassan, 2005; Howden & Jones, 2004; Kaiser, 1999; Karim et al., 1996; Lal, 2011; Lal et al., 1998; Erda et al., 2005; Matthews & Wasmann, 2003; Moya et al., 1998; Reyenga et al., 1999; Rosenzweig et al., 1994; Southworth et al., 2000; Tao & Zhang, 2011; Tubiello et al., 2000; Thornton et al., 2010; Tingem & Rivington, 2009; Xiao et al., 2005; Yates & Strzepek, 1998; Zhang & Liu, 2005.

Management option	Cultivar adjustment (n=56)	Planting date adjustment (n=19)	Planting date and cultivar adjustment (n=152)	Irrigation optimisation (n=17)	Fertiliser optimisation (n=10)	Other (n=9)
Benefit (%) from using adaptation	23 (6.8, 35.9)	3 (2.1, 8.3)	17 (9.9, 26.1)	3.2 (2, 8.2)	1 (0.25, 4.8)	6.45 (3.2, 12.8)

Table 7-3: Schematic key risks for food security and the potentials for adaptation in the near- and long-term for high and low levels of warming.



Box 7-1 Table

Projected Impacts for Crops and Livestock in Global Regions and Sub-Regions under Future Scenarios

Crop yield impacts in () correspond to () in the scenario column. - CO_2, without CO_2 effects; + CO_2, with CO_2 effects; I, irrigated; R, rainfed. In Europe: Atl., Atlantic; Cont., continental; Med., Mediterranean. pp, precipitation. N, north; E, east; W, west; S, south; C, central.

Regional Impacts on Crops

Region	**Subregion**	**Yield Impacts (%)**	**Scenario**	**Reference**
World		Maize: up to -4 (-12) Rice: -9.5(-12) Wheat -10 (-13)	CSIRO(MIROC) 2050	Nelson et al, 2010
East Asia	China	Rice: -19 (+3.5); -32(+2.5);-40(+0.18) Maize: -22(-11) ;-28 (-18) ; -34(-26)	+1ºC; +2ºC;+3ºC - CO_2(+CO_2)	Chapter 24
	Eastern China	Rice: –10 to +3 (+7.5 to +17.5)/ –26.7 to +2 (0 to +25)/ –39 to –6 (–10 to + 25)	2030/2050/2080 - CO_2 (+CO_2)	Tao et al 2013
	China (3H Plain)	Wheat-maize: +4.5±14.8/ -5.8 ±25.8	+2ºC / +5ºC,	Chapter 24
	North China Plain	IWheat : -0.9 (+23) RWheat : -1.9 (+28)	2085-00 -CO_2 (+CO_2)	Yang et al 2013
	China YangtzeRiver	IRice : -14.8 (-3.3) RRice: -15.2 (-4.1)	2021-2050 -CO_2 (+CO_2)	Chapter 24
South Asia	South Asia	Maize: -16 ; Sorghum: -11	2050	Knox et al, 2012
	South Asia	Net cereal production -4 to -10	+2ºC	Lal (2010)
	India	Sorghum winter: up to -7; -11; -32	A2 2020, 2050, 2080	Chapter 24
	India	IRice: -4,-7,-10 RRice: -6, -2.5; -2.5	2020,2050,2080 +CO_2	Kumar et al 2013
	India NE India Coastal India W.Ghats	IRice -10/+5RRice:-35/+5Maize:up to -40Wheat:up to-20 IRice -10/+5RRice:-20/+15IMz:-50/-15RMz:-35/+10 IRice:-11/+5RRice:-35/+35Maize,Sorghum up to -50	2030 +CO_2	Kumar et al 2011
	India	Monsoon Maize-21 to 0;-35 to 0 ;-35 to 0 Winter Maize -13 to +5 ; -50 to +5 ; -60 to -21	2020;2050;2080 A2	Byjesh et al 2010
	Pakistan	Wheat: -7 / -24 (Swat), +14 / +23 (Chitral)	+1.5ºC / +3ºC	Chapter24
	Pakistan	Wheat: -6/-8 Rice: -16/-19	B2/A2 2080	Chapter24

West Asia	Jordan (Yarmouk)	Barley -8/+5 Wheat: -20/ +18	-20% pp/ +20% pp	Chapter24
Africa	All regions	Wheat -17 Maize -5 Sorghum -15 Millet -10	2050	Knox et al, 2012
	All regions	Maize: -24 ± 19	2090 +5ºC	Thornton et al 2009
	East Africa	Maize: -3 to +15 ; -8.6 to +17.8 Beans: -1.5 to +21.8; -18.1 to +23.7	2030;2050	Thornton et al 2010
	Sahel	Millet -20/-40	+2ºC/+3ºC	Ben Mohamed 2011
Central & South America	Brazil (NE)	Maize: 0 to -10, Wheat: -1 to -14, Rice : -1 to -10	2030	Chapter27
	Brazil (South)	Maize: -15 Bean: +45	2080 + CO_2	Chapter27
	Paraguay	Wheat: +4/-9/-13 (-1/+1/-5) Maize +3/+1/+6 (+3/+3/+8) Soybean: 0/10/-15 (0/-15/-2)	2020/2050/2080; A2 (B2)	Chapter 27
	Central America	Wheat -1 to -9 Rice: 0 to -10	2030	Chapter27
		Maize: 0/0/-10/-30 Bean: -4/-19/-29/-87 Rice: +3/-3/-14/-63	2030/2050/2070/2100	Chapter27
	Panama	Maize: -0.5/+2.4/+4.5 (-0.1/-0.8/+1.5)	2020/2050/2080 A2 (B1) + CO_2	Chapter27
	Andean region	Wheat: -14/ +2 Barley: -1 / -8 Potato: 0/ -5 Maize: 0 / -14	2030	Chapter27
	Chile	Maize: -5% to -10% Wheat: -10% to -20%	2050 A1F1 + CO_2	Chapter27
	Argentina	Wheat: -16/-11 (+3/+3) Maize: -24/-15 (+1/0) Soybean: -25/-14 (+14/+19)	2080 A2/B2 - CO_2 (+CO_2)	Chapter27
North America	US Midwest US SE US Gt Plains	Maize: -2.5 (-1.5) Soy: +1.7 (+9.1) Maize: -2.5 (-1.5) Soy: -4.4 (+2.4) Wheat: -4.4 (+2.4)	+0.8ºC (+CO_2)	Hatfield et al 2011
	US NW	Winter Wheat: +20/+30, Spring Wheat:+7/+3	2040/2080 +CO_2	Stockle et al 2010
	Canadian Prairies	Small grains: -48 to + 18 Oilseeds: -50 to +25	+1ºC, +2ºC,+20% pp, -20% pp	Kulsh-restha 2011
Europe	Boreal /Alpine/AtlN Atl C/Atl S/ContN ContS/Med N/MedS	+34 to +54/+20 to +23/-5 to +22 +5 to +19/-26 to -7/-8 to +4 +11 to +33/0 to -22/+5 to -27	2080 A2 B2 HadCM3/ HIRHAM ECHAM4/RCA3	Iglesias et al 2012
Austra-lia	South	Wheat: -15/-12	Low/High PAWC 2080 +CO_2	Luo et al, 2009
	South-East	Wheat: -29 (-25)	2080 (+CO_2)	Anwar et al, 2007

Regional Impacts on Livestock

Region	Sub-region	Climate change impacts	Scenarios	Reference
Africa	Botswana	Cost of supplying water from boreholes could increase by 23% due to increased hours of pumping, under drier and warmer conditions.	2050	Chapter 22
	Lowlands of Africa	Reduced stocking of dairy cows, a shift from cattle to sheep and goats, due to high temperature.	2050	Chapter 22
		Livestock keeping could benefit from increased temperature.		
	Highlands of East Africa	Maize stover availability head per head of cattle may decrease due to water scarcity.	2050	Chapter 22
	East Africa	Dairy yields decrease by 10-25%.	2050	Chapter 22
	South Africa		2046-2065/2080 - 2100 ECHAM5/MPI-OM, GFDL-CM2.0/2, MRI-CGCM2.3.2 (A2)	Nesamvuni et al. 2012
Europe	Netherlands	Dairy production affected at daily mean temperatures above 18°C.		Chapter 23
	Italy	Mortality risk to dairy cattle increased by 60%by exposure to high air temp. and high air humidity during breeding.		Chapter 23
	France	No impact on dairy yields.	ARPEGE (A2) 1970-1999, 2020-2049, 2070-2099	Graux et al, 2011
	French Uplands	Annual grassland production system significantly reduced by four year exposure to climatic conditions.	A2, 2070s	Graux et al, 2011
	Ireland, France	Grassland dairy system increases potential of dairy production, with increased risk of summer-autumn forage failure in France.	A1B, by the end of century	Graux et al, 2011
	Overall Europe	Spread of bluetongue virus (BTV) in sheep and ticks in cattle due to climate warming.	2080	Graux et al. 2011
		No increase in risk of incursion of Crimean-Congo haemorrhagic fever virus in livestock		Chapter 23

Austral-asia	Northern Australia	3ºC increase will cause 4% reduction in gross value of beef, sheep and wool sector.	Rainfall: - or + 10%, A1B, 2030	Chapter 25
	Australia (other than Tasmania)	Dairy output will decline under 1ºC increase in temperature.	2030	Chapter 25
	25 sites in southern Australia	Profitability of fodder supply production decline at most sites due to shorter growing season.	2050	Chapter 25
	Southern Australia	Decline in NPP of grassland from historical climate will be 7% in 2030, 9% in 2050 and 14% in 2070. Operating profit to fall by 27% in 2030, 32% in 2050 and 48% in 2070.	SRES A2; 2030, 2050, 2070	Moore and Ghahramani, 2013
	Tasmania Victoria NSW S. Australia	Dairy yields increase 0.5-6.2% Dairy yields decrease 1.3-6.7% Dairy yields decrease 1.4-6.6% Dairy yields decrease 2.2-8.1%	ECHAM5/MPI-OM (A1B) 2050	Hanslow et al. 2012
	New Zealand	National pasture production for dairy, beef and sheep will decrease by 4%.	2030	Wratt et al., 2008
Central and South America	Andean Mountain countries	Beef and dairy cattle, pigs and chicken could decrease between 0.9 and 3.2% while sheep could increase by 7%.	Hot and dry scenario, 2060	Chapter 27
	Columbia Venezuela Ecuador	Beef cattle choice declined.	Milder and wet scenario, 2060	Chapter 27
	Argentina & Chile	Beef cattle choice increased.	Future climate change	Chapter 27
	Brazil	Milk production and feed intake in cattle strongly affected.		Silva et al., 2009
North America	Central USA	Dairy yields decrease 16-30%.	CGCMI/Hadley, Baseline CO_2/2x CO_2/3x CO_2	Mader et al, 2009

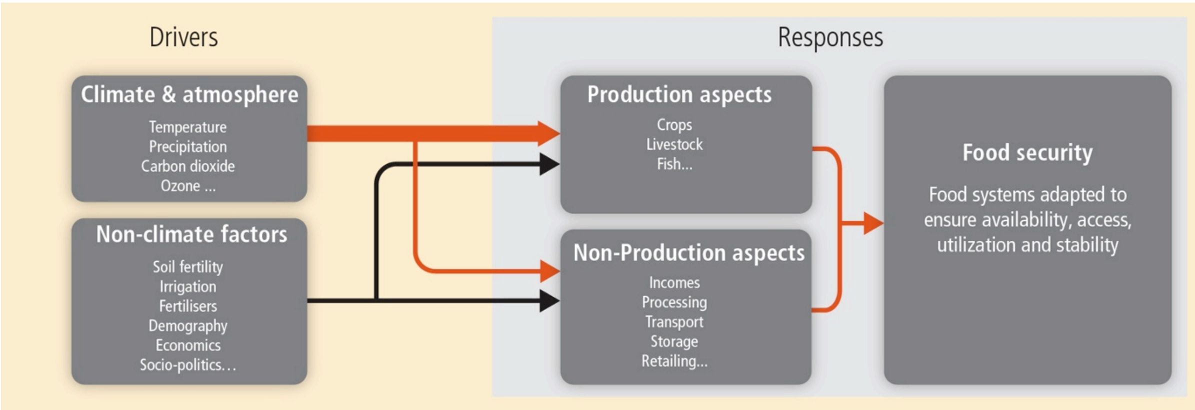


Figure 7-1: Main issues of the chapter. Drivers are divided into climate and non-climate elements, affecting production and non-production elements of food systems, thereafter combining to provide food security. The thickness of the red lines is indicative of the relative availability of refereed publications on the two elements.

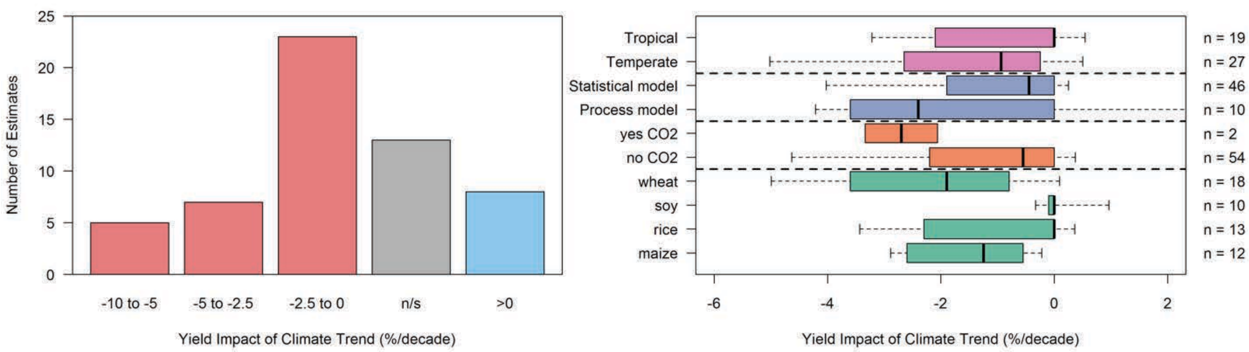


Figure 7-2: Summary of estimates of the impact of recent climate trends on yields for four major crops. Studies were taken from the peer-reviewed literature and used different methods (i.e., physiological process-based crop models or statistical models), spatial scales (stations, provinces, countries, or global), and time periods (median length of 29 years). Some included effects of positive CO_2 trends (7.3.2.1.2) but most did not. (a) shows number of estimates with different level of impact (% yield per decade), (b) shows boxplot of estimates separated by temperate vs. tropical regions, modelling approach (process-based vs. statistical), whether CO_2 effects were included, and crop. Boxplots indicate the median (vertical line), 25th-75th percentiles (box), and 10th-90th percentiles (whiskers) for estimated impacts in each category, and n indicates the number of estimates. Studies were for China (Tao *et al.*, 2006; Tao *et al.*, 2008; Wang *et al.*, 2008; You *et al.*, 2009; Chen *et al.*, 2010; Tao *et al.*, 2012), India (Pathak *et al.*,2003; Auffhammer *et al.*, 2012), United States (Kucharik and Serbin, 2008), Mexico (Lobell *et al.*, 2005), France (Brisson *et al.*, 2010; Licker *et al.*, 2013) Scotland (Gregory and Marshall, 2012), Australia (Ludwig *et al.*, 2009), Russia (Licker *et al.*, 2013), and some studies for multiple countries or global aggregates (Lobell and Field, 2007; Welch *et al.*, 2010; Lobell *et al.*, 2011). Values from all studies were converted to percentage yield change per decade. Each study received equal weighting as insufficient information was available to judge the uncertainties of each estimate. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

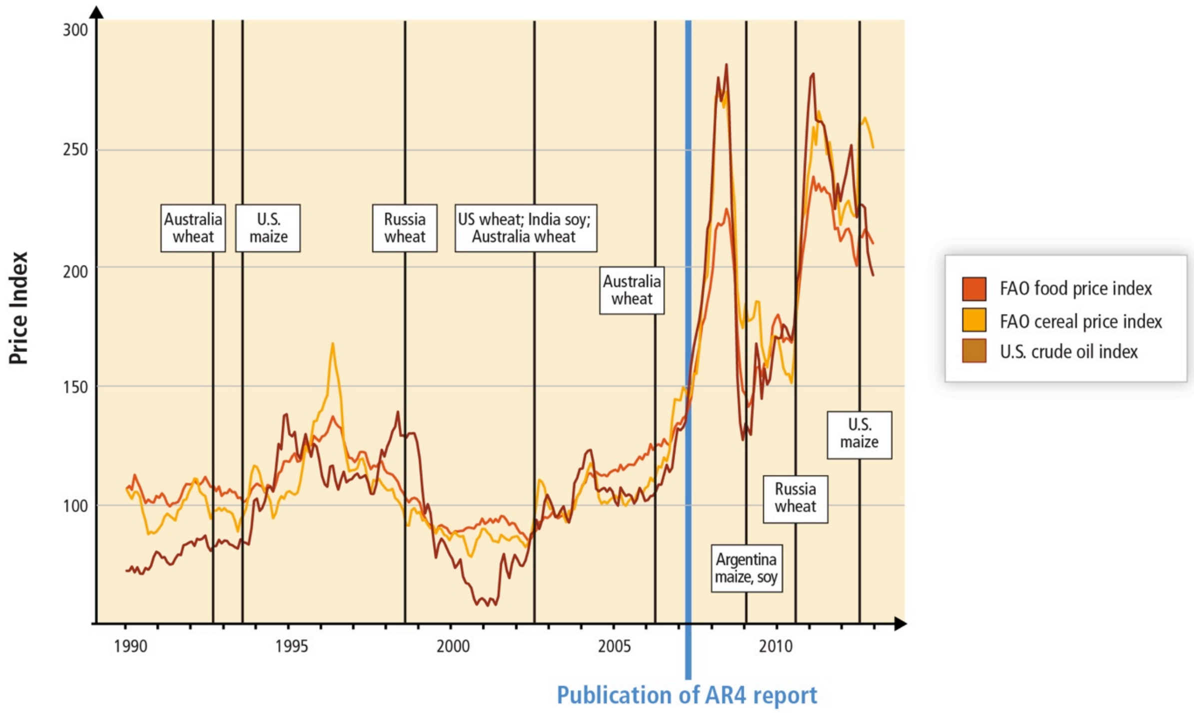


Figure 7-3: Since the AR4 report, international food prices have reversed historical downward trend. Plot shows history of FAO food and cereal price index (composite measures of food prices), with vertical lines indicating events when a top 5 producer of a crop had yields 25% below trend line (indicative of a seasonal climate extreme). Australia is included despite not being a top five producer, because it is an important exporter and the drops were 40% or more below trend line. Prices may have become more sensitive to weather-related supply shortfalls in recent years. At the same time, food prices are increasingly associated with the price of crude oil (blue line), making attribution of price changes to climate difficult. Thus, there is clear evidence since AR4 that prices can rise rapidly, but the role of weather in these increases remains unclear. All indices are expressed as percentage of 2002-2004 averages. Food price and crop yield data from FAO (http://www.fao.org/worldfoodsituation/foodpricesindex and http://faostat.fao.org/) and oil price data from http://www.eia.gov.

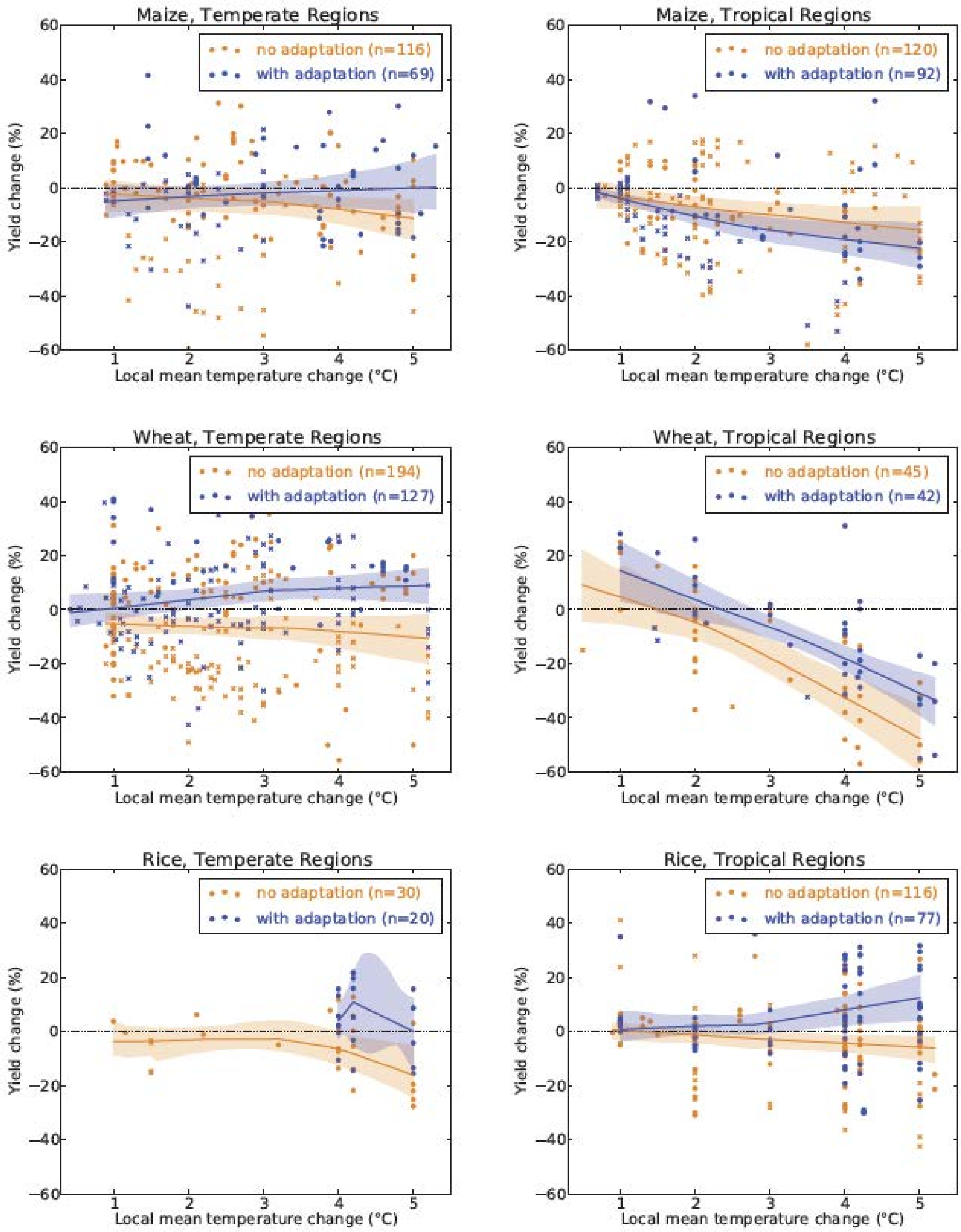


Figure 7-4: Percentage simulated yield change as a function of local temperature change temperature for the three major crops and for temperate and tropical regions. Dots indicate where a known change in atmospheric CO_2 was used in the study; remaining data are indicated by x. Note that differences in yield value between these symbols do not measure the CO_2 fertilisation effect, since changes in other factors such as precipitation may be different between studies. Non-parameteric regressions (LOESS, span=1 and degree=1) of subsets of these data were made 500 times. These bootstrap samples are indicated by shaded bands at the 95% confidence interval. Regressions are separated according to the presence (blue) or absence (red) of simple agronomic adaptation (Table 7-2). In the case of tropical maize the central regression for absence of adaptation is slightly higher than that with adaptation. This is due to asymmetry in the data – not all studies compare adaptated and non-adapted crops. Figure 7-8 presents a pair-wise adaptation comparison. Note that four of the 1048 datapoints across all six panels are outside the yield change

range shown. These were omitted for clarity. Some of the studies have associated temporal baselines, with centre-points typically between 1970 and 2005. Note that local warming in cropping regions generally exceeds global mean warming (Figure 21-3). Data are taken from a review of literature: Abou-Hadid (2006); Abraha & Savage (2006); Aggarwal & Mall (2002); Alexandrov (1999); Alexandrov & Hoogenboom (2000); Alexandrov et al. (2002); Arndt et al. (2011); Brassard & Singh 2008); Brassard & Singh (2007); Butt et al. (2005); Byjesh et al. (2010); Chhetri et al. (2010); Chipanshi et al. (2003); Corobov (2002); Izaurralde et al. (2001); DeJong et al. (2001); Deryng et al. (2011); Droogers (2004); Easterling et al. (2003); El Maayar et al. (2009); El-Shaher et al. (1997); Ewert et al. (2005); Gbetibouo & Hassan (2005); Howden & Jones (2004); Iqbal et al. (2011); Izaurralde et al (2005); Jones & Thornton (2003); Kaiser (1999); Kapetanaki & Rosenweig (1997); Karim et al. (1996); Krishnan et al. (2007); Lal (2011); Lal et al. (1998); Li et al. (2011); Erda et al. (2005); Liu et al. (2010); Lobell & Ortiz-Monasterio (2007); Luo et al. (2003); Matthews & Wasmann (2003); Moya et al. (1998); Osborne et al. (2013); Piao et al. (2010); Porter & Semenov (2005); Reyenga et al. (1999); Rosenzweig et al. (1994); Rowhani et al. (2011); Sands & Edmond (2005); Schlenker & Roberts (2009); Shuang-He et al. (2011); Southworth et al. (2000); Tan et al. (2010); Tao & Zhang (2010); Tao & Zhang (2011); Tubiello et al. (2000); Thomson et al. (2005); Thornton et al. (2009); Thornton et al. (2011); Thornton et al. (2010); Tingem & Rivington (2009); Tingem et al. (2008); Walker & Schulze (2008); Winters et al. (1998); Xiao et al. (2005); Xiong et al. (2007); Yates & Strzepek (1998); Zhang & Liu (2005); Zhao et al. (2005). **[Illustration to be redrawn to conform to IPCC publication specifications.]**

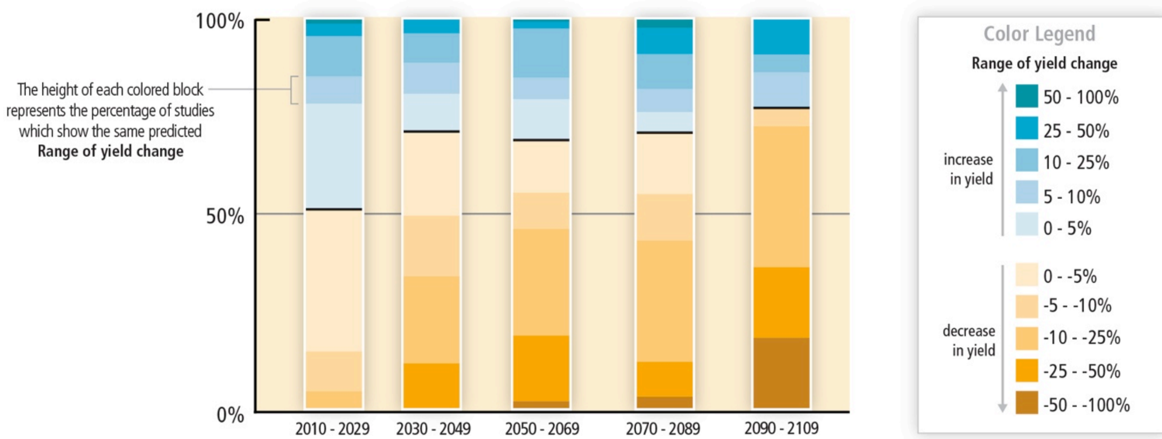


Figure 7-5: Projected changes in crop yield as a function of time. The y-axis indicates percentage of studies and the colours denote percentage change in crop yield. The sum of absolute bar heights in each time period equals 100%. Data are plotted according to the 20-year period in which the centre point of the projection period falls. Data taken from Abraha & Savage, 2006; Alexandrov & Hoogenboom, 2000; Arndt et al., 2011; Berg et al., 2012; Brassard & Singh, 2008; Brassard & Singh, 2007; Butt et al., 2005; Calzadilla et al., 2009; Chhetri et al., 2010; Ciscar et al., 2011; Deryng et al., 2011; Giannakopoulos et al., 2009; Hermans et al., 2010; Iqbal et al., 2011; Izaurralde et al, 2005; Kim et al., 2010; Lal, 2011; Li et al., 2011; Lobell et al., 2008; Moriondo et al., 2010; Muller et al., 2010; Osborne et al., 2013; Peltonen-Sainio et al., 2011; Piao et al., 2010; Ringler et al., 2010; Rowhani et al., 2011; Schlenker & Roberts, 2009 ;Shuang-He et al., 2011; Southworth et al., 2000; Tan et al., 2010; Tao & Zhang, 2010; Tao & Zhang, 2011; Tao et al., 2009; Thornton et al., 2009; Thornton et al., 2011; Thornton et al., 2010; Tingem & Rivington, 2009 Tingem et al., 2008; Walker & Schulze, 2008; Wang et al., 2011; Xiong et al., 2009; Xiong et al., 2007.

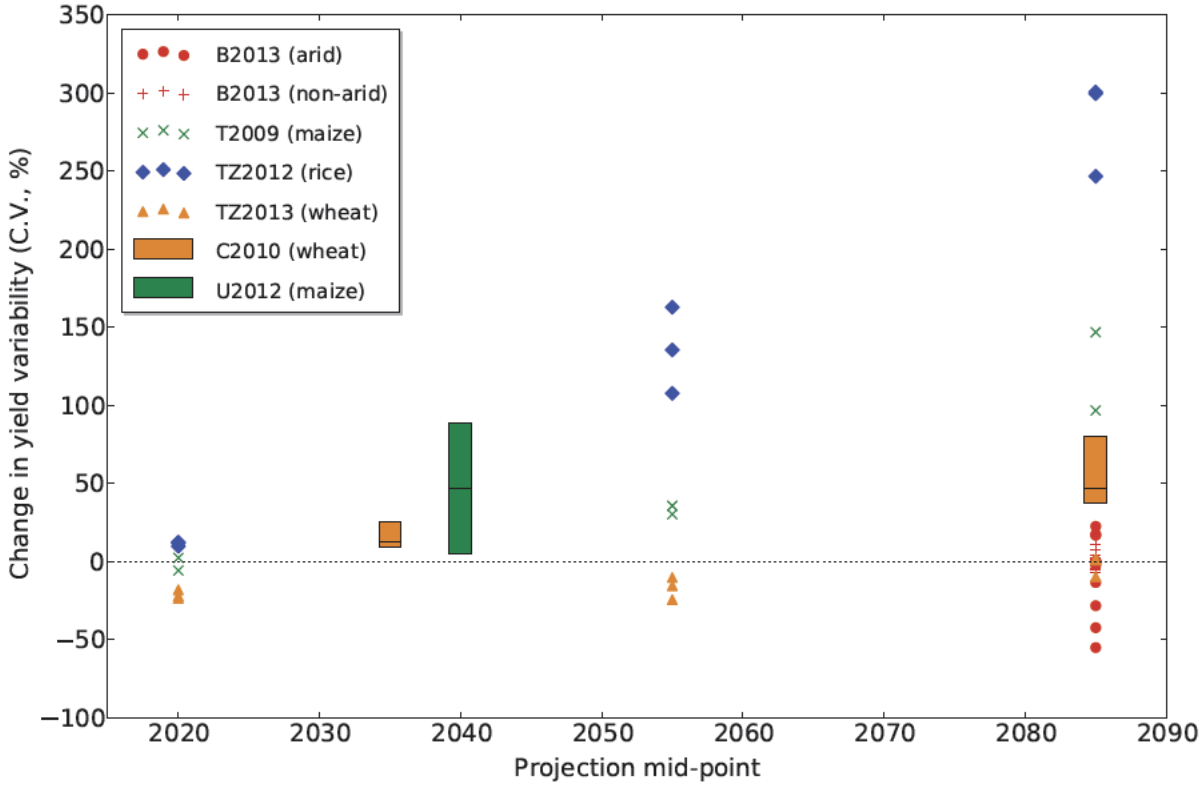


Figure 7-6: Projected percentage change in coefficient of variation (CV) of yield for wheat (gold), maize (green), rice (blue) and C_4 crops (red) taken from C2010 (Challinor et al., 2010), B2013 (Berg et al., 2013), T2009 (Tao et al., 2009), TZ2013 (Tao and Zhang, 2010), TZ2012 (Tao and Zhang, 2011) and U2012 (Urban et al., 2012). U2012 and C2012 plot multiple data points: U2012 shows the range (mean plus and minus one standard deviation) of percentage changes in CV. For C2012 paired CV changes were not available, so the box shows changes in the mean CV, the mean CV plus one standard deviation, and the mean CV minus one standard deviation. 81 datapoints are plotted in the figure, although the underlying data consist of many thousands of crop model simulations. The studies used a range of scenarios (SRES A1B, A2, A1F1 and B1). B2013 is a global study of the tropics, U2012 is for US maize, and the remaining studies are for China.

[Illustration to be redrawn to conform to IPCC publication specifications.]

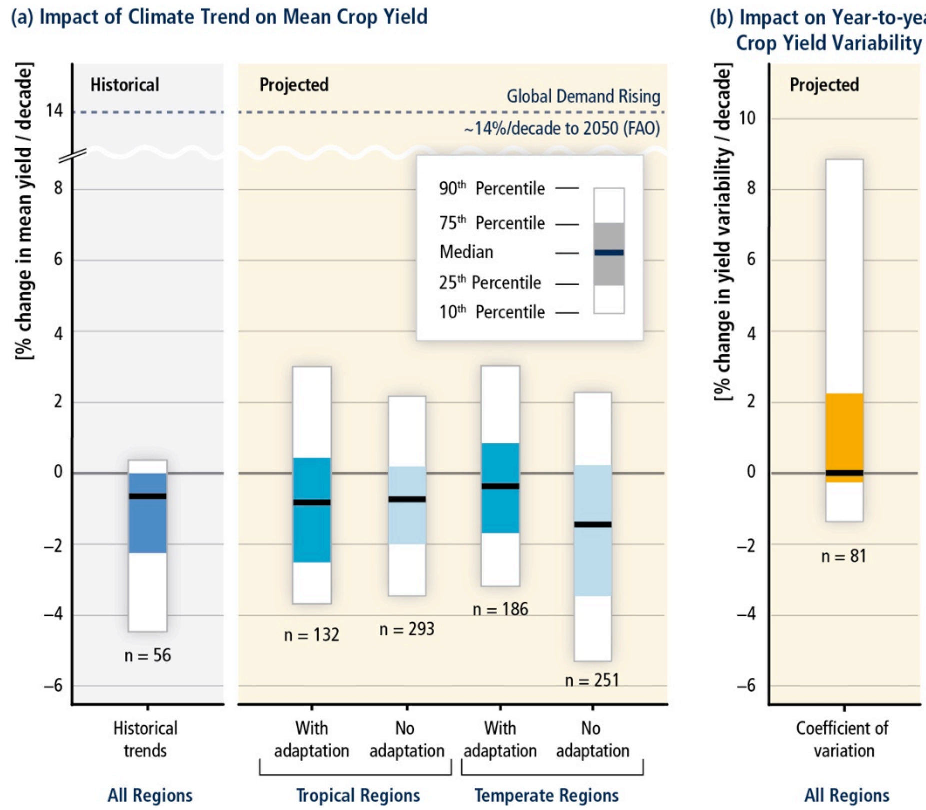


Figure 7-7: Boxplot summary of studies that quantify impact of climate and CO_2 changes on crop yields, including historical and projected impacts, mean and variability of yields, and for all available crops in temperate and tropical regions. All impacts are expressed as average impact per decade (a 10% total impact from a 50 year period of climate change would be represented as 2% per decade). References for historical impacts are given in Figure 7-2, for projected mean yields in Figure 7-5, and for yield variability in Figure 7-6. N indicates the number of estimates, with some studies providing multiple estimates. In general, decreases in mean yields and increases in yield variability are considered negative outcomes for food security. Also indicated on figure is the expected increase in crop demand of 14% per decade (Alexandratos and Bruinsma, 2012), which represents a target for productivity improvements to keep pace with demand.

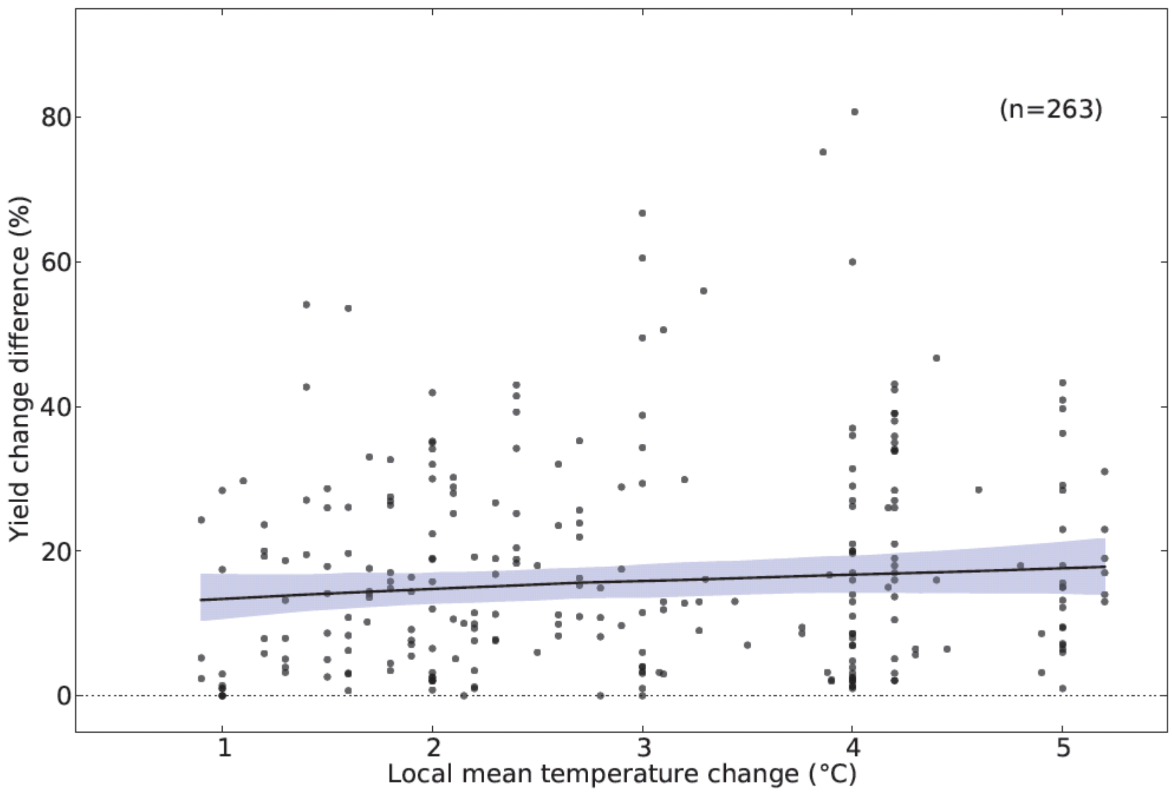


Figure 7-8: Simulated yield benefit from adaptation calculated as the difference between the yield change from baseline (%) for paired non-adapted and adapted cases as affected by temperature and aggregated across all crops. The shaded bands at the 95% confidence interval are calculated as for Fig 7.4. Data points (n=31) where assessed benefit of management changes are negative are not included as farmers are unlikely to intentionally adopt these. Data sources are the same as for Table 7-2 and only studies that examine both a 'no adaptation' and an 'adaptation' scenario are used so as to avoid the issues arising from un-paired studies documented in Fig7.4 for tropical maize. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

Chapter 8. Urban Areas

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Executive Summary

Urban climate adaptation can build resilience and enable sustainable development. (8.1, 8.2, 8.3)

Action in urban centres is essential to successful global climate change adaptation. Urban areas hold more than half the world's population and most of its built assets and economic activities. They also house a high proportion of the population and economic activities most at risk from climate change, and a high proportion of global greenhouse gas emissions are generated by urban-based activities and residents **(***medium confidence based on high agreement, medium evidence*) (8.1).

Much of key and emerging global climate risks are concentrated in urban areas. Rapid urbanization and rapid growth of large cities in low- and middle-income countries have been accompanied by the rapid growth of highly vulnerable urban communities living in informal settlements, many of which are on land at high risk from extreme weather (*medium confidence, based on high agreement, medium evidence)* (8.2, 8.3, Table 8-2 and 8-3).

Cities are composed of complex inter-dependent systems that can be leveraged to support climate change adaptation via effective city governments supported by cooperative multi-level governance. This can enable synergies with infrastructure investment and maintenance, land-use management, livelihood creation and ecosystem services protection (*medium confidence based on medium agreement, limited evidence*) (8.3, 8.4).

Urban adaptation action that delivers mitigation co-benefits is a powerful, resource-efficient means to address climate change and to realize sustainable development goals (medium confidence based on *high agreement, medium evidence*) (8.4).

Urban climate change risks, vulnerabilities, and impacts are increasing across the world in urban centres of all sizes, economic conditions and site characteristics. (8.2)

Urban climate change-related risks are increasing (including rising sea levels and storm surges, heat stress, extreme precipitation, inland and coastal flooding, landslides, drought, increased aridity, water scarcity and air pollution) **with widespread negative impacts on people** (and their health, livelihoods and assets) **and on local and national economies and ecosystems** (*very high confidence based on high agreement, high evidence*). These risks are amplified for those who live in informal settlements and in hazardous areas and either lack essential infrastructure and services or where there is inadequate provision for adaptation (8.2, Table 8-2).

Climate change will have profound impacts on a broad spectrum of infrastructure systems (water and energy supply, sanitation and drainage, transport and telecommunication)**, services** (including health care and emergency services), **the built environment and ecosystem services.** These interact with other social, economic and environmental stressors exacerbating and compounding risks to individual and household well-being (*medium confidence based on high agreement, medium evidence*) (8.2).

Cities and city regions are sufficiently dense and of a spatial scale that they influence their local micro-climate. Climate change will interact with these conditions in a variety of ways, some of which will exacerbate the level of climate risk (*high confidence, based on high agreement, high evidence*) (8.2).

Urban climate adaptation provides opportunities for both incremental and transformative development. (8.3, 8.4)

Urban adaptation provides opportunities for incremental and transformative adjustments to development trajectories towards resilience and sustainable development via effective multi-level urban risk governance, alignment of policies and incentives, strengthened local government and community adaptation capacity, synergies with the private sector and appropriate financing and institutional development. Opportunities to do so are high in many rapidly growing cities where institutions and infrastructure are being developed, though there is limited evidence of this being realised in practice (*medium confidence, based on high agreement, limited evidence*) (8.4).

Urban adaptation can enhance economic comparative advantage, reducing risks to enterprises and to households and communities (*medium confidence based on high agreement, based on medium evidence*) (8.3).

City-based disaster risk management with a central focus on risk reduction is a strong foundation on which to address increasing exposure and vulnerability and thus to build adaptation. Closer integration of disaster risk management and climate change adaptation along with the incorporation of both into local, sub-national, national and international development policies can provide benefits at all scales *(high confidence, based on high agreement, medium evidence)* (8.3).

Ecosystem-based adaptation is a key contributor to urban resilience (*medium confidence, based on high agreement (among practitioners), medium evidence*) (8. 3).

Effective urban food-security related adaptation measures (especially social safety nets but also including urban and peri-urban agriculture, local markets and green roofs) **can reduce climate vulnerability especially for low-income urban dwellers** (*medium confidence based* on *medium agreement, medium evidence*) (8.3).

Good quality, affordable, well-located housing provides a strong base for city-wide climate change adaptation minimising current exposure and loss. Possibilities for building stock adaptation rest with owners and public, private and civil society organisations (*high confidence, based on high agreement, robust evidence*) (8.3, 8.4)

Reducing basic service deficits and building resilient infrastructure systems (water supply, sanitation, storm and waste water drains, electricity, transport and telecommunications, health care, education and emergency response) **can significantly reduce hazard exposure and vulnerability to climate change, especially for those who are most at risk or vulnerable** *(very high confidence, based on high agreement, robust evidence)* (8.3).
3.8 For most key climate change associated hazards in urban areas, risk levels increase from the present (with current adaptation) to the near-term but high adaptation can reduce these risk levels significantly. It is less able to do so for the longer-term, especially under a global mean temperature increase of 4°C (Tables 8-3 and 8-6**).**

Implementing effective urban adaptation is possible and can be accelerated. (8.4)

Urban governments are at the heart of successful urban climate adaptation because so much adaptation depends on local assessments and integrating adaptation into local investments, policies and regulatory frameworks (*high confidence*) (8.4).

Well governed cities with universal provision of infrastructure and services have a strong base for building climate resilience if processes of planning, design and allocation of human, capital, and material resources are responsive to emerging climate risks (*medium confidence, based on high agreement, medium evidence*) (8.4).

Building human and institutional capacity for adaptation in local governments, including scope for reflecting on incremental and transformative adaptation pathways, accelerates implementation and improves urban adaptation outcomes (*high confidence based on high agreement, medium evidence*) (8.4).

Coordinated support from higher levels of governments, the private sector and civil society and horizontal learning through networks of cities and practitioners benefits urban adaptation (*medium confidence based on medium agreement, medium evidence*) (8.4).

Leadership within local governments and also across all scales is important in driving successful adaptation and in promoting and sustaining a broad base of support for the urban adaptation agenda *(medium confidence based on high agreement, medium evidence)* (8.4).

Addressing political interests, mobilising institutional support for climate adaptation and ensuring voice and influence to those most at risk are important strategic adaptation concerns (*medium confidence based on medium agreement, limited evidence*) (8.4).

Enabling the capacity of low-income groups and vulnerable communities, and their partnership with local governments, can be an effective urban adaptation strategy (*medium evidence based on high confidence, limited evidence*) (8.3, 8.4).

Urban centres around the world face severe constraints to raising and allocating resources to implement adaptation. In most low-and middle-income country cities, infrastructure backlogs, lack of appropriate mandates and lack of financial and human resources severely constrain adaptation action. Small urban centres often lack economies of scale for adaptation investments and local capacity to act, as they have relatively low national and international profiles (*medium confidence based on high agreement*, *medium evidence)* (8.3, 8.4).

International financial institutions provide limited financial support for adaptation in urban areas. There is limited current commitment to finance urban adaptation from different levels of government and international agencies (*medium confidence based* on *high agreement, limited evidence*) (8.4).

A scientific evidence base in each urban centre is essential for effective adaptation action. This includes local risk and vulnerability assessments and information and data with which to consider current and future risk, adaptation and development options (*medium confidence based on high agreement, medium evidence)* (8.4).

Dealing with the uncertainty associated with climate change projections and **balancing them** with actions to address **current vulnerabilities and adaptation costs helps to assist implementation** in urban areas (*medium confidence based on medium agreement, medium evidence)* (8.2, 8.4).

8.1. Introduction

8.1.1. Key Issues

Adaptation to climate change depends centrally on what is done in urban centres – which now house more than half the world's population and concentrate most of its assets and economic activities (United Nations, 2012; World Bank, 2008). As 8.4 emphasizes, this will require responses by all levels of government as well as individuals and communities, the private sector and civil society. The serious impacts of extreme weather on many urban centres each year demonstrate some of the risks and vulnerabilities to be addressed (IFRC, 2010; United Nations, 2009). Climate change will usually add to these and other risks and vulnerabilities. Urban policies also have major implications for mitigation, especially for future levels of greenhouse gas emissions and for delivering co-benefits, as discussed in WGIII. This chapter focuses on the possibilities for governments, enterprises and populations to adapt urban centres to the direct and indirect impacts of climate change.

The level of funding needed for sound urban adaptation could exceed the capacities of local and national governments and international agencies (Brugmann, 2012; Parry *et al.*, 2009). Much of the investment will have to come from individuals and households, communities and firms through their decisions to address adaptation and resilience (see Agrawala and Fankhauser, 2008; Fankhauser and Soare, 2013). This might suggest little role for governments, especially local governments. But whether these small scale decisions by households, communities and firms do contribute to adaptation depends in large part on what local governments do, encourage, support and prevent – as well as their contribution to providing required infrastructure and services. An important part of this is the provision by local governments of appropriate regulatory frameworks and the application of building standards, to ensure that the choices made by individuals, households and firms support adaptation and prevent maladaptation. For instance, land use planning and management have important roles in ensuring sufficient land for housing that avoids dangerous sites and protects key ecological services and systems (UN-Habitat, 2011a).

In reviewing adaptation needs and options for urban areas, the documentation reviewed for this Chapter points to two key conclusions. The first is how much the adaptive capacity of any city depends on: the quality of provision and coverage of infrastructure and services; the capacities for investments and land-use management; and the degree to which buildings and infrastructure meet health and safety standards. This capacity provides a foundation for city resilience on which adaptation can be built. There is little of this foundation in most urban centres in low-income and many in middle-income nations. The second conclusion is the importance of city and municipal governments acting now to incorporate climate change adaptation into their development plans and policies and infrastructure investments. This includes not only building that foundation of resilience (and its institutional, governance and financial underpinnings) but also mobilizing new resources, adjusting building and land-use regulations and continuously developing the local capacity to respond. This is not to diminish the key roles of other actors. But it will fall to city and municipal government to provide the scaffolding and regulatory framework within which other stakeholders contribute and collaborate. Thus, adaptation in urban areas depends upon the competence and capacity of local governments and a locally-rooted iterative process of learning about changing risks and opportunities, identifying and evaluating options, making decisions, and revising strategies in collaboration with a range of actors.

8.1.2. Scope of the Chapter

This chapter focuses on what we know about the potential impact of climate change on urban centres and their populations and enterprises (8.2), what measures are being taken to adapt to these changes (and protect vulnerable groups) (8.3) and what institutional and governance changes can underpin adaptation (8.4). Both this and Chapter 9 highlight the multiple linkages between rural and urban areas that have relevance for adaptation. This chapter also overlaps with Chapter 10, especially in regard to infrastructure, although this chapter focuses on urban infrastructure and in particular the infrastructure that comes within the responsibilities or jurisdiction of urban governments.

This chapter draws its urban statistics from the United Nations Population Division (see United Nations, 2012). Urban centres vary from those with few thousand (or in some nations a few hundred) inhabitants to metropolitan areas with more than 20 million inhabitants. There is no international agreement – and considerable national variation – in how urban areas are defined (see United Nations, 2012). The main differences are in how settlements with a few hundred up to 20,000 inhabitants are classified; depending on the country, some, most or all of these may be classified as urban or rural. There are also differences in how urban boundaries are set. In some places, they encompass the urban built up area or the central urban core; in others, they go well beyond the built up area and include large areas devoted to agriculture (Satterthwaite, 2007).

The issue here is whether provision for adaptation includes ‘rural’ populations living around urban centres and within urban jurisdictions. In addition, it is common for part of the workforce in larger urban centres to live outside the urban centre and to commute – and this may include many that live in settlements designated as rural. There is also no agreed definition for what constitutes a city – although the term city implies an urban centre with some economic, political or cultural importance and would not be applied to most small urban centres.

8.1.3. Context – An Urbanizing World

In 2008, for the first time, more than half the world’s population was living in urban centres and the proportion continues to grow (United Nations, 2012). Three quarters of the world’s urban population and most of its largest cities are now in low- and middle-income nations. A comparison of Figures 8.1 and 8.2 highlights the increase in the number of large cities from 1950 to what is projected for 2025. UN projections suggest that almost all the increase in the world's population up to 2050 will be in urban centres in what are currently low- and middle-income nations (see Table 8-1). Most of the GDP of most nations and globally is generated in urban centres and most new investments have concentrated there (Satterthwaite *et al.*, 2010; World Bank, 2008). Clearly, just in terms of the population, economic activities, assets and climate risk they increasingly concentrate, adapting urban areas to climate change requires serious attention.

[INSERT TABLE 8-1 HERE
Table 8-1: The distribution of the world's urban population by region, 1950–2010 with projections to 2030 and 2050. Source: Derived from statistics in United Nations, 2012.]

[INSERT FIGURE 8-1 HERE
Figure 8-1: Global and regional maps showing the location of urban agglomerations with 750,000 plus inhabitants in 1950. Source: Derived from statistics in United Nations, 2012.]

[INSERT FIGURE 8-2 HERE
Figure 8-2: Global and regional maps showing the location of urban agglomerations with 750,000 plus inhabitants projected for 2025. Source: Derived from statistics in United Nations, 2012.]

Most urbanization is underpinned by an economic logic. All wealthy nations are predominantly urbanized and rapid urbanization in low- and middle-income nations is usually associated with rapid economic growth (Satterthwaite *et al.*, 2010; World Bank, 2008). Most of the world's largest cities are in its largest economies (*ibid*). If rapid urbanization and rapid city population growth is associated with economic success, it suggests that more resources should be available there to support adaptation. But as discussed in 8.3, this is rarely the case. In most urban centres in low- and middle-income nations including many successful cities, local governments have been unable to manage their economic and physical expansion and there are large deficits in provision for infrastructure and services that are relevant to climate change adaptation. Around one in seven people in the world live in poor quality, overcrowded accommodation in urban areas with inadequate provision (or none) for basic infrastructure and services, mostly in informal settlements (Mitlin and Satterthwaite, 2013; UN-Habitat, 2003a). Much of the health risk and vulnerability to climate change is concentrated in these settlements (Mitlin and Satterthwaite, 2013). So this chapter is concerned not only with an adaptation deficit for but also with a development deficit that is relevant to this risk and vulnerability.

Many aspects of urban change in recent decades have been so rapid that they have overwhelmed government capacity to manage them. Among the 611 cities with over 750,000 inhabitants in 2010, 47 had populations that had grown more than twenty fold since 1960; in 120, the growth was more than tenfold (statistics in this paragraph are drawn from data in United Nations, 2012). The increasing concentration of the world's urban population and its largest cities outside the highest income nations represents an important change. Over the 19th and 20th centuries, most of the world's urban population and most of its largest cities were in its most prosperous nations. Now, urban areas in low- and middle-income nations have close to two-fifths of the world's total population, close to three-quarters of its urban population, and most of its large cities. In 2011, of the 23 'mega-cities' (with populations over 10 million), only 5 were in high-income nations (two in Japan, two in USA, one in France). Of the remaining 18, four were in China, three in India and two in Brazil. But over three fifths of the world's urban population is in urban centres with less than 1 million inhabitants and it is here that much of the growth in urban population is occurring.

Underlying these population statistics are large and complex economic, social, political and demographic changes, including the multiplication in the size of the world's economy and the shift in economic activities and employment structures from agriculture to industry and services (and within services to information production and exchange) (Satterthwaite, 2007). One of the most significant changes has been the growth in the size and importance of cities whose economies increased and changed as a result of globalization (Sassen, 2012). Another is the number of large cities that are now centres of large extended metropolitan regions.

One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centres. There are tens of thousands of urban centres worldwide with very large and measureable differences in population, area, economic output, human development, quality and coverage of infrastructure and services, ecological footprint and greenhouse gas emissions. The differences in adaptive capacity are far less easy to quantify. Table 8-2 illustrates differences in adaptive capacity and factors that influence it. It indicates how each urban centre falls within a spectrum in at least four key factors that influence adaptation: local government capacity; the proportion of residents served with risk-reducing infrastructure and services; the proportion living in housing built to appropriate health and safety standards; and the levels of risk from climate change's direct and indirect impacts. This chapter and Table 8-2 also draw on detailed case studies to illustrate this diversity – New York (Solecki, 2012), Durban (Roberts and O'Donoghue, 2013) and Dar es Salaam (Kiunsi, 2013). In 8.5, there are tables of current and indicative future climate risks for Dar es Salaam, Durban, London and New York.

[INSERT TABLE 8-2 HERE
Table 8-2: The large spectrum in the capacity of urban centers to adapt to climate change.]

Many attributes of urban centres can be measured and compared. As noted above, populations vary from a few hundred to more than 20 million. Areas vary from less than one to thousands of square kilometres. Average life expectancy at birth varies from over 80 years to under 40 years, and under-five mortality rates vary by a factor of 20 or more (Mitlin and Satterthwaite, 2013). Average per capita incomes vary by a factor of at least 300; so too does the funding available to local governments per person (UCLG, 2010). Greenhouse gas emissions per person (in tonnes of carbon dioxide equivalent) vary by more than 100 (Dodman, 2009; Hoornweg *et al.*, 2011).

There are large differences between urban centres in the extent to which their economies are dependent on climate-sensitive resources (including commercial agriculture, water and tourism).There are also large variations in the scale and nature of impacts from extreme weather. As Table 8-2 suggests, there are urban indicators relevant for assessing the resilience to climate change impacts that urban areas have acquired (including the proportion of the population with water piped to their homes, sewers, drains, health care and emergency services); it is more of a challenge to find indicators for the climate change related risks and for the quality and capacity of government.

Recent analyses of disaster impacts show that a high proportion of the world's population most affected by extreme weather events is concentrated in urban centres (IFRC, 2010; United Nations, 2009; United Nations, 2011). As shown in Table 8-2, a high proportion of these urban centres lack both local governments with the capacity to reduce disaster risk, and much of the necessary infrastructure. Their low-income households may require particular assistance due to greater exposure to hazards, lower adaptive capacity, more limited access to infrastructure or insurance, and fewer possibilities to relocate to safer accommodation, compared to wealthier residents.

All successful urban centres have had to adapt to environmental conditions and available resources, although local resource constraints have often been overcome by drawing on resources and using sinks from 'distant elsewheres' (McGranahan, 2007; Rees, 1992); this includes importing goods that are resource intensive and whose fabrication involves large greenhouse gas emissions. The growth of urban population over the last century has also caused a very large anthropogenic transformation of terrestrial biomes. Urban centres cover only a small proportion of the world's land surface – according to Schneider *et al.* (2009) only 0.51 per cent of the total land area; only in Western Europe do they cover more than 1 per cent. However, their physical and ecological footprints are much larger. The net ecological impact of urban centres includes the decline in the share of wild and semi-natural areas from about 70 per cent to less than 50 per cent of land area, largely to accommodate crop and pastoral land to support human consumption. It has led not only to a decrease in biodiversity but to fragmentation in much of the remaining natural areas and a threat to the ecological services that support both rural and urban areas. Future projections (Seto *et al.*, 2012) suggest that if current trends continue, urban land cover will increase by 1.2 million square kilometres by 2030, nearly tripling global urban land area between 2000 and 2030. This would mean a "considerable loss of habitats in key biodiversity hotspots", destroying the green infrastructure that is key in helping areas adapt to climate change impacts (*ibid.*, p. 16083) as well as increasing the exposure of population and assets to higher risk levels.

Many of the challenges and opportunities for urban adaptation relate to the central features of city life – the concentration of people, buildings, economic activities and social and cultural institutions (Romero-Lankao and Dodman, 2011). Agglomeration economies are usually discussed in relation to the advantages for enterprises locating in a particular city. But the concentrations of people, enterprises and institutions in urban areas also provide potential agglomeration economies in lower unit costs for piped water, sewers, drains and a range of services (solid waste collection, schools, health care, emergency services, policing) and in the greater capacity for people, communities and institutions to respond collectively (Hardoy *et al.*, 2001). At the same time, the advantages that come with these concentrations of people and activities are also accompanied by particular challenges – for instance, the management of storm and surface run-off and measures to reduce heat islands. Large cities concentrate demand and the need for ecological services and natural resources (water, food and biomass), energy and electricity, and many city enterprises rely on lifeline infrastructure and supply chains that can be disrupted by climate change (see 8.3.3, also United Nations, 2013).

Thus, the increasing concentration of the world's population in urban centres means greater opportunities for adaptation but more concentrated risk if they are not acted on. Many urban governments lack the capacity to do so, especially those in low- and lower-middle income nations. The result is large deficiencies in infrastructure and services. Urban centres in high-income nations, although much better served, may also face particular challenges – for instance, aging infrastructure and the need to adapt energy systems, building stock, infrastructure and services to the altered risk set that climate change will bring (see Zimmerman and Faris (2010) and Solecki (2012) for discussions of this for New York). Many studies have shown that working with a range of government and civil society institutions at local and supra-local levels increases the effectiveness of urban adaptation efforts; support and enabling frameworks from higher levels of government were also found to be helpful (see 8.4 and many of the studies listed in Box 8-1).

8.1.4. Vulnerability and Resilience

For each of the direct and indirect impacts of climate change, there are groups of urban dwellers that face higher risks (illness, injury, mortality, damage to or loss of homes and assets, disruption to incomes) (Hardoy and Pandiella, 2009; Mitlin and Satterthwaite, 2013). Age may be a factor (for instance infants and elderly people are more sensitive to particular hazards such as heat stress) or health status (those with particular diseases, injuries or disabilities may be more sensitive to these impacts). Or it may be that they live in buildings or in locations facing greater risks – for instance on coasts or by rivers with increased flood risks – or that they lack coping capacities. Women may face higher risks in their work and constraints on adaptation if they face discrimination in access to labour markets, resources, finance, services and influence (see Cross-chapter box on gender and other sources of marginalization). These are often termed vulnerable groups – although, to state the obvious, they are only vulnerable to direct climate change impacts to the extent that the hazard actually poses a risk. Remove people's exposure to the hazard (e.g. provide drains that prevent flooding) and there is limited or no impact. Infants may face serious health risks when water supplies are contaminated by flooding, but rapid and effective treatment for diarrhoea and quickly re-establishing availability of drinking quality water greatly reduces impacts (Bartlett, 2008). Adaptations by individuals, households, communities, private enterprises or government service providers can all reduce risks.

Adaptation in a particular area or settlement may have clear benefits for the inhabitants there, but can also have knock-on effects on the wellbeing of inhabitants in other areas. Diverting a river course or building an embankment to protect new development may prevent flooding in one location, but may cause or increase flooding somewhere else (see Alam and Rabbani, 2007 for Dhaka; Revi, 2005 for Mumbai).

Assessments of vulnerability to climate change draws on assessments in other contexts – including the vulnerability of low-income groups to stresses and shocks (see, for instance, Chambers, 1989 and Pryer, 2003) and to disasters (see Cannon, 1994; Manyena, 2006). The term is generally used in relation to an inability to cope with external changes including avoiding harm when exposed to a hazard. This includes people's inability to avoid the hazard (exposure), anticipate it and take measures to avoid it or limit its impact, cope with it and recover from it (Hardoy and Pandiella, 2009). Vulnerable groups may be identified on the basis of any of these four factors. The definition of resilience used in this Report when applied to urban centres means the ability of urban centres (and their populations, enterprises and governments) and the systems on which they depend to anticipate, reduce, accommodate or recover from the effects of a hazardous event in a timely and efficient manner (see the glossary).

The term vulnerability is also applied to sectors, including food processing, tourism, water, energy and mobility infrastructure and their cross-linkages, for instance, the dependency of perishable commodities on efficient transport. Much tourism is sensitive to climate change, which can damage key tourist assets such as coral reefs and beaches or make particular locations less attractive to tourists because of more extreme weather. The term is also applied to natural systems/ecosystems (e.g. mangroves, coastal wetlands, urban tree canopy). If the adaptive capacity of these systems is increased, they can also provide natural protection from the impacts of climate change in urban areas (see for instance 8.2.4.5 and 8.3.3.7 for more details).

8.1.4.1. Differentials in Risk and Vulnerability within and between Urban Centres

In urban centres where virtually all buildings meet health and safety standards, where land-use planning prevents developments on sites at risk and where there is universal provision for infrastructure and basic services, the exposure differentials between high- and low-income groups to climate-related risk are quite low. Having a low-income and few assets in such urban centres does not necessarily imply greater vulnerability to climate change (Mitlin and Satterthwaite, 2013). But typically, the larger the deficit in infrastructure and service provision, the larger the differentials in exposure to most climate change impacts between income groups. Low-income groups in low- and middle-income nations are often disproportionately vulnerable because of poor quality and insecure housing, inadequate infrastructure and lack of provision for health care, emergency services and disaster risk reduction (*ibid.,* IFRC, 2010; IPCC, 2012; UN-Habitat, 2011a; United Nations, 2009). Most deaths from disasters are concentrated in low- and middle-income countries – including over 95 per cent of deaths from natural disasters between 1970 and 2008 (IPCC, 2012). More than 95 per cent of the deaths from storms and floods registered on the EM-DAT from 2000 to September 2013 were in low- and middle-income nations.[1]

[FOOTNOTE 1: These are drawn from data in the The International Disaster Database EM DAT accessed on 16 September 2013.]

An analysis of annual fatalities from tropical cyclones showed these to be heavily concentrated in low-income nations even though there was high exposure in many upper-middle and high-income nations (and these nations had larger economic losses) (United Nations, 2009). These analyses do not separate rural and urban populations – but there is a growing body of evidence that most urban deaths from extreme weather events are in low-income and lower-middle income countries (*ibid.*, IFRC, 2010). Analyses of risks across many cities usually show the cities at highest risk from extreme weather or particular kinds of such weather (e.g., floods) to be primarily in high-income countries (see Hallegatte *et al.*, 2013; Munich Re, 2004). But this is because these analyses are based on estimates of economic costs or economic losses. If they were based instead on deaths and injuries, the ranking would change fundamentally (see also Balica *et al.*, 2012). The official statistics on disaster deaths are also known to considerably under-state total deaths, in part because many deaths go unrecorded, in part because of the criteria that a disaster event has to meet to be included (one of the following criteria must be fulfilled: ten or more people reported killed; 100 or more people reported affected; declaration of a state of emergency; or call for international assistance) (United Nations, 2009).

There are dramatic examples of extreme weather events in high-income countries with very large impacts, including high mortality. But the analyses in United Nations (2009) and IFRC (2010), and the reports of deaths from extreme weather in many of the case studies listed in Box 8-1, suggest that most extreme weather disaster deaths in urban centres are in low- and lower-middle income nations, and that risks are concentrated in informal settlements. As noted by IPCC (2012), the occupants of these settlements are typically more exposed to climate events with limited or no hazard-reducing infrastructure, low-quality housing and limited capacity to cope.

Where provision for adequate housing, infrastructure and services is most lacking, the capacity of individuals, households and community organizations to anticipate, cope and recover from the direct and indirect losses and impact of disasters (of which climate-related events are a sub-set) becomes increasingly important (see 8.4). The effectiveness of early warning systems, the speed of response and the effectiveness of post-disaster response is especially important to those who are more sensitive and have less coping capacity. The effectiveness of such responses depends on an understanding of the specific vulnerabilities, needs and priorities of different income-groups, age groups and groups that face discrimination, including that faced by women and by particular social or ethnic groups (UN-Habitat, 2011a).

8.1.4.2. Understanding Resilience for Urban Centres in Relation to Climate Change

In relation to disasters, resilience is usually considered to be the opposite of vulnerability, but vulnerability is often discussed in relation to particular population groups while resilience is more often discussed in relation to the systemic capacity to protect them and reduce the impact of particular hazards through infrastructure or climate-risk sensitive land-use management. In recent years, a literature has emerged discussing resilience to climate change for urban centres and what contributes to it (see Brown *et al.*, 2012; da Silva *et al.*, 2012; Leichenko, 2011; Moench *et al.*, 2011; Muller, 2007; Pelling, 2011a). Addressing resilience for cities is more than identifying and acting on specific climate change impacts. It looks at the performance of each city's complex and interconnected infrastructure and institutional systems including interdependence between multiple sectors, levels and risks in a dynamic physical, economic, institutional and socio-political environment (Gasper *et al.*, 2011; Kirshen *et al.*, 2008). When resilience is considered for cities, certain systemic characteristics are highlighted – for instance flexibility, redundancy, responsiveness, capacity to learn and safe failure (Brown *et al.*, 2012; da Silva *et al.*, 2012; Moench *et al.*, 2011; Tyler *et al.*, 2010), as well as take account of the multiple inter-dependencies between different sectors (see 8.2).

When a specific city is being considered, the level and forms of resilience are often related to specific local factors, services and institutions – for instance, for each district in a city, will the storm and surface drains cope with the next heavy rainfall? During hot days, will measures to help those at risk from heat stress reach all high-risk groups? (see the cross-chapter box on heat stress and heat waves for more details). Here, resilience is not only the ability to recover from the impact but the ability to avoid or minimize the need to recover and the capacity to withstand unexpected or unpredicted changes (United Nations, 2011). An important aspect of resilience is the functioning of institutions to make this possible and the necessary knowledge base (da Silva *et al.*, 2012).The emerging literature on the resilience of cities to climate change also highlights the need to focus on resource availabilities and sinks beyond the urban boundaries. It may also require coordinated actions by institutions in other jurisdictions or higher levels of government (for instance watershed management upstream of a city to reduce flood risks; see Brown *et al.* (2012), Ramachandraiah (2011). There are also the slow onset impacts that pose particular challenges and that may also be outside the jurisdiction of urban governments – for instance, the impact of drought on agriculture, which can raise food prices and reduce rural incomes and demand for urban services.

Resilience to extreme weather for urban dwellers is strongly influenced by factors mentioned already - the quality of buildings, the effectiveness of land-use planning and the quality and coverage of key infrastructure and services. It is also influenced by the effectiveness of early warning systems and public response measures (IFRC, 2010; UN-Habitat, 2011a) and by the proportion of households with savings and insurance and able to afford safe, healthy homes. Safety nets for those with insufficient incomes are also important, along with the administrative capacity to ensure these reach those in need. Urban governments have importance for most of this, although their capacity to provide usually depends on the revenue raising powers and legislative and financial support from higher levels of government. These in turn are driven in part by political pressure from urban dwellers and innovation by city governments. Private companies or non-profit institutions may provide some of these but the framework for provision and quality control is provided by local government or local offices or national or provincial government.

Cities in high-income nations and many in middle-income nations have become more resilient to extreme weather (and other possible catalysts for disasters) through a range of measures responding to risks and to the political processes that demand such responses (IFRC, 2010; Satterthwaite, 2013; UN-Habitat, 2011a). The universal provision of piped water, sewers, drains, health care and emergency services and standards set and enforced on housing quality and infrastructure were not a response to climate change but what was built over the last 100-150 years in response to the needs and demands of residents. This has produced what can be termed accumulated resilience in the built environment to extreme weather and built the capacity of local governments to act on risk reduction (see for instance Hardoy and Ruete (2013) on Rosario, Argentina). In addition, it helped build the institutions, finances and governance systems that can support climate change adaptation (Satterthwaite, 2013). Building and infrastructure standards can be adjusted as required (if there is infrastructure in place that can be adjusted - for instance by increasing capacity for storm and surface water drainage systems). Existing levels of service provision can be modified to take into account new risks or risk levels, as can city planning and land-use management (for instance, by keeping city expansion away from areas facing higher risk levels). Private sector investments can support these kinds of adjustments (for instance, changing insurance premiums and coverage) (IFRC, 2010; UN-Habitat, 2011a; United Nations, 2013). All of these provide the foundation on which to build adaptive capacity to withstand climate-change related direct and indirect impacts.

Whether this will happen depends on the willingness of urban governments to take this on, the demands of local inhabitants and their capacity to organize and press for change, and the capacity for learning and cooperation within local institutions. Obviously, it also depends on global agreements that slow and stop the increases in risk from GHG emissions and other drivers of climate change. Many cities with accumulated resilience may still not be equipped to respond to the changed hazards and risks associated with climate change (IPCC, 2012). The issue here becomes whether the institutions and political pressures that built the accumulated resilience are able to shift to *resilience building as a directed process* – and to respond dynamically and effectively to evolving and changing climate-related risks (and the evolving and changing knowledge bases that supports this).

For urban centres with little accumulated resilience, resilience as a process is also important, both to help reduce over time the (often very large) deficiencies in most or all the infrastructure, services and regulatory frameworks that provide resilience in high-income nations, and to build resilience to climate change impacts (see Table 8-2). For around a third of the world's urban population, this has to be done in a context of limited incomes and assets and poor living conditions and little current coping capacity to stresses or shocks (IPCC, 2012; United Nations, 2009). Just an increase in the price of food staples, a drop in income or a new cost, like medicine for a sick family member, can quickly mean inadequate food, hunger and reduced capacity to work (Mitlin and Satterthwaite, 2013).

This implies the need for a specific perspective on how climate change adaptation must be supported. It highlights the intimate relationship between resilience to climate change impacts and the quality of governance, especially local governance. The government's capacity and willingness to listen to, work with, support and serve those who lack resilience is fundamental (IPCC, 2012). This is demonstrated by the many successful partnerships between local government and grassroots organizations formed by residents of informal settlements that have built or improved homes and neighborhoods (see 8.4).

Thus, resilience can be considered in relation to individuals/households, communities and urban centres. In each of these, it includes the capacity to undertake anticipatory adaptation - action that avoids or reduces a climate change impact, for instance by living in a safe location, having a safe house, having risk reducing infrastructure. It also includes reactive adaptation to cope with the impact of an event, to 'bounce back' to the previous state (Shaw and Theobald, 2011). For urban centres, 'bouncing back' includes the government capacity to rapidly restore key services and repair infrastructure. Ideally, for climate change adaptation, responses by urban populations, enterprises and governments should allow 'bounce forward' to a more resilient state. This is discussed in disaster risk reduction and is termed 'building-back better' (Lyons, 2009). This is part of the shift from resilience to transformative adaptation shown in Table 8-2 where urban centres have integrated their development, disaster risk reduction and adaptation policies and investments within an understanding of the need for mitigation and sustainable ecological footprints (see also Manyena *et al.*, 2011; Pelling and Dill, 2010; Shaw and Theobald, 2011).

8.1.5. Conclusions from the Fourth Assessment (AR4) and New Issues Raised by this Chapter

AR4's chapter on Industries, Settlements and Human Society (Wilbanks *et al.*, 2007) notes that variability in environmental conditions has always been a given, but that when change is more extreme, persistent or rapid than has been experienced in the past, especially if it is not foreseen and capacities for adaptation are limited, the risks will increase [7.1.1]. The chapter also noted that, except for abrupt extreme events, climate change impacts are not currently dominant issues for urban centres [7.1.3]. Their importance lies in their interaction with other stressors, which may include rapid population growth, political instability, poverty and inequality, ineffective local governments, jurisdictional fragmentation and aging or inadequate infrastructure [7.2]. Key challenges identified for turning attention to adaptation include the difficulties of estimating and projecting the magnitudes of climate risk in particular places and sectors with precision and a weak knowledge base on the costs of adaptation (issues that are still challenges today).

Wilbanks *et al.* (2007) describe how the interactions between urbanization and climate change have led to concentrations of urban populations in low-income nations with weak adaptive capacity. They also describe the interactions between climate change and a globalized economy with long supply chains, resulting in impacts spreading from directly affected areas and sectors to other areas and sectors through complex linkages [7.2]. Many impacts will be unanticipated and overall effects are poorly estimated when only direct impacts are considered. Key global vulnerabilities include interregional trade and migration patterns. This Chapter also describes how climate change impacts and most vulnerabilities are influenced by local contexts, including geographic location, the climate sensitivity of enterprises located there, development pathways and population groups unable to avoid dangerous sites and homes [7.3; 7.4.3]. Key risks are most often related to climate phenomena that exceed thresholds for adaptation (e.g. extreme weather or abrupt changes) and limited resources or institutional capacities to reduce risk and cope (for instance, with increased demands on water and energy supplies and often on health care and emergency response systems).

Individual adaptation may not produce systemic adaptation. In addition, adaptation of systems may not benefit all individuals or households, because of the different vulnerability of particular groups and places [7.6.6]. Adaptation will be well served by a greater awareness of threats and alternatives beyond historical experience and current access to finance. Technological innovation for climate adaptation comes largely from industry and services that are motivated by market signals, which may not be well matched with adaptation needs and residual uncertainties. Many are incremental adjustments to current business activities.

For the types of infrastructure most at risk – including most transport, drainage and electricity transmission systems and many water supply abstraction and treatment works, reserve margins can be increased and back-up capacity developed [7.6.4]. Adaptation of infrastructure and building stock often depends on changes in the institutions and governance framework e.g. in planning regulations and building codes. Climate change has become one of many changes to be understood and planned for by local managers and decision makers [7.6.7]. For instance, planning guidance and risk management by insurers will have roles in locational choice for industry.

Since AR4, a much larger and more diverse literature has accrued on current and potential climate change risks for urban populations and centres (see 8.2). The literature on urban ‘adaptation’ and on building resilience at city and regional scales has also expanded, (see 8.3 and 8.4) including work on urban centres in low- and middle-income nations (see Box 8-1). Far more city governments have published documents on adaptation. There is more engagement with urban adaptation by some professions, including architects, engineers, urban planners and disaster risk reduction specialists (see da Silva, 2012; Engineering the Future, 2011; Engineers Canada, 2008; UN-Habitat, 2011a; United Nations, 2009). There are also assessments and books that focus specifically in climate change and cities with a strong focus on adaptation (see Bicknell *et al.*, 2009; Bulkeley, 2013; Cartwright *et al.*, 2012; Rosenzweig *et al.*, 2011; UN-Habitat, 2011a; Willems *et al.*, 2012).

This makes a concise and comprehensive summary more difficult. But it has also allowed for more clarity on what contributes to resilience in urban centres and systems. Specifically, there is now:

- a more detailed understanding of key urban climate processes, including drivers of climate change, and improved analytical and down-scaled integrated assessment models at regional and city scale;
- a more detailed understanding on the governance of adaptation in urban centres and the adaptation responses being considered or taken. This includes a large and important grey literature produced by or for city governments and some international agencies and in many high-income and some middle-income nations, support for this from higher levels of government;
- more nuanced understanding of the many ways in which poverty and discrimination exacerbates vulnerability to climate impacts (see also Chapter 13);
- more detailed studies on particular built environment responses to promote adaptation (see for instance the growth in the literature on green and white roofs);
- more case studies of community-based adaptation and its potential contributions and limitations;

- more consideration of the role of ecosystem services and of green (land) and blue (water) infrastructure in adaptation;
- more consideration of the financing, enabling and supporting of adaptation for households and enterprises;
- more on learning from innovation in disaster risk reduction;
- a greater appreciation of the inter-dependencies between different infrastructure networks and of the importance of 'hard' infrastructure and of the institutions that plan and manage it;
- more examples of city governments and their networks contributing to national and global discussions of climate change adaptation (and mitigation), including establishing voluntary commitments (see for instance the Durban Adaptation Charter for local governments) and engaging with the Conference of Parties.

A range of key uncertainties and research priorities emerge from the literature reviewed in this Chapter:

- the limits to understanding and predicting impacts of climate change at a fine grained geographic and sectoral scale
- inadequate knowledge on the vulnerabilities of urban citizens, enterprises and centres to the direct impacts of climate change, to second and third order impacts and to the interdependence between systems;
- inadequate knowledge on the vulnerability of the built environment, buildings, building components, building materials and the construction industry to the direct and indirect impacts of climate change and of the most effective responses for new-build and for retrofitting;
- inadequate knowledge on the adaptation potentials for each urban centre (and its government) and their costs, and on the limits on what adaptation can achieve (informed by a new literature on loss and damage);
- serious limitations on geophysical, biological and socio-economic data needed for adaptation at all geographic scales, including data on nature-society links and local (fine-scale) contexts (see WMO, 2008) and hazards;
- uncertainties about trends in societal, economic and technological change with or without climate change including the social and political underpinnings of effective adaptation;
- understanding the different impacts and adaptation responses for rapid and slow onset disasters;
- developing the metrics for measuring and monitoring success in adaptation in each urban centre:
  - human deaths and injuries from extreme weather
  - number of permanently or temporarily displaced people and others directly and indirectly affected
  - impacts on properties, measured in terms of numbers of buildings damaged or destroyed
  - impacts on infrastructure, services and lifelines
  - impacts on ecosystem services
  - impacts on crops and agricultural systems and on disease vectors
  - impacts on psychological well-being and sense of security
  - financial or economic loss (including insurance loss)
  - impacts on individual, household and community coping capacities and need for external assistance.

8.2. Urbanization Processes, Climate Change Risks, and Impacts

8.2.1. Introduction

This section assesses the connections between urbanization and climate change in relation to patterns and conditions of climate risk, impact, and vulnerability. The focus is on urbanization's local, regional and global environmental consequences and the processes that may lead to increased risk exposure, constrain people in high-risk livelihoods and residences, and generate vulnerabilities in critical infrastructure and services. Understanding urbanization and associated risk and vulnerability distributions is critical for an effective response to climate change threats and their impacts (Bicknell *et al.*, 2009; Bulkeley, 2010; Romero-Lankao and Qin, 2011; Solnit, 2009; Vale and Campanella, 2005). It is also critical for the promotion of sustainable urban habitats and the transition to increased urban resilience. There is a particular interest here in the ability of cities to respond to environmental crises, and the resilience and sustainability of cities (Solecki *et al.*, 2011; Solecki, 2012).

The section assesses the direct impacts of climate change on urban populations and urban systems. Together, with shifts in urbanization, these direct impacts change the profile of societal risk and vulnerability. Both can alter transition pathways that lead towards greater resilience and sustainable practices and the basis of how such practices are managed within a community. Understanding and acting on the connections between climate change and urbanization are also crucial since changes in one can affect the other. We investigate a range of direct impacts including those on physical and ecological systems, social and economic systems, and coupled human-natural systems. Where relevant to understanding, cascading impacts (where systems are tightly coupled) and secondary (indirect) impacts also are noted.

8.2.2. Urbanization – Conditions, Processes, and Systems within Cities

8.2.2.1. Magnitude and Connections to Climate Change

The spatial, temporal, and sustainability-related qualities of urbanization are important for understanding the shifting, complex interactions between climate change and urban growth. Given the significant and usually rising levels of urbanization (see 8.1.3), a growing proportion of the world's population will be exposed to the direct impacts of climate change in urban areas (de Sherbinin *et al.*, 2007; Revi, 2008; UN-Habitat, 2011a). Urban centres in Africa, Asia, Latin America with less than a million inhabitants are where most population growth is expected (United Nations, 2012) but these smaller centres are "often institutionally weak and unable to promote effective mitigation and adaptation actions".(Romero-Lankao and Dodman, 2011, p. 114).

Urbanization alters local environments via a series of physical phenomena that can result in local environmental stresses. These include urban heat islands (higher temperatures, particularly at night, in comparison to outlying rural locations) and local flooding that can be exacerbated by climate change. It is critical to understand the interplay between the urbanization process, current local environmental change and accelerating climate change. For example, in the past, long-term trends in surface air temperature in urban centres have been found to be associated with the intensity of urbanization (Chen *et al.*, 2011; Fujibe, 2008; Fujibe, 2011; He *et al.*, 2007; Iqbal and Quamar, 2011; Jung, 2008; Kalnay *et al.*, 2006; Kolokotroni *et al.*, 2010; Ren *et al.*, 2007; Rim, 2009; Sajjad *et al.*, 2009; Santos and Leite, 2009; Stone, 2007; Tayanç *et al.*, 2009). Climate change can influence these microclimate and localized regional climate dynamics. For example, urbanization (micro scale to meso scale) can strengthen and/or increase the range of the local urban heat island (UHI) altering small scale processes, such as a land-sea breeze effect, katabatic winds, etc., and modifying synoptic scale meteorology (e.g., changes in the position of high pressure systems in relation to UHI events). Climate modeling exercises indicate an 'urban effect' that leads locally to higher temperatures. Building material properties are influential in creating different urban climate temperature regimes, which can alter energy demand for climate control systems in buildings (Jackson *et al.*, 2010).

The dense nature of many large cities has a pronounced influence on anthropogenic heat emissions and surface roughness, linked to the level of wealth, energy consumption and micro and regional climate conditions. Anthropogenic heat fluxes for large cities can be very high: a global analysis indicates up to 50-500 W m^{-2} (Allen *et al.*, 2011; Flanner, 2009) in London (Iamarino *et al.*, 2012) and in Singapore (Quah and Roth, 2012) with values locally reaching 1500 W m^{-2} in Tokyo (Ichinose *et al.*, 1999). Strong seasonal, diurnal and meteorological variability in temperature also influence the level of significance of urbanization-related changes on specific cities.

The large spatial extent and significant amount of built environment of megacities (10 million or more inhabitants) can have significant impacts on the local and regional energy balance and associated weather, climate, and related environmental qualities such as air quality. Grimmond (2011) found increasing evidence that cities can influence weather (e.g., rainfall, lightning) through complex urban land use–weather–climate directional feedbacks (see also Ohashi and Kida, 2002). Spatially massive urban centres also can affect downwind locations by raising temperature and negatively impacting air quality (Bohnenstengel *et al.*, 2011). Megacity impact on air flows has been modeled for New York and Tokyo (Holt and Pullen, 2007; Holt *et al.*, 2009; Thompson *et al.*, 2007). Megacity-coastal interactions may impact the hydrological cycle and pollutant removal processes through the development of fog, clouds, and precipitation in cities and adjoining coastal areas (Ohashi and Kida, 2002; Shepherd *et al.*, 2002). Other modeling efforts define building density and design and the scale of urban development as important local determinants of the influence of urbanization on local temperature shifts (Oleson, 2012; Trusilova *et al.*, 2008).

8.2.2.2. Spatiality and Temporal Dimensions

Spatial settlement patterns are a critical factor in the interactions among urbanization, climate-related risks, and vulnerability. One aspect is density, ranging from concentrated to dispersed, with most planned urban settlements decreasing in population density with distance from the core (Seto *et al.*, 2012; Solecki and Leichenko, 2006). In cities with large fringe and unplanned settlements, this pattern can be reversed. In both cases, urban growth is experienced through horizontal expansion and sprawl (United Nations, 2012), fostering extensive networks of critical infrastructure, which are frequently vulnerable to climate change (Rosenzweig *et al.*, 2011; Solecki *et al.*, 2011). Rapid urban population growth in the last decade also has been increasingly marked by growth in vertical density (high-rise living, and working), especially in Asia. Higher density living offers opportunities for resource conservation but also challenges for planning and urban management (see 8.3.3.).

Urbanization is associated with changing dimensions of migration and materials flows into and out of cities and also within them (Grimm *et al.*, 2008). The level of increase (or in some cases decrease) of these conditions creates a dynamic quality of risk in cities. Rapidly changing cities must try to manage this growth through housing and infrastructure development while simultaneously understanding the relative impact of climate change. For example in sub-Saharan Africa, the combination of relatively high population growth rates and increasing levels of urbanization brings a rise in exposure to climate change impacts (Parnell and Walawege, 2011). The conflation of local environmental change resulting from urbanization with climate change shifts makes the identification and implementation of effective adaptation strategies more difficult. Water shortages, for instance, already a chronic concern for many cities in low and middle-income nations, typically worsen as the population and demand continue to grow (Muller, 2007). Climate change-related reductions or uncertainties in supply combine with this existing instability to create the conditions for greater management and governance crises (Gober, 2010; Milly *et al.*, 2008).

8.2.2.3. Urbanization and Ecological Sustainability

The urbanization-climate change connection has important implications for ecological sustainability. Climate change can accelerate ecological pressures in cities, as well as interact with existing urban environmental, economic, and political stresses (Leichenko, 2011; Wilbanks and Kates, 2010). This is an especially important in a world where transgressions of key planetary boundaries such as climate change and biodiversity may take humanity out of the globe's "safe operating" space (Rockström *et al.*, 2009, p. 1) into an unsafe and unpredictable future. A study by Trusilova *et al.* (2008) analyses the urbanization-induced disturbances of the carbon cycle in Europe through the land use change, local climate modification, and atmospheric pollution. This study shows that urban effects spread far beyond the city's boundaries and trigger complex feedback/responses in the biosphere (Trusilova *et al.*, 2008). Urbanization changes land use cover, generally reduces the amount of ecologically intact land and causes fragmentation of the remaining land, which reduces habitat value for species and increases the likelihood of further ecological degradation.

The linkage between urbanization, ecological sustainability and climate change is well illustrated by the example of New Orleans. This city's geophysical vulnerability is shaped by its low-lying location, accelerating subsidence, rising sea levels, and heightened intensity and frequency of hurricanes - a combination of natural phenomena exacerbated by "settlement decisions, canal development, loss of barrier wetlands, extraction of oil and natural gas, and the design, construction, and failure of protective structures and rainfall storage" (Wilbanks and Kates, 2010 p. 726; see also Ernstson et al., 2010). For cities in arid regions, already struggling with water shortages often in the context of rising demand, climate change may further reduce water availability because of shifts in precipitation and/or evaporation (Gober, 2010).

8.2.2.4. Regional Differences and Context-Specific Risks

Case studies and regional reviews assessing urban vulnerabilities to climate change have revealed diverse physical and societal challenges and large differences in levels of adaptive capacity (Hunt and Watkiss, 2011; Rosenzweig *et* *al.*, 2011). Research on African cities (Castán Broto *et al.*, 2013; Kithiia, 2011; Simon, 2010) has highlighted the lack of capacity and awareness of climate change, and often extremely high levels of vulnerability among the continent's large and rapidly growing urban poor populations. Other reviews have considered cities in Latin America (Hardoy and Romero-Lankao, 2011; Luque *et al.*, 2013), North America (Zimmerman and Faris, 2011), Europe (Carter, 2011), and Asia (Alam and Rabbani, 2007; Birkmann *et al.*, 2010; Kovats and Akhtar, 2008; Liu and Deng, 2011; Revi, 2008). The global distribution of urban risks is highly context-specific, dynamic, and uneven among and within regions. Absolute exposure to extreme events over the next few decades will be concentrated in large cities and countries with urban populations in low-lying coastal areas, as in many Asian nations (McGranahan *et al.*, 2007). Settlements located in river flood plains also are prone to flooding during extreme or persistent precipitation/severe storm conditions.

Many cities include dangerous sites, such as steep slopes, low lands adjacent to unprotected riverbanks and ocean shorelines, and have structures that do not meet building codes (Hardoy *et al.*, 2001; Pelling, 2003). Context specific risks and associated vulnerability also relates to the socio-economic status of residents. Women, children, health-compromised people and the elderly in informal settlements are generally most vulnerable to climate change impacts. Poor access to infrastructure and transport, low incomes, limited assets and dangerous locations can combine to put them at high risk from disasters (Moser and Satterthwaite, 2009).

8.2.3. Climate Change and Variability Impacts - Primary (Direct) and Secondary (Indirect) Impacts

Climate change will lead to increased frequency, intensity and/or duration of extreme weather events such as heavy rainfall, warm spells and heat events, drought, intense storm surges and associated sea-level rise (see Hunt and Watkiss, 2011; IPCC, 2007; IPCC, 2012; Romero-Lankao and Dodman, 2011; Rosenzweig *et al.*, 2011). Several urban aspects of these changes are described below.

8.2.3.1. Urban Temperature Variation: Means and Extremes

The three maps in Figure 8-3 show where the world's largest urban agglomerations are concentrated in relation to changes in observed and projected temperature. 8.3a shows the location of the largest urban agglomerations in 2010 against the backdrop of the observed history of climate-induced temperature rise (1901-2012). The dot for each urban agglomeration is colour-coded according to its population growth rate between 1970 and 2010. Those that had the most rapid population growth rates for these four decades are strongly clustered in Asia (especially in China and India) and in Latin America and sub-Saharan Africa (with many on the coast). This map highlights the temperature rise of over 1 degree C in areas in North and Central Asia, Western Africa, South America and parts of North America, indicating the potential differential exposure of large cities to climate risk.

[INSERT FIGURE 8-3 HERE
Figure 8-3: Large urban agglomerations and temperature change. Sources: Maps drawn from IPCC, 2013; urban agglomeration population and population growth data from United Nations, 2012.]

8-3b shows the location of the largest urban agglomerations according to projected populations for 2025 within the world map showing projected temperature changes for the mid-21st century, using Representative Concentration Pathway (RCP) 2.6. This is a scenario with strong mitigation. Projected populations for urban agglomerations were not made up to 2050 because there is no reliable basis for making these. Each urban agglomeration's future population is much influenced by its economic performance and by social, demographic, economic and political changes that cannot be predicted so far into the future. Assuming that almost all the large urban agglomerations in 2025 will still be large urban agglomerations in 2050, 8-3b suggests that a number of large urban agglomerations in almost all continents, will be exposed to a temperature rise of over 1.5 degree (over pre-industrial levels) by mid-century, using the RCP 2.6 scenario (IPCC, 2013).

8-3c shows a similar map showing projected temperature changes for the mid-21st century but using the RCP 8.5 scenario. This scenario, based on unchanged current GHG emission trends by mid-century, shows that the bulk of the world's population living in the largest urban agglomerations (based on their 2025 populations) will be exposed to a minimum 2 degree temperature rise over pre-industrial levels, excluding urban heat island effects. By late-century, under the RCP 2.6 scenario, a number of the urban agglomerations that were among the largest in 2025 will be exposed to temperature rise of up to 2.5 degrees over pre-industrial levels (excluding urban heat island effects), especially in the high latitudes. This implies that mean temperature rise in some cities could be over 4 degrees C. The RCP 8.5 scenario by late-century (with unchanged current GHG emission trends), shows that the bulk of the world's population living in large urban agglomerations will be exposed to a minimum 2.5 degree temperature rise. Some cities in high latitudes experience a mean 3.5 degree rise, or over 5 degrees when combined with UHI effects. Peak seasonal temperatures could be even higher. Temperature increases of 6-8 degrees in the Arctic and temperature rise in Antarctica would contribute to sea-level rise that would impact coastal cities across the world.

Increased frequency of hot days and warm spells will exacerbate urban heat island effects, causing heat-related health problems (Hajat *et al.*, 2010) and, possibly, increased air pollution (Blake *et al.*, 2011; Campbell-Lendrum and Corvalan, 2007), as well as an increase in energy demand for warm season cooling (Lemonsu *et al.*, 2013). Conversely, widespread reduction in periods of very cold weather will mean a decline in heating demands (Mideksa and Kallbekken, 2010) and potential reduction in mortality from cold waves.

Climate change will modify urban heat islands (UHI) in cities. Recent studies with physically based models (Früh *et al.*, 2011; McCarthy *et al.*, 2010; Oleson, 2012) show mixed signals, with reductions in UHI in many areas of the world and increases in some in response to climate change simulations. London's annual number of nights with heat islands stronger than 4ºC has increased by 4 days per decade since the late 1950s; meanwhile, the average nocturnal heat island intensity rose by approximately 0.1ºC per decade over the same period (Wilby, 2007). Projections suggest that by 2050, London's nocturnal UHI in August could rise another 0.5°C, representing a 40 per cent increase in the number of nights with intense UHI episodes (*ibid*). However, McCarthy *et al.* (2011), looking specifically at London and Manchester, found 0.1ºC or less (Tmin) increase in expected UHI by the 2050s. Future projections of UHI under global warming conditions were also conducted for Tokyo where a potential increase of the urban heat island intensity of 0.5º C was defined (Adachi et al 2012). Adachi et al. (2012) model an increase in UHI from 1.0º C to 1.5º C by the 2070s. In addition to the greater UHI intensity, air temperature in August is projected to increase about 2ºC by the 2070s according to an average of 5 Global Climate Models (GCM) under the SRES A1b scenario (note: range of uncertainty in GCMs is about 2ºC).

Climate change in New York City is expected to increase extended heat waves, thus exacerbating existing UHI conditions (Rosenzweig *et al.*, 2009). Increased night time minimum temperatures are associated with increased cooling demand and health-related stresses. For cities in India, the implications of future climate for connections between urbanization and the development of UHI, have been defined (Mohan *et al.*, 2011a; Mohan *et al.*, 2011b; Mohan *et al.*, 2012). Overall, the current trend of increasingly frequent extreme events is expected to increase with climate change (Manton, 2010). The comparison of the annual mean minimum temperatures of two stations in Delhi (Safdarjung and Palam) since the 1970s show night temperature trends synchronizing with the city's pace of expansion (Mohan *et al.*, 2011a).

8.2.3.2. Drought and Water Scarcity: Means and Extremes

Drought can have many effects in urban areas, including increases in water shortages, electricity shortages (where hydropower is a source), water-related diseases (though use of contaminated water), and food prices and food insecurity from reduced supplies. These may all contribute to negative economic impacts and increased rural to urban migration (Farley *et al.*, 2011; Herrfahrdt-Pähle, 2010; Vairavamoorthy *et al.*, 2008). An estimated 150 million people currently live in cities with perennial water shortage, defined as less than 100 litres per person per day of sustainable surface and groundwater flow within their urban extent. Averages across all climate change scenarios, noting the role of demographic growth, suggest a large increase in this number, possibly up to 1 billion by 2050 (McDonald *et al.*, 2011).

8.2.3.3. Coastal Flooding, Sea Level Rise, and Storm Surge

Sea-level rise represents one of the primary shifts in urban climate change risks, given the increasing concentration of urban populations in coastal locations and within low-elevation zones (McGranahan *et al.*, 2007). The new IPCC estimates for global mean sea level rise are for between 26 and 98 cm by 2100; this is higher than the 18-59 cm projected in AR4 (IPCC, 2013). Rising sea levels, the associated coastal and riverbank erosion, or flooding in conjunction with storm surge could have widespread effects on populations, property and coastal vegetation and ecosystems, and present threats to commerce, business, and livelihoods (Carbognin *et al.*, 2010; Dossou and Gléhouenou-Dossou, 2007; El Banna and Frihy, 2009; Hanson *et al.*, 2011; Nicholls, 2004; Pavri, 2010; Zanchettin *et al.*, 2007). This is well illustrated by several large-scale recent disasters including Hurricane Sandy in the New York metropolitan region. Lowland areas in coastal cities such as Lagos, Mombasa, or Mumbai are usually more at risk of flooding, especially where there is less provision for drainage (Adelekan, 2010; Awuor *et al.*, 2008; Revi, 2008). Structures on infilled soils in the lowlands of Lagos and Mumbai are more exposed to risks of flood hazards than similar structures built on consolidated materials (*ibid.)* Many near coastal cities such as Dhaka have sites at risk from both riverine and coastal storm surge (Mehrotra *et al.*, 2011a).

Cities with extensive port facilities and large scale petro-chemical and energy-related industries are especially vulnerable to risks from increased flooding (Hallegatte *et al.*, 2013). Hanson *et al.* (2011) estimate the change in flooding by the 2070s in the exposure of large port cities to coastal flooding with scenarios of socio-economic growth, sea level rise and heightened storm surge, and subsidence. They find that with a 0.5 meter rise in sea-level, the population at risk could more than triple while asset exposure is expected to increase more than ten-fold. The "top-20" cities identified for both population and asset exposure to coastal flooding in both the current and 2070 rankings are spread across low, middle, and high-income nations, but are concentrated in Asian deltaic cities. They include: Mumbai, Guangzhou, Shanghai, Miami, Ho Chi Minh City, Kolkata, New York, Osaka-Kobe, Alexandria, Tokyo, Tianjin, Bangkok, Dhaka, and Hai Phong. Using asset exposure as the metric, cities in high-income nations and in China figure prominently: Miami, New York City, Tokyo and New Orleans as well as Guangzhou, Shanghai and Tianjin. Detailed site specific studies can define the local level of sea level rise and other local factors such as harbour development, dredging and erosion, groundwater withdrawal and subsidence and other factors.

8.2.3.4. Inland Flooding, Hydrological and Geo-Hydrological Hazards at Urban Scale

Exposure to climate related hazards will vary with differences in the geomorphologic characteristics of cities (Luino and Castaldini, 2011). Heavy rainfall and storm surges would impact urban areas through flooding which in turn can lead to the destruction of properties and public infrastructure, contamination of water sources, water logging, loss of business and livelihood options and increase in water borne and water-related diseases, as noted in wide range of studies (Adelekan, 2010; de Sherbinin *et al.*, 2007; Dossou and Gléhouenou-Dossou, 2007; Douglas *et al.*, 2008; Hardoy and Pandiella, 2009; Kovats and Akhtar, 2008; Nie *et al.*, 2009; Revi, 2008; Roberts, 2008; Sharma and Tomar, 2010; Shepherd *et al.*, 2011). Case studies of inland cities have considered the elevated risk of flooding due to climate change, as in Kampala (Lwasa, 2010) and travel disruptions in Portland (Chang *et al.*, 2010). There have been significant research attempts to improve modelling of the frequency and condition of extreme precipitation events and resulting flooding (Nelson *et al.*, 2008; Olsson *et al.*, 2009; Onof and Arnbjerg-Nielsen, 2009; Ranger *et al.*, 2011; Sen, 2009).

The review on the world-wide impacts of climate change on rainfall extremes and urban drainage by Willems *et al.* (2012) has shown that typical increases in rainfall intensity at small urban hydrology scales range from 10% to 60% from control periods in the recent past (typically 1961-1990) up to 2100. These changes in extreme short-duration rainfall events may have significant impacts for urban drainage systems and pluvial flooding. Results so far indicate more problems with sewer sub charging, sewer flooding and more frequent combined sewer overflow (CSO) spills. Extreme rainfall changes in the range of 10-60% may lead to changes in flood and CSO frequencies and volumes in the range 0-400% depending on system characteristics. This is because floods and overflows, when runoff or sewer flow thresholds are exceeded, can react to rainfall (changes) in a highly non-linear way (Arnbjerg-Nielsen *et al.*, 2013; Willems *et al.*, 2012; Willems and Vrac, 2011; Willems, 2013).

8.2.3.5. Emerging Human Health, Disease, and Epidemiology Issues in Cities

WHO/WMO (2012) and Barata *et al.* (2011) note that climate change may affect the future social and environmental determinants of health, including clean air, safe drinking water, sufficient food and secure shelter. There is good evidence that temperature extremes (heat and cold) affect health, particularly mortality rates (see 11.2.2). Increased warming and physiological stress on human comfort level is predicted in a variety of cities in sub-tropical, semi-arid, and temperate sites (Blazejczyk *et al.*, 2012; Thorsson *et al.*, 2011); see also Figure 8-3. For more discussion on cities and impacts of increased warming in specific regions, see the regional chapters (Chapters 21-30).

Recent studies have illustrated the impact of heat stress on urban populations in low- and middle-income countries (see for instance Burkart *et al.* (2011) for Bangladesh and Egondi *et al.* (2012) for children in Nairobi's informal settlements). Hot days are known to have significant impacts on health that can be exacerbated by both drought conditions and high humidity. Studies in high-income countries show the elderly more vulnerable to heat-related mortality (see Oudin Åström *et al.* (2011) for a review of this). In urban settings where child mortality is high, extreme temperatures have been shown to have an impact on mortality (e.g., Egondi *et al.*, 2012). People in some occupations are more at risk, as they are exposed to higher temperatures for long durations (see Hoa *et al.*, 2013) and low-income households are more at risk when heat waves disrupt or limit income-earning opportunities (see Kovats and Akhtar, 2008, see also 11.2.7 for more detailed discussion of occupational heat stress).

Climate change has implications for urban air quality (Athanassiadou *et al.*, 2010), air pollution, and health policy (see Chapter 11 of WGI AR5). The impacts on urban air quality in particular urban areas are highly uncertain and may include increases and decreases of certain pollutants (Jacob and Winner, 2009; Weaver *et al.*, 2009). Urban air quality in most cities already is compromised by localized air pollution from transport and industry, and often commercial and residential sources. Emerging literature shows strong evidence that climate change will generally increase ozone in the US and Europe, but that the pattern of that change is not clear, with some areas increasing and some decreasing (Katragkou *et al.*, 2011; Lam *et al.*, 2011). The effects on particulate matter (PM) are also unclear, as are the effects on ozone and PM outside of the US and Europe (Dawson *et al.*, 2013).

The incidence of asthma exacerbation may be affected by climate-change related increases in ground level ozone exposures (Barata *et al.*, 2011; Gamble *et al.*, 2009; Kinney, 2008; O'Neill and Ebi, 2009; Reid *et al.*, 2009); other pollutants may also be affected, particularly in cities with PM10 and ozone levels far above WHO guidelines (WHO, 2011). Climate change may change the distribution, quantity, and quality of pollen in urban areas, as well as the timing and duration of pollen seasons. WHO/WMO (2012) notes that diarrhoeal diseases, malnutrition, malaria and dengue are climate-sensitive and in the absence of appropriate adaptation, could be adversely affected by climate change (see chapter 11).

8.2.4. Urban Sectors: Exposure and Sensitivity

This section assesses how the observed and forecast direct impacts of climate change influence the exposure of city residents, buildings, infrastructure, and systems to risk. It considers key affected sectors and populations and possible interrelations. Direct impacts include all costs and losses attributed to the impact of hazard events, but exclude systemic impacts, for example on urban economies through price fluctuations following a disaster or the impact of disaster losses on production chains (see UN-ECLAC, 1991). Both the temporal and spatial scale of the shifts in climate risk across cities and urbanizing sites in the next few decades are considered. In addition, we analyze the change in the scale and character of risks in cities, as climate extremes, means and long-term trends (e.g., sea-level rise) change.

Climate change will have profound impacts on a broad spectrum of city functions, infrastructure and services and will interact with and may exacerbate many existing stresses. These impacts can occur both *in situ* and through long-distance connections with other cities and rural sites of resource production and extraction (Seto *et al.*, 2012; Wackernagel *et al.*, 2006). The interaction between climate change and existing environmental stresses can lead to a range of synergies, challenges, and opportunities for adaptation with complex interlinkages and often highly uncertain or non-linear processes (Ernstson *et al.*, 2010). For example, the 2007 floods in the city of Villahermosa, which covered two thirds of Tabasco State in Mexico, had serious consequences for the city's economic base, with damages and losses equivalent to 30 per cent of the state's annual GDP (CEPAL, 2008). The flood that struck the Chao Phraya River in 2011 caused a high loss of life and damages to many companies and several industrial estates in Bangkok (estimated local damage and loss was 3.5 trillion Yen), but it also disrupted global scale industrial supply chains (Komori *et al.*, 2012). Urban centres serving prosperous agricultural regions are particularly sensitive to climate change if water supply or particular crops are at risk. In Naivasha, Kenya, drought threatens high-value export-oriented horticulture (Simon, 2010). Urban centres that serve as major tourism destinations may suffer when the weather becomes stormy or excessively hot and lead to a loss of revenue. Recent assessments have projected the rising population and asset exposure in large port cities (see 8.2.3.3, also Hanson *et al.*, 2011; Munich Re, 2004), alongside case studies in Copenhagen (Hallegatte *et al.*, 2011b) and Mumbai (Ranger *et al.*, 2011). By 2070, the exposed assets in cities such as Ningbo (China), Dhaka (Bangladesh) and Kolkata (India) may increase by more than 60-fold (Hanson *et al.*, 2011).

Infrastructure will similarly be affected by systemic and cascading climate risks (Hunt and Watkiss, 2011). Climate stresses, particularly extreme events, will have effects across interconnected urban systems, within and across multiple sectors (Gasper *et al.*, 2011). The cascading effects are especially evident in the water, sanitation, energy, transport, and communications sectors, due to the often tightly coupled character of urban infrastructure systems (see Rosenzweig and Solecki (2010) for a discussion of this for New York City). The U.S. National Climate Assessment effort has looked at the impacts of climate change on infrastructure, considering the water, land, and energy nexus, as well as on a large number of industries (Skaggs *et al.*, 2012; Wilbanks *et al.*, 2012). These systemic cascades can have both direct and indirect economic impacts (Hallegatte *et al.*, 2011b; Ranger *et al.*, 2011), which can extend from the built environment to urban public health (Frumkin *et al.*, 2008; Keim, 2008). A critical element is the impact for infrastructure investments with long operational lives, in some cases 100 years or more (Hallegatte and Dumas, 2009). In low- and most middle-income cities, very large additional investment is needed to address deficits in infrastructure and services; without this investment, making the short to long-term trade-off to improve resilience is difficult (Dodman and Satterthwaite, 2009). This is an opportunity for 'climate smart' infrastructure planning that considers how to combine pro-poor development and climate change adaptation and mitigation. This is a more difficult task for cities such as New York with dense aging infrastructure and materials that "may not be able to withstand the projected strains and stresses from a changing climate" (Zimmerman and Faris, 2010, p. 63). These cities also have the opportunity, when replacing aging infrastructure, to integrate climate considerations into the new infrastructure decision-making processes.

8.2.4.1. Water Supply, Wastewater, and Sanitation

Water and sanitation systems affect household well-being and health, as well as influencing urban economic activities, energy demands and the rural-urban water balance (Gober, 2010). Climate change will impact residential water demand and supply and its management (O'Hara and Georgakakos, 2008). Among the projected impacts are altered precipitation and runoff patterns in cities, sea level rise and resulting saline ingress, constraints in water availability and quality, and heightened uncertainty in long-term planning and investment in water and waste water systems (Fane and Turner, 2010; Major *et al.*, 2011; Muller, 2007). Local government departments and utilities responsible for water supply and waste water management must confront these new climatic patterns and major uncertainties in availabilities and learn to respond to dynamic and evolving sets of constraints (Milly *et al.*, 2008).

Climate change will increase the risk and vulnerability of urban populations to reductions in groundwater and aquifer quality (e.g., Praskievicz and Chang, 2009; Taylor and Stefan, 2009), subsidence and increased salinity intrusion. High levels of groundwater extraction have led to serious subsidence problems in cities such as Bangkok (Babel *et al.*, 2006) and Mexico City (Romero-Lankao, 2010), which damage buildings, fracture pipes and can increase flood risks (see also Jha *et al.*, 2012). This problem can be compounded in coastal cities when saline intrusion reduces ground water quality and erodes structures.

In many rapidly developing cities, the impact of climate change on water supplies will interact with growing population, growing demand and economic pressures, potentially heightening water stress and negative impacts on the natural resource base, with effects for water quality and quantity. Caribbean nations, for example, with their expanding middle-class urban population, face sharply raised demands for water, and the associated challenges of managing runoff, storm water, and solid wastes. Projected reductions in rainfall amounts at specific times in particular locations would aggravate such water stresses (Cashman *et al.*, 2010).

In Shanghai, climate change is expected to bring decreased water availability as well as flooding, groundwater salinization and coastal subsidence. The city's population of 17 million is projected to continue expanding, often within areas that are "likely increasingly flood-prone" (de Sherbinin *et al.*, 2007, p. 60). Groundwater depletion has contributed to land subsidence in these already vulnerable areas, reinforcing the water stresses and risks of erosion (*ibid.*). In several large Andean cities, including Lima, La Paz, and Quito, declining volumes of glacial melt water have been observed, with expected further declines (Buytaert *et al.*, 2010; Chevallier *et al.*, 2011).

Several studies estimate how climate change will alter relationships among water users, exacerbating tensions and conflicts between the various end-users (residential, commercial, industrial, agricultural, and infrastructural) (Roy *et al.*, 2012; Tidwell *et al.*, 2012). In small and mid-sized African cities, the effect of flooding on well water quality is a growing concern (Cissé *et al.*, 2011). Floods, droughts and heavy rainfall have also impacted agriculture and urban food sources, and can exacerbate food and water scarcity in urban areas (Gasper *et al.*, 2011). But not all water systems are projected to experience negative impacts. Chicago's Metropolitan Water Reclamation District (MWRD) found that reduced precipitation due to climate change would decrease pumping and general operations costs, since sewers will contain less rainwater in drier seasons (Hayhoe *et al.*, 2010).

Wastewater and sanitation systems will be increasingly overburdened during extreme precipitation events if attention is not paid to maintenance, the limited capacity of drainage systems in old cities, or lack of provision for drainage in most unplanned settlements and in many urban centres (Howard *et al.*, 2010; Mitlin and Satterthwaite, 2013; Wong and Brown, 2009). In the city of La Ceiba, Honduras, stakeholders concluded that urban drainage and improved management of the Rio Cangrejal watershed were top priorities for protection against projected climate change impacts; the city lacks a stormwater drainage system but experiences regular flooding (Smith *et al.*, 2011).

Flooding is often made worse by uncontrolled city development that builds over natural drainage channels and flood plains or by a failure to maintain drainage channels (often blocked by solid wastes where waste collection is inadequate). These problems are most evident in cities where there are no drains or sewers to help cope with heavy precipitation (see Douglas *et al.*, 2008) and no service to collect solid wastes (in many cities in low-income nations, less than half the population has regular solid waste collection – see Hoornweg and Bhada-Tata (2012). Many cities in high-income nations also face challenges. An analysis of three cities in Washington State, assessing future streamflows and peak discharges, concluded that "concern over present (drainage) design standards is warranted" (Rosenberg *et al.*, 2010, p. 347). Climate change was identified as a key driver affecting Britain's future sewer systems. According to the model used, the volume of sewage released to the environment by combined sewage overflow spills and flooding was projected to increase by 40 per cent (Tait *et al.*, 2008).

8.2.4.2. Energy Supply

Energy exerts a major influence on economic development, health, and quality of life. Any climate change-related disruption or unreliability in power or fuel supplies can have far-reaching consequences, affecting urban businesses, infrastructure, services (including healthcare and emergency services) and residents, as well as water treatment and supply, rail-based public transport, and road traffic management (Finland Safety Investigations Authority, 2011; Halsnæs and Garg, 2011; Hammer *et al.*, 2011; Jollands *et al.*, 2007).

Past experiences with power outages indicate some of the knock-on effects (Chang *et al.*, 2007). New York City's blackout of 2003 lasted 28 hours and halted mass transport, surface vehicles due to signaling outages, and water supply (Rosenzweig and Solecki, 2010). A review of climate change impacts on the electricity sector (Mideksa and Kallbekken, 2010) projects reductions in the efficiency of water cooling for large electricity generating facilities, changes in hydropower and wind power potential, and changing demand for heating or cooling in the US and

Europe. Low-income households in Chittagong use candles or kerosene lamps during frequent power outages; this was found to disturb children's studies, increase expenses, and overheat homes (Rahman *et al.*, 2010).

Climate change will alter patterns of urban energy consumption, particularly with respect to the energy needed for cooling or heating (for a review, see Mideksa and Kallbekken, 2010). Climate change will bring increases in air conditioning demand and in turn heightened electricity demand (Radhi (2009), see also Hayhoe *et al.* (2010) for a discussion of this in relation to Chicago). In temperate and more northern regions, winter temperature increases may decrease energy demand (Mideksa and Kallbekken, 2010). In most cases within individual cities, potential increases in summertime electricity demand from climate change will exceed reductions in winter energy demand reductions (Hammer *et al.*, 2011). Less is known about the demand side impacts in low and lower-middle-income nations, where large sections the urban population still lack access to electricity (Johansson *et al.*, 2012; Satterthwaite and Sverdlik, 2012). Most of these nations are expected, as noted, to have increased mean temperatures or rising frequency of heat waves (IPCC, 2007).

Many cities' economies will be affected if water scarcity and variability interrupt hydropower supplies. For instance, reductions in hydroelectric generation will have impacts on the economies of many urban centres in Brazil as well as in neighbouring countries (de Lucena *et al.*, 2010; de Lucena *et al.*, 2009; Schaeffer *et al.*, 2011). Cities in sub-Saharan Africa often rely on hydropower for their electricity, and failures in supplies can lead "to a more general 'urban failure' " (Muller, 2007, p. 106). Laube *et al.* (2006) discuss water shortages in Ghana following low precipitation periods, and the potential for competition between hydropower and water provision, including to downstream urban centres. Declining water levels in the Hoover Dam have raised the possibility that Los Angeles will lose a major power source, and that Las Vegas will face a severe decline in drinking water availability (Gober, 2010).

Summer heat waves, with spikes in demand for air conditioning, can result in brownouts or blackouts (Mideksa and Kallbekken, 2010; Mirasgedis *et al.*, 2007). Cities in the temperate regions of Australia already experience regular blackouts on hot summer days, largely due to residential air-conditioner use (Maller and Strengers, 2011). Research in Boston suggested that rising energy demands in hotter summers have meant a "disproportional impact on (the) elderly and poor, increased energy expenditures; loss of productivity and quality of life" (Kirshen *et al.*, 2008, p. 241). Any increase in the frequency or intensity of storms may disrupt electricity distribution systems because of the collapse of power lines and other infrastructure (Rosenzweig *et al.*, 2011, see also Chapter 10).

8.2.4.3. Transportation and Telecommunications

Climate change-related extreme events will affect urban transportation and telecommunication infrastructure, including a variety of capital stock, such as bridges and tunnels, roads, railways, pipelines, and port facilities, data sensors, and wire and wireless networks (Hallegatte *et al.*, 2011a; Jacob *et al.*, 2011; Koetse and Rietveld, 2009; Major *et al.*, 2011). In the Gulf Coast region of the United States, 27 percent of major roads, 9 percent of rail lines, and 72 percent of ports are at or below 122 cm (4 ft) in elevation. With a storm surge of 7 m (23 ft), more than half the area's major highways, almost half the rail miles, 29 airports, and virtually all the ports are subject to flooding (Savonis *et al*, 2008). Assessing possible disruptions of transport networks within cities and urban systems is critical. Loss of telecommunication access during extreme weather events can inhibit disaster response and recovery efforts because of its critical role in providing logistical support for such activity (Jacob *et al.*, 2011).

Ports are central to international trade and climate change poses substantial challenges related to exposed locations in coastal zones, low-lying areas and deltas; long lifespans of key infrastructure and interdependencies with trade, shipping and inland transport services that are also vulnerable (Asariotis and Benamara, 2012; Oh and Reuveny, 2010). Hurricane Sandy crippled the New York region, leading to a week-long shut-down of one of the largest container ports in the U.S. (Hallegatte *et al.*, 2013).

Large sections of the urban population in low- and middle-income nations live in settlements without all-weather roads and paths that allow for emergency vehicle access and rapid evacuation. For instance, in Chittagong, Bangladesh, extremely narrow roads limit emergency access to most of informal neighbourhoods, exacerbating health and fire risks (Rahman *et al.*, 2010). In Lagos's informal settlements, a 2006 resident survey ranked roads second to drainage in terms of needed facilities (Adelekan, 2010). Evacuations in low-income areas may also be hampered by hazardous locations, absence of public transport and inadequate governance. Following the 2003 and 2006 floods in Santa Fe, Argentina, the lack of information and official evacuation mechanisms prevented timely responses; some residents also chose to stay in their homes to protect their possessions from looters (Hardoy and Pandiella, 2009).

Low-income urban residents can also be profoundly affected during and after extreme weather events that damage critical public transit links, prevent access to work, and heighten exposure to health risks. Interviews in Georgetown, Guyana, found that the limited transport access of low-income households during floods made them more prone to losing time from work or school, compared to wealthier households. Poorer households rarely owned cars, and wading barefoot through floodwaters exposed them to waterborne pathogens (Linnekamp *et al.*, 2011). Some studies find urban women walk or use public transport more than men (World Bank, 2010c); hence, the gendered impact of transport disruptions may merit greater consideration (see Levy, 2013; UN-Habitat, 2011a).

The literature on urban transport and climate change focuses more on mitigation, with less attention to vulnerability, impacts, and adaptation (Hunt and Watkiss, 2011). Existing studies on impacts are often limited to the short-term demand side, particularly in passenger transport (Koetse and Rietveld, 2009). However, climate change creates several challenges for transport systems. The daily functioning of most transport systems is already sensitive to fluctuations in precipitation, temperature, winds, visibility, and for coastal cities, rising sea levels with the associated risks of flooding and damages (Love *et al.*, 2010). Transport is highly vulnerable to climate variability and change, and the economic importance of transport systems has increased with the rise of just-in-time delivery methods, heightening the risk of losses due to extreme weather (Gasper *et al.*, 2011).

In addition to adapting road transport, cities should ensure bridges, railway cuttings, and other hard infrastructure are resilient to climate change over their service lifespan (Jaroszweski *et al.*, 2010). Few studies have examined the effects of climate change on railways, but rail system failures are known to be related to high temperatures, icing, and storms (Koetse and Rietveld, 2009); see Dobney *et al.* (2008) for future heat related delays in UK railways; also Palin *et al.* (2013) offers a broad discussion of climate change effects on the UK rail network. Very few studies have examined the vulnerability of air and seaborne transport and infrastructure, but climate change could mean more and lengthier weather-related delays and disruption (Becker *et al.*, 2012; Eurocontrol, 2008).

Loss of sea ice can benefit some cities by increasing opportunities for developing road networks or ports. However, it may be costly to adapt road, air and water transport networks to the known environmental risks associated with such redevelopment (Larsen *et al.*, 2008). For industries and communities in Northern Canada, reduced freshwater-ice levels creates longer shipping seasons and could also promote new seaports in marine environments. But thawing of permafrost can also result in instability and major damage to roads, infrastructure, and buildings in and around northern cities and towns, and inland towns will require sizable investments to replace winter ice roads with land-based roads (Prowse *et al.*, 2009).

The direct impacts of extreme weather on transport are more easily assessed than the indirect impacts or possible knock-on effects between systems. Studies have often examined the direct impacts of flooding on transport infrastructure, but the indirect costs of delays, detours, and trip cancellation may also be substantial (Koetse and Rietveld, 2009). Mumbai's 2005 floods caused injuries, deaths and property damage but also serious indirect impacts as most city services were shut down for five days without contact via rail, road or air (Revi, 2005). Transport and other urban infrastructure networks are often interdependent and located in close proximity to one another, yet only a few assessments have considered the joint impacts (Hayhoe *et al.*, 2010; Kirshen *et al.*, 2008).

Transportation systems are critical for effective disaster response – for example, where populations have to be evacuated prior to an approaching storm or where provision is urgently needed for food, water and emergency services to affected populations.

Key elements in cities' communications systems may have to be strengthened – for instance to avoid masts toppling due to strong winds and electrical support facilities that need to be moved or protected against flooding (Zimmerman and Faris, 2010, p. 74). New York City's dispersed communications network faces several climate-related risks. Electrical support facilities can be flooded; cell phone towers can topple in strong winds or become corroded as sea levels rise (Zimmerman and Faris, 2010). In Alaska, telecommunications towers are settling due to warming permafrost (Larsen *et al.*, 2008). Emergencies may generate a demand for communications that exceeds systems' capacities. During the extreme rainfall event in 2005, Mumbai's telecommunications networks ceased to function due to a mix of overload, shut down of the power system and lack of diesel supplies for generators (Revi, 2005).

8.2.4.4. Built Environment, and Recreation and Heritage Sites

Housing ideally provides its occupants with a comfortable, healthy and secure living environment and protects them from injuries, losses, damage and displacement (Haines *et al.*, 2013). For many low-income households, livelihoods also depend on home-based enterprises, and housing is key to protecting their assets and preventing disruption of their incomes. Decent housing has particular importance for vulnerable groups, including infants and young children (Bartlett, 2008), older residents or those with disabilities or chronic health conditions.

Urban housing is often the major part of the infrastructure affected by disasters, according to Jacobs and Williams (2011). Extreme events like cyclones and floods inflict a heavy toll, particularly on structures built with informal building materials and outside of safety standards (United Nations, 2011). Dhaka's 1998 floods damaged 30 percent of the city's units; of these, more than two-thirds were owned by the lower-middle classes and the poorest (Alam and Rabbani, 2007). Adelekan (2012) shows that a relatively modest increase in wind speeds during storms caused widespread damage in central Ibadan. Relative to the preceding decade, the period from 1998 to 2008 showed higher mean maximum wind gusts and more frequent windstorms with peak gusts greater than 48 knots, and the impacts were severe in part because of the high concentration of residents in damaged buildings. Increased climate variability, warmer temperatures, precipitation shifts, and increased humidity will accelerate the deterioration and weathering of stone and metal structures in many cities (Bonazza *et al.*, 2009; Grossi *et al.*, 2007; Smith *et al.*, 2008; Stewart *et al.*, 2011; Thornbush and Viles, 2007).

Recreational sites such as parks and playgrounds will also be affected. In New York City, these are defined as critical infrastructure and are often located in low elevation areas subject to storm surge flooding (Rosenzweig and Solecki, 2010). Little research has examined the effects upon urban tourism in particular (Gasper *et al.*, 2011).
The increased risks that climate change brings to the built environment (Spennemann and Look, 1998; Wilby, 2007) also apply to built heritage. This has led to the Venice Declaration on Building Resilience at the Local Level Towards Protected Cultural Heritage and Climate Change Adaptation Strategies, which brings together UNESCO, UN-HABITAT, EC and individual city mayors. An example is Saint-Louis in Senegal, a coastal city and World Heritage Site on the mouth of the Senegal river, which has frequent floods and large areas at risk from river and coastal flooding. There are initiatives to reduce flooding risks and relocate families from locations most at risk, but the local authority has very limited investment capacity (Diagne, 2007; Silver *et al.*, 2013).

8.2.4.5. Green Infrastructure and Ecosystem Services

Climate change will alter ecosystem functions affected by changes in temperature and precipitation regimes, evaporation, humidity, soil moisture levels, vegetation growth rates (and allergen levels), water tables and aquifer levels, and air quality. It will also accentuate the value of ecosystems services and green infrastructure for adaptation. "Green infrastructure" refers to interventions to preserve the functionality of existing green landscapes (including parks, forests, wetlands or green belts), and to transform the built environment through phytoremediation and water-management techniques and by introducing productive landscapes (Foster *et al.*, 2011b; La Greca *et al.*, 2011; Zhang *et al.*, 2011). These can influence the effectiveness of pervious surfaces used in storm water management, green/white/blue roofs, coastal marshes used for flood protection, urban agriculture and overall biomass production. Mombasa will experience more variable rainfall as a result of climate change, making the expansion of green infrastructure more difficult (Kithiia and Lyth, 2011). Trees in British cities will be increasingly prone to heat stress and attacks by pests, including new non-native pathogens and pests that can survive under warmer or wetter conditions (Tubby and Webber, 2010). Urban coastal wetlands will be inundated with sea level rise. In New York City, remnant coastal wetlands will be lost to sea-level rise because bulk heading and intensive coastal development will prevent their natural movement inland (Gaffin *et al.*, 2012).

8.2.4.6. Health and Social Services

The effects of climate change will also be evident across urban public services including health and social care provision, education, police and emergency services (Barata *et al.*, 2011, see also Chapter 11). Most urban centres in low-income nations and many in middle-income nations lack adequate social and public service provision (Bartlett, 2008; UN-Habitat, 2003a) while higher-income cities are only beginning to consider climate change in their health or disaster management plans (Brody *et al.*, 2010). Although there are few studies on adapting education, police, or other key services, a growing public health literature has discussed multi-sectoral adaptation strategies (Huang *et al.*, 2011). Cities' existing public health measures provide a foundation for adapting to climate change, such as heat warning systems or disease surveillance (Bedsworth, 2009; McMichael *et al.*, 2008). Negative climate impacts have been highlighted on some of the most vulnerable in society– including children (Ebi and Paulson, 2010; Sheffield and Landrigan, 2011; Watt and Chamberlain, 2011); the elderly (Oven *et al.*, 2012; White-Newsome *et al.*, 2011) and the severely disadvantaged (Ramin and Svoboda, 2009) (see Chapter 11).

8.2.5. Urban Transition to Resilience and Sustainability

The question of how to promote increased resilience and enhanced sustainability in urban areas (as illustrated in Table 8-2) has become a central research topic and policy consideration. It is well recognized that climate change risks affect this process by heightening uncertainties and altering longstanding patterns of environmental risk in cities, many of which continue to face other significant stressors such as rapid population growth, increased pollution, resource demands and concentrated poverty (Mehrotra *et al.*, 2011a; Wilbanks and Kates, 2010). This section discusses how climate change increasingly affects municipal decision-making frames and alters local conceptions of cities as vehicles for economic growth, for political change, for meeting livelihoods and basic needs as well as larger-scale goals of resilience and sustainability.

In recent years, different models of urban environmental transition have been introduced to illustrate the connections between health hazards and environmental impacts as cities and neighbourhoods develop – for example, shifts from a "sanitary city" focused on public health and basic service provision to a "sustainable city" focused on long-term planning, resource efficiency and ecosystem services (McGranahan, 2007). The latter includes consideration of a city's use of global and local sinks for wastes that lie outside its boundaries *(ibid.*, Wilson, 2012). Within these models, key variables have been identified that make cities vulnerable to climate change (e.g., extensive infrastructure networks, high density population in exposed or other sensitive sites).

There is the opportunity to promote societal transition that enhances resiliency and adaptive capacity in the face of accelerated climate change (Ernstson *et al.*, 2010; Gusdorf *et al.*, 2008; Mdluli and Vogel, 2010; Pelling and Manuel-Navarrete, 2011; Pelling, 2011a; Tompkins *et al.*, 2010). Transition in this context can take place at a broad scale, but can also often occur with incremental changes, potentially precipitating regime level shifts (Pelling and Manuel-Navarrete, 2011). Although such shifts also can happen as a result of discrete regime failure (Pelling, 2011a), this is less common. Such transformational changes have been observed in a variety of urban disaster contexts. Most often they follow urban earthquake events (e.g., in Nicaragua, Guatemala, Turkey) but are also associated with flooding in Bangladesh (Pelling, 2011a). Disasters can enable regime level change at moments in history where competing approaches to development have political voice, an organizational base that articulates competing analysis of the causes of the disaster and weak systemic counter response (*ibid.)*.

Climate change may exacerbate existing social and economic stressors in cities with the potential to affect urban livelihoods, engender political or social upheaval, or generate other negative impacts upon human security (Bunce *et al.*, 2010; Siddiqi, 2011; Simon and Leck, 2010) – see regional chapters for this report for more details). Climate change could potentially contribute to violent conflicts and spur migration from highly vulnerable sites in cities or increasingly environmentally stressed locales (Adamo, 2010; de Sherbinin *et al.*, 2011; Reuveny, 2007). But there is considerable uncertainty regarding projections. Migration may represent an important household strategy to adapt by diversifying income-sources and livelihoods (Tacoli, 2009). Although climate change can significantly disrupt livelihoods, outcomes will depend upon particular social structures, state institutions, and other broader determinants of human security (Barnett and Adger, 2007). In sum, “dwindling resources in an uncertain political, economic and social context are capable of generating conflict and instability, and the causal mechanisms are often indirect” between climate and conflict (Beniston, 2010, p. 567).

Different management solutions to climate change also have implications for equity (Pelling *et al.*, 2012). For example, the privatization of urban water supply and sanitation systems can advantage specific groups over others. Conversely, community-based solutions that also build social capital can be a component in generating urban resilience. However, even these solutions may exacerbate inequality at the city level, with only those local areas with strong levels of social capital being able to benefit most from community led action or garner support from international and national partners (Pelling *et al.*, 2012; UN-Habitat, 2007).

Table 8-3 serves as the link between Section 8.2 (which focuses on climate change risks and impacts) and Section 8.3 (which focuses on adaptation). It summarizes key risks from climate change to urban areas and the potential to reduce risk through adaptation for the present, near-term (2030-2040) and long-term (2080-2100). Table 8-6 has comparable summaries of key risks and potential for adaptation for Dar es Salaam, Durban, London and New York City. For the long-term, under a global mean temperature increase of 2°C above preindustrial levels, many key risks increase from the near term. High adaptation can reduce these risk levels, although for most key risks not as much as high adaptation in the near term. For the long term under a temperature increase of 4°C above preindustrial levels, almost all key risks are ‘very high’ and with many of them remain very high with high adaptation.

[INSERT TABLE 8-3 HERE
Table 8-3: Urban areas: current and indicative future climate risks. Key risks are identified based on an assessment of the literature and expert judgments by chapter 8 authors, with the evaluation of evidence and agreement presented in supporting chapter sections. Each key risk is characterized as very low to very high. For the near-term era of committed climate change (2030-2040), projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options (2080-2100), risk levels are presented for global mean temperature increases of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state.]

8.3. Adapting Urban Areas

8.3.1. Introduction

Since the Fourth Assessment, the literature on urban climate change adaptation has increased significantly, especially in three aspects:

- the examination of risks and vulnerabilities for particular cities;
- the definition of ‘resilience’ and identification of opportunities to strengthen resilience at all scales;
- documentation produced by or for particular city governments on adaptation.

There is less on local government decisions to include adaptation in plans and investment programmes, but see (2012) and (2008; 2010)for exceptions. As described below, studies have also examined how to link adaptation and city development plans and adaptation measures for key sectors.

It has been suggested that “the complexities and uncertainties associated with climate change pose by far the greatest challenges that planners have ever been asked to handle” (Susskind, 2010, p. 219). Municipal and higher-level adaptation plans will need to take into account uncertainty about future climates and extremes. These will need to consider direct and indirect economic costs, including the trade-off of inaction and locking into ill-adapted infrastructure versus investment in adaptation when climate change is less than anticipated (Hallegatte *et al.*, 2007a). Several U.S. studies have considered the cost on inaction for specific states (Backus *et al.*, 2012; Niemi *et al.*, 2009a; Niemi *et al.*, 2009b; Niemi *et al.*, 2009c; Repetto, 2011a; Repetto, 2011b; Repetto, 2012a; Repetto, 2012b; Repetto, 2012c; Repetto, 2012d; Wilbanks *et al.*, 2012).

While local governments are the fulcrum of urban adaptation planning, challenges include inadequate resources and technical capacities and a lack of data on climate-related risks and vulnerabilities. Existing climate models are not downscaled to the city level. Data on climate change risks are infrequently collected and often fragmented across city government departments (Hardoy and Pandiella, 2009). Many proposed adaptation measures respond to specific local or regional hazard risks that may not be directly climate-related (Bulkeley, 2010). To encourage local dialogue in adaptation planning, urban climate data need to be integrated geographically, across time-scales, and consider the range of regional benefits and costs of climate policy (Ruth, 2010).

8.3.2. Development Plans and Pathways

As AR4 emphasized, many of the forces shaping greenhouse gas emissions also underlie development pathways – including the scale, nature and location of investment in infrastructure (Wilbanks *et al.*, 2007). These influence the form and geography of urban development as well as the scale and location of climate-related risks to urban buildings, enterprises and populations. Local, provincial and national government share responsibility for encouraging new investments and migration flows away from high risk sites through climate sensitive disaster risk management, urban planning and zoning and infrastructure investments. But the priority given to economic growth usually means this is rarely implemented with vigour (Douglass, 2002; Reed *et al.*, 2013).

8.3.2.1. Adaptation and Development Planning

Urban adaptation is becoming important to some national and regional governments and many city governments. In high-income countries, interactions and division of responsibility between national and local level have been examined (see, for instance, Massetti *et al.* (2007) for Italy and Juhola and Westerhoff (2011) for Italy and Finland); also local adaptation implementation through subsidies and flexible schemes in different contexts and the transfer of authority and resources to city level (for the Netherlands, see Gupta *et al.*, 2007). New decision making strategies for local governments consider the complexity and dynamics of evolving socio-ecological systems (Kennedy *et al.*, 2011), for instance, adaptation plans and responses in Sydney to cope with sea level rise and storms (Hebert and Taplin, 2006) and adaptation planning in California (Bedsworth and Hanak, 2010).

The literature on urban adaptation in low and middle-income nations has grown since AR4 (see Box 8-1 for publications since 2007). A 2011 review (Hunt and Watkiss, 2011) could draw on eight case studies in Asia, five in Africa, four in South America – as well as cases from Europe, Northern America and Australasia.

_____ START BOX 8-1 HERE _____

Box 8-1. Recent Literature on Urban Adaptation in Low- and Middle-Income Nations

Among the papers and books considering climate change adaptation in urban areas since 2007 are those on Cape Town (Cartwright *et al.*, 2012; Mukheibir and Ziervogel, 2007; Ziervogel *et al.*, 2010), Durban (Cartwright *et al.*, 2013; Roberts and O'Donoghue, 2013; Roberts, 2008; Roberts, 2010; Roberts *et al.*, 2012), and other urban centres in Africa (Adelekan, 2012; Castán Broto *et al.*, 2013; Douglas *et al.*, 2008; Kithiia and Lyth, 2011; Kiunsi, 2013; Lwasa, 2010; Silver *et al.*, 2013; Wang *et al.*, 2009; World Bank, 2011); urban centres in Bangladesh (Alam and Rabbani, 2007; Banks *et al.*, 2011; Haque *et al.*, 2012; Jabeen *et al.*, 2010; Roy *et al.*, 2013); India (Revi, 2008; Saroch *et al.*, 2011; Sharma and Tomar, 2010); Pakistan (Khan *et al.*, 2008); Philippines (Button et al 2013); and Latin America (Hardoy and Ruete, 2013; Hardoy and Velásquez Barreto, 2014; Hardoy and Pandiella, 2009; Hardoy and Romero Lankao, 2011; Luque *et al.*, 2013; Romero-Lankao, 2007; Romero-Lankao, 2010). In China, discussions of division of responsibility between national and local levels include (Li, 2013; Liu and Deng, 2011; Teng and Gu, 2007).

Other papers or books discussing urban adaptation in low- and middle nations include (Agrawala and van Aalst, 2008; Ayers, 2009; Bartlett, 2008; Bicknell *et al.*, 2009; Bulkeley and Castan Broto, 2013; Bulkeley and Tuts, 2013;

de Sherbinin *et al.*, 2007; Kovats and Akhtar, 2008; Manuel-Navarrete *et al.*, 2011; McGranahan *et al.*, 2007; Moench *et al.*, 2011; Moser *et al.*, 2010; Rosenzweig *et al.*, 2011; Tanner *et al.*, 2009; UN-Habitat, 2011a; World Bank, 2010b).

_____ END BOX 8-1 HERE _____

Four issues can be highlighted around urban adaptation:

- low and middle-income nations have most of the world's current and future urban population;
- key development issues of poverty and social inequality may be aggravated by climate change;
- human agency among low-income inhabitants and organizations is important in building local responses;
- well-functioning multilevel governance helps in developing adaptation strategies (Sánchez-Rodríguez, 2009).

Although few publications suggest specific operational strategies, they do stress the importance of the link between climate adaptation and development – urban infrastructure and other development deficits can contribute to adaptation deficits. Manuel-Navarrete *et al.* (2011) explore this interplay in the Mexican Caribbean where hurricane exposure and vulnerability are influenced by political decisions and contingent development paths. Few reports exist on multidimensional approaches to operational adapation. There are some examples of adaptation integrated with development interventions and addressing structural drivers of social and urban vulnerability – for instance Climate Action Plans of Mexico City, Cartagena and San Andrés de Tumaco (Sánchez-Rodríguez, 2009).

Despite growing acceptance of its importance, there are reasons for the general lack of attention to urban adaptation. First, national climate change policies usually give little attention to urban adaptation compared to sectors like agriculture. The ministries or agencies responsible for these policies often have little involvement in urban and little influence on those whose cooperation is essential e.g. for social policies, public works and local government (Hardoy and Pandiella, 2007; Ojima, 2009; Roberts, 2010). Social policies and priorities influence the social and spatial distribution of climate-related risk and vulnerability – for instance, provision for health care, emergency services and safety nets - yet few agencies recognize their potential role in reducing risk and vulnerability.

A second factor is the initial focus for many cities on mitigation rather than adaptation (with commitments made to lowering greenhouse gas emissions), in part because of the focus of international support. Local decision-makers frequently view climate change as a marginal issue, but adaptation usually ranks lower than mitigation on the agenda (Bulkeley, 2010; Simon, 2010). Mexico City focuses on mitigation, but adaptation is still a vague concept (GDF, 2006; GDF, 2008) seen more, for instance, as a capacity to cope with floods through early warning systems than through comprehensive, long-term measures like watershed management to reduce the speed and volume of flood waters. There is still little literature on adaptation for Brazilian cities (Ojima, 2009; Soares, 2009). In Sao Paulo, adaptation is limited to broad declarations about necessary actions, even as the city gets hit by floods, landslides and water scarcity (Martins and da Costa Ferreira, 2011; Nobre *et al.*, 2010; Puppim de Oliveira, 2009).The pressure on national and local governments to act is lessened by the scant public awareness of the importance of climate change adaptation (Nagy *et al.*, 2007), and a "knowledge gap" between policymakers and scientists (Sánchez-Rodríguez, 2011). However, as 8.4 describes, interest in urban adaptation is growing, encouraged by the increasing engagement of transnational municipal networks and donor agencies (Bulkeley, 2013).

8.3.2.2. Disaster Risk Reduction and its Contribution to Climate Change Adapation

The growing concentration of people and activities in urban centres and the increasing number and scale of cities can generate new patterns of disaster hazard, exposure and vulnerability, as evident in the rising number of localized disasters in urban areas in many low- and middle-income nations associated with extreme weather (storms, flooding, fires and landslides) (Douglas *et al.*, 2008; United Nations, 2009; United Nations, 2011). This is relevant to climate change adaptation, given the increasing frequency and intensity of potentially hazardous weather events associated with climate change. Extreme weather events have also helped raise awareness of citizens and local governments of local risks and vulnerabilities.

Exposure to weather-related risk in growing urban areas increases when local governments fail to address their responsibilities by expanding or upgrading infrastructure and services and reducing risk through building standards and appropriate land-use management (United Nations, 2009; United Nations, 2011). This is typical in countries with low per capita GDPs and weak local governance (i.e., in the first two categories of Table 8-2), and can be exacerbated by rapid urban population growth. Urbanization accompanied by more capable and accountable local governments can reduce disaster risk, as evident in the declines in mortality from extreme weather (and other) disasters in many middle- and all high-income nations (United Nations, 2011). The most urbanized nations generally have the lowest mortality to these events (United Nations, 2009).

Local government investment is usually a small proportion of total investment in and around an urban centre, but has particular importance in risk reduction. Urban governments have explicit responsibilities for many assets which may be risk prone, often including schools, hospitals, clinics, water supplies, sanitation and drainage, communications and local roads and bridges (IFRC, 2010). Even where private provision for these assets is significant, local government usually coordinates such provision and has a significant planning and regulation role, ensuring buildings and infrastructure meet needed standards and guiding development away from high-risk areas.

From the late 1980s, some Latin American cities took a new approach to disaster risk, involving three processes:

- detailed analyses of local disaster records, including smaller events than those in international databases;
- recognition that most disasters were the result of local failures to assess and act on risk;
- recognition of the central roles of local governments in disaster risk reduction, supported national and local civil defence organizations, working with civil society and settlements most at risk (IFRC, 2010; United Nations, 2009).

This led to institutional and legislative changes at national or regional level (Gavidia, 2006; IFRC, 2010). In Colombia, a national law supports disaster risk reduction and a National System for Prevention and Response to Disasters, shifting the main responsibility for action to municipal administrations. In Nicaragua, the National System for Disaster Prevention, Mitigation and Response (SINAPRED), works with local government to integrate disaster mitigation and risk reduction into local development processes (von Hesse *et al.*, 2008). Other initiatives in Central and South America include the influence of La Red (IFRC, 2010), the DIPECHO project, “Developing Resilient Cities” and UNDP and GOAL in Central America. In growing numbers of cities in Asia (Shaw and Sharma, 2011) and Africa (Pelling and Wisner, 2009), experiences with community-driven ‘slum’ or informal settlement upgrading has led to a recognition of its potential to reduce risk and vulnerability to extreme weather events, most effectively when supported by local government and civil defence response agencies (Archer and Boonyabancha, 2011; Boonyabancha, 2005; Carcellar *et al.*, 2011).

The Homeless People’s Federation of the Philippines developed a series of effective responses following major disasters, including community-rooted data gathering (assessing destruction and victims’ immediate needs); trust and contact building; support for savings; registering community organizations; and identifying needs, including building materials loans for repairs. The effectiveness of these measures is much enhanced with local government support (Carcellar *et al.*, 2011) and these experiences have helped inform community-based adaptation (see 8.4).

International networks supporting innovation in disaster risk reduction and/or climate change adaptation and inter-city learning include La Red in Latin America that has been operating for 3 decades (IFRC, 2010) and the cities programme of the Asian Disaster Preparedness Centre (ADPC). As donor interest has grown in supporting disaster risk management as a vehicle for climate change adaptation, a number of urban resilience programmes have developed including ACCCRN – the Asian Cities Climate Change Resilience Network (Brown *et al.*, 2012), the UNISDR - United Nations International Strategy for Disaster Reduction Making Cities Resilient network (Johnson and Blackburn, 2014), the ICLEI – Local Governments for Sustainability city adaptation network and UN-Habitat’s Cities and Climate Change Initiative.

Despite growing international support for urban disaster risk management, local governments have difficulty accessing the resources to make real change (von Hesse *et al.*, 2008). Local government risk reduction investments are not seen as priorities and have to compete for scarce resources with what are judged to be more pressing needs. Effective policies are often tied to the terms of particular mayors or political parties (Hardoy *et al.*, 2011; Mansilla *et* *al.*, 2008). In most cases, risk reduction is not integrated into development plans or all relevant local government departments. Manizales, Colombia, is an exception: risk reduction has long been seen as part of local development and collective interests take precedence over party political interests (Hardoy and Velásquez Barreto, 2014).

Disaster risk management is increasingly positioned as a frontline sector for integrating climate change adaptation into everyday decision-making and practices (IPCC, 2012), as seen in the plans of municipalities such as Tegucigalpa and Montevideo (Aragón-Durand, 2011). Where it is taken seriously, it offers real opportunities for synergy as the long-range nature of climate change concerns and its policy visibility can enhance local support for disaster risk management. There is considerable scope in international frameworks and national responsibilities for better coordination to make urban disaster risk management climate resilient (Aragón-Durand, 2008; IPCC, 2012).

8.3.3. Adapting Key Sectors

8.3.3.1. Adapting the Economic Base of Urban Centres

Section 8.2 described how climate change can change the comparative advantages of cities and regions – for instance by influencing climate sensitive resources, water availability and flooding risks. Many case studies show how extreme weather can impede economic activities, damaging industrial infrastructure and disrupting ports and supply chains (see 8.2.3.4). Vugrin and Turnquist (2012) discuss design for resilience in distribution networks such as electric power, gas, water, food production and manufacturing supply chains. This requires absorptive capacity (to withstand extreme weather), adaptive capacity (e.g. service provision through alternative paths) and restorative capacity (quick and cheap recovery).

When urban centres fail to adapt to risks, it may discourage new investment and lead enterprises to move or expand to safer locations. Multinational corporations and many national businesses are adept at changing location in response to changing opportunities and risks, including high insurance costs. Disasters can change perceptions of risk. Businesses may adapt to avoid impacts in their own facilities but be affected by impacts to utilities and other businesses or to their workforce and the services they use (schools, hospitals) (da Silva, 2012; Hallegatte *et al.*, 2011a). Limited local capacity to reconstruct means increased vulnerability to future extreme events and less new investment weakens the economic base (Benson and Clay, 2004; Hallegatte *et al.*, 2007b; Hallegatte *et al.*, 2011a). Past experience in the U.S. and Europe show the difficulties city governments can face in attracting new investment when a city or region's main activity weakens. If climate change forces changes to economic structure and business models, transitions may be hard to manage (Berger, 2003). Specific adaptation policies may make the transition more rapid and less painful. For instance, adaptation is generally cheaper and easier in greenfield sites – as low-risk sites are chosen, trunk infrastructure to appropriate standards is installed and building and land-use regulations enforced. Retrofitting existing infrastructure and industries is generally more expensive (McGranahan *et al.*, 2007).

Within and around urban centres, local governments may require several strategies to strengthen resilience including selective relocation, better land use planning and revised building regulations to retrofit or flood-proof structures (Hanson *et al.*, 2011). Synergies can be encouraged where land-use management around a city supports rural livelihoods, and protects ecosystem services (see 8.3.3.7). There may be opportunities for proactive adaptation outside larger cities where much of the future urban growth will occur. Manizales, Colombia, which has long had innovative environmental and disaster risk reduction policies has begun incorporating climate change and environmental management into its local development agenda, including the establishment of city climate monitoring systems (Hardoy and Velásquez Barreto, 2014). But most smaller urban centres are institutionally weaker and may lack the investment capacity and critical infrastructure.

Adapting the urban economic base may require short- and long-term strategies to assist vulnerable sectors and households. The consequences of climate change for urban livelihoods may be particularly profound for low-income households who generally lack assets or insurance to help them cope with shocks (Moser and Satterthwaite, 2009). The informal sector is a significant part of the economy for most urban centres, providing employment for large numbers. But the effects of extreme weather on the informal economy are rarely considered, as in 2003 floods in Santa Fe, Argentina (Hardoy and Pandiella, 2009). In Kelurahan Pabean Pekalongan in Central Java, batik production, the primary livelihood, is being disrupted by increasingly frequent floods (UN-Habitat, 2011b). Cash transfers and safety nets are being considered to help low-income groups cope with the short-term impacts of climate change (Sanchez and Poschen, 2009), as well as climate variability. But these will not address all the risks they face or support collective or public investments in risk-reducing infrastructure and services.

There is a growing discussion of the importance of support for a 'green economy' with green infrastructure to help shift nations' economic and employment base towards lower carbon, more resilient, more sustainable patterns that respect regional and global ecological and resource limits. For urban centres, this means highlighting new (or adapted) business opportunities that limit anthropogenic climate change, resource depletion and environmental degradation. Sometimes social inclusivity and eco-efficiency are included as mutually reinforcing principles (e.g. Allen and Clouth, 2012). The literature has begun to explore the changes needed in production systems (especially in carbon intensity, waste generation and management), buildings, transport systems, electricity generation (including incorporating solar and wind) and consumption patterns of wealthier groups (Hammer *et al.*, 2011; UN-Habitat, 2012a; UN-Habitat, 2012b; UN-Habitat, 2012c; UN-Habitat, 2012d; World Economic Forum, 2013). As yet, there is too little detailed discussion of how a green economy can be fostered in relation to particular cities or in regard to the incentives and regulations that can shift private investment to this.

The 'waste economy' in cities in low- and middle-income nations is important to the green economy, providing livelihoods (Hardoy *et al.*, 2001; Hasan *et al.*, 2002; Medina, 2007) and contributing to waste reduction and GHG emission reduction (Ayers and Huq, 2009). In Brazil's main cities, over half a million people are engaged in waste picking and recycling (Fergutz *et al.*, 2011); in Lima an estimated 17,000 and in Cairo, 40,000 (Scheinberg *et al.*, 2011). The ways city governments choose to work with (or ignore) those in this waste economy have obvious implications for employment and for resource use.

For some cities, there is documentation of the adaptation costs to protect or enhance the economic base. Hallegatte *et al.* (2013) assess present and future flood losses in the world's 136 largest coastal cities and show that the estimated costs of adaptation are far below the estimate of losses in the absence of adaptation. The paper also highlights the differences in the cities most at risk, depending on whether the ranking is by economic average annual losses or by such losses as a proportion of each city's GDP. In the first, it is mainly cities in high-income nations, in the second, mainly prosperous cities in middle-income nations.

Mombasa may have to redesign and reconstruct the city's ports, protect cement industries and oil refineries and relocate some industries inland, all requiring major capital investments (Awuor *et al.*, 2008). Adaptation can help protect many parts of Rio de Janeiro's diverse economy (including manufacturing, oil refineries, shipyards and tourism) and the large populations living in informal settlements (favelas) on land at risk of landslides (de Sherbinin *et al.*, 2007). Defences needed to safeguard coastal industries and residential areas could threaten Rio's beach tourist industry and cause further erosion to other unprotected areas. As in most cities, making Rio's economic base more resilient to climate change means resolving such trade-offs, and dialogue among local stakeholders (Ruth, 2010).

As yet, there is little evidence that cities' adaptive capacities influence private sector investments. But private investment is influenced by the quality and availability of infrastructure and services that are an essential part of adaptive capacity. Many cities in Asian high growth economies are located in low-elevation coastal zones undergoing rapid urbanisation and economic transformation (McGranahan *et al.*, 2007). Cyclones are common in many of these coastal settlements. Rising concentrations of people, infrastructure, and industries along India's coasts, without adaptation, could mean non-linear increase in vulnerability over the next two decades (Revi, 2008). The same is true for China (McGranahan *et al.*, 2007). In most nations, urban governments find it difficult to prevent new developments on sites at risk of flooding, especially in locations attractive for housing or commerce, even when there are laws and regulations in place to prevent this (see Olcina Cantos *et al.* (2010) for an example in Alicante in Spain).

There are few economic assessments of climate change risks in West African coastal cities. Many cities or districts and their industries, infrastructure and tourism will be a challenge to protect, as in Cotonou (Dossou and Gléhouenou-Dossou, 2007), Lagos (Douglas *et al.*, 2008) and Dakar (Wang *et al.*, 2009).These and other important economic centres in the Gulf of Guinea (including Abidjan and Port Harcourt) have large areas close to mean sea level and highly vulnerable to erosion and rising sea levels. Rapid construction, destruction of mangrove swamps and inadequate refuse collection compound the risks (Simon, 2010).

8.3.3.2. Adapting Food and Biomass for Urban Populations

Many urban dwellers in low- and middle-income countries suffer hunger, while a larger number face food and nutrition insecurity (Ahmed *et al.*, 2007; Cohen and Garrett, 2010; Crush *et al.*, 2012; Montgomery *et al.*, 2003) due more to their low incomes than to overall food shortages (Cohen and Garrett, 2010; Crush *et al.*, 2012). For these low-income urban households, food expenditures generally represent more than half of total expenditures (Cohen and Garrett, 2010), putting them at particular risk from real increases in long-term food prices or temporary spikes associated with disasters.

Climate change impacts can have far-reaching influences on food security and safety, but these “will crucially depend on the future policy environment for the poor” (Schmidhuber and Tubiello, 2007, p. 708, see also Douglas, 2009). Agriculture has managed to keep up with rising demands worldwide, despite rapid population growth, the reduction in agricultural workers that accompanies urbanisation, and dietary shifts that are more carbon- and often land- intensive (Satterthwaite *et al.*, 2010). But food security may be eroded by competing pressures for water or bio-fuels. In addition, there may be tensions between managing land-use to reduce flood risk and food and energy policies (Wilby and Keenan, 2012). Adapting urban food systems represents a major challenge and will necessitate radical changes in food production, storage and processing (and in reducing waste), in transport/the supply chain and in access (Godfray *et al.*, 2010). Both supply and demand side constraints must be considered. Climate-change related constraints on agricultural production affect urban consumers through reduced supplies or higher prices; falling production and farmer incomes reduces their demand for urban goods and services; disruption to urban centres can mean disruption to the markets, services or remittance flows on which agricultural producers rely (Tacoli, 2003). Thus, strengthening urban food security needs to take account of complex rural-urban linkages (Revi, 2008) and responses must bridge rural and urban boundaries.

Urban centres that are seriously impacted by extreme weather face serious challenges in ensuring that those affected have access to adequate and safe food and water supplies. Flooding, drought, or other extreme events often lead to food price shocks in cities (Bartlett, 2008) as well as spoiling or destroying food supplies for many households. After the 2004 floods in Bangladesh, Dhaka’s rice prices increased by 30 percent and vegetable prices more than doubled, with urban slum-dwellers and rural landless poor the worst affected (Douglas, 2009). When facing increased food prices, the urban poor adopt a range of strategies such as reduced consumption, fewer meals, purchasing less nutritious foods, or increasing income earning work hours, particularly for women and children (Cohen and Garrett, 2010). But these erode nutrition and health status, especially of the most vulnerable and fail to strengthen resilience, particularly in the context of more frequent disasters.

Adaptive local responses include support for urban and peri-urban agriculture, green roofs, local markets and enhanced safety nets. Food price increases may be moderated by improving the efficiency of urban markets, promoting farmers’ markets, investing in infrastructure and production technologies (Cohen and Garrett, 2010). Food security may be enhanced by support for urban agriculture and street food vendors (*ibid.*, Lee-Smith, 2010) and access to cheaper food or measures like cash transfers (e.g. Brazil’s Bolsa Familia Programme) or, for older groups, pensions (Soares *et al.*, 2010). Initially rural in focus, cash transfer programmes have expanded in urban areas, in some places reaching much of the low-income population (Johannsen *et al.*, 2009; Mitlin and Satterthwaite, 2013; Niño-Zarazúa, 2010).

8.3.3.3. Adapting Housing and Urban Settlements

The built environment in urban areas has to adapt to the range of climate change impacts outlined in 8.2, in order to protect urban populations and economies and protect among society’s most valuable assets. Knowledge and innovation are required for adapting existing and new buildings. This will be built on the bedrock of affordable housing appropriate for health and safety, built to climate-resilient standards and with the structural integrity to protect its occupants long term against extreme weather (United Nations, 2009; United Nations, 2011). The resilience of poor quality housing, often at risk from extreme weather, can be enhanced via structural retrofitting, interventions that reduce risks (for instance expanding drainage capacity to limit or remove flood risks) and non-structural interventions (including insurance). Attention to all three is more urgent where housing quality is low, where settlements are on high-risk sites and in cities where climate change impacts are greatest. Enhancing the resilience of buildings that house low-income groups will usually be expensive and may face political challenges (see Roaf *et al.*, 2009).The range of actors in the housing sector, the myriad connections to other sectors and the need to promote mitigation, adaptation as well as development goals point to the importance of well-coordinated strategies that can support resilience (Maller and Strengers, 2011).

There have been studies in increasing numbers of cities to identify measures to adapt housing (and other buildings) and discussions on revising standards, although it is difficult to set standards with uncertain forecasts and scenarios and evolving risks (Engineers Canada, 2008). There is less evidence of the action plans, budget commitments and regulation changes to implement them. Measures identified in a Bangkok assessment included flood-proofing homes, building elevated basements, and moving power-supply boxes upstairs, along with keeping enough food, water, fuel, and other supplies for 72 hours; it also pointed to regulatory changes to bolster resilience including land use restrictions in floodplains and other at-risk sites and revised safety and fire codes for buildings and other structures (BMA and UNEP, 2009). Cape Town's climate change framework (2006) proposed housing interventions including regulations for building informal housing, in part to reduce the need for emergency response and anticipate projected climate change. Regulations in New York and Boston are being updated to address climate-related risks (Boston, 2011; City of New York, 2011). London and Melbourne's adaptation plans both consider strategies combining green infrastructure and housing interventions (GLA, 2010; UN-Habitat, 2011a).

Housing and other buildings and extreme heat: More attention is being paid to extreme heat in particular cities (for instance, Chicago 2008; Chicago 2010; City of Toronto 2013; Tomlinson *et al.* (2011) for Birmingham, Matzarakis and Endler (2010) for Freiberg, GLA (2010) for London, and Giguère (2009) for Quebec); also in regard to low-income housing in Athens (see Sakka *et al.*, 2012).

Attention is required to buildings that provide protection from hot days and to populations more vulnerable to extreme heat, including those who work outside (see cross-chapter box on heat stress and heat waves). In locations with large daily variations in temperature, the response can include upgrading homes with limited ventilation and low thermal mass. Chicago's 2008 Climate Action Plan discussed the need for innovative cooling ideas for property owners (Chicago, 2008, p. 52). Air conditioning and other forms of mechanical cooling are too expensive, unavailable for the many urban households with no electricity, and mal-adaptive when electricity generation contributes to greenhouse gas emissions. Residents' vulnerabilities may be exacerbated if electricity supplies are unreliable; blackouts tend to occur on the hottest days when demand is highest (Maller and Strengers, 2011, p. 3). The literature on adaptations for extreme heat focuses on high-income nations and more attention is required to this in urban centres in low- and middle-income nations.

Passive cooling can be used in both new-build and retrofitted structures to reduce solar and internal heat gains, while enhancing natural ventilation or improving insulation (Hacker and Holmes, 2007; Roberts, 2008a; Roberts, 2008b). Passive designs, using super-insulation, ventilation, and other measures to ensure energy is not required for most of the year, as in the Beddington Zero Energy Development (BedZED) in London (Chance, 2009) or Germany's Passive Haus standard (Rees 2009) have set precedents for mitigating household emissions but they can simultaneously contribute to adaptation. Thermal mass can be used for cooling, "because it introduces a time-delay between changes in the outside temperature and the building's thermal response necessary to deal with the high daytime temperatures" (Hacker and Holmes, 2007, p. 103). Structures in southern Europe already use solar shading, ventilation, and thermal mass to promote enhanced cooling (*ibid.*). Simulations for London (under UKCIP02 Medium-High emissions scenarios) suggest that passive designs are an "eminently viable option for the UK, at least over the next 50 years or so" (*ibid.*, p. 111). There are several obstacles though: opening windows may be hampered by security concerns or noise pollution (Hacker and Holmes, 2007). Modern windows may not ventilate well, and site restrictions and cost can impede the use of passive cooling in refurbishing existing buildings (Roberts, 2008a).

Housing and disaster-preparedness measures: When populations are displaced or temporarily evacuated, provision for emergency shelters and services have to be able to respond, especially for vulnerable residents. For instance, after Cyclone Larry in Queensland (in 2006) and New South Wales' coastal flooding (in 2007), officials recalled the strains faced in shelters and the coordination difficulties with emergency health workers, police, insurance, and other agencies (Jacobs and Williams, 2011). This points to the range of social support, structural strategies, and interagency efforts that local authorities may develop to adapt to climate change. For many urban centres, there is also the issue of how to move populations at risk, which presents many challenges (Roaf *et al.*, 2009).

Urban centres facing extreme heat require plans that provide early warning for citizens, inform them of measures they can take and ensure adequate water provision, back up electricity, emergency healthcare, and other public services focused on vulnerable residents, especially infants and the elderly in hospitals and residential facilities (Brown and Walker, 2008; Hajat *et al.*, 2010) or living alone. Public buildings with cooling may also be required. Cities with responses to hot days for those most at risk are mainly from high-income nations. Several hundred million urban dwellers in low- and middle-income nations have no access to electricity (Johansson *et al.*, 2012) or mechanical devices that help with cooling.

8.3.3.4. Adapting Urban Water, Storm, and Waste Systems

It is challenging to summarize key adaptation strategies from the highly heterogeneous mix of urban areas across the globe. In high-income and some middle-income nations, virtually all the urban population is served by drinking quality water piped to the home 24 hours a day, by systems of sanitation that minimize risks of faecal contamination and by storm and surface drainage. Many urban centres in such nations may face serious climate change-related challenges for water, but do not have to address the fact that much of their population lacks piped water, toilets or storm drains. They can also bill users for much of the funds required for water provision and management.

At the other extreme are a very large number of urban centres with large deficits in provision for water, sanitation and drainage and with weak, under-resourced institutions (UN-Habitat, 2003b; UNEP, 2012). Around a billion people live in informal settlements where providers responsible for water and sanitation are often unwilling to invest or not allowed to do so (Mitlin and Satterthwaite, 2013). New York City can develop a ten billion dollar plan to assure adequate water supplies (Solecki, 2012); many cities in sub-Saharan Africa not only have very large deficits in piped water, sewers and drains but very limited investment capacities (see, for instance, Kiunsi (2013) for Dar es Salaam).

Some studies have sought to estimate the costs of adapting urban water and sanitation systems, pointing to the need for significant investments (Arnell, 2009). Muller (2007) suggests that $1-2.7 billion is required annually in sub-Saharan African cities to adapt existing water infrastructure; this does not include the cost of addressing deficient infrastructure. Another $1-2.6 billion a year is required to adapt new developments (including water storage, waste-water treatment and electricity generation).

Adapting urban water supply systems: For cities with climate change adaptation plans, water and waste water management are usually important components (see, for instance, Helsinki Region Environmental Services Authority, 2012). Major *et al.* (2011) list a range of cities that have begun to adapt water systems and other infrastructure including Boston, London, Halifax (Canada), New York, Seattle and Toronto. The US Government has developed a guide for adaptation strategies for water utilities (US EPA, 2013). But developing such measures is not yet common place.

Supply-side approaches to seasonal water shortages are frequently advocated. An analysis of 21 draft Water Resources Management Plans in the UK found that agencies usually favoured reservoirs and other supply-side measures to adapt to climate change, although authors suggest that demand-side interventions may also be needed (Charlton and Arnell, 2011). To expand its reservoir capacity after 1998 floods exposed existing infrastructure, Rotterdam developed plans combining adaptation and urban renewal goals, mixing economic activities with water-based adaptive designs, including 'water retention squares' and green roofs; floating houses; and networks of channels (Van der Brugge and De Graaf, 2010). Seattle has used demand-side strategies to cut water consumption including aggressive conservation measures, system savings and price increases (Vano *et al.*, 2010).

In Mexico City, a number of measures in the water sector have been proposed many times since the 1950s but not acted on, including a decrease in water use and the restoration and management of urban and rural micro-basins (Romero-Lankao, 2010). Adaptation measures have been conceived as too general and lacking institutional commitment. In Durban, where the water sector is revenue earning and seen as critical to development, the importance of climate change adaptation was recognized as a priority (Roberts, 2010). In Cape Town, which faces profound challenges in ensuring future supplies, water management studies identified the need to consider climate change and population and economic growth (Mukheibir and Ziervogel, 2007). During the 2005 drought, the local authority substantially increased water tariffs, considered a most effective way to promote efficient water usage (Mukheibir, 2008). Other measures may include water restrictions; reuse of grey water; consumer education; or technological solutions such as low-flow systems or dual flush toilets (*ibid*).

In Phoenix, Arizona, a rapidly expanding desert city projected to reach 11 million people by 2050, most peripheral growth depends on groundwater (Bolin *et al.*, 2010). Simulations explored how water usage may be reduced to achieve safe yield while accommodating future growth. Reducing current high use may be achieved through urban densification, increased water prices and water conservation measures *(ibid).* Gober *et al.* (2010) agree that stringent demand and supply policies can forestall "even the worst climate conditions and accommodate future population growth, but would require dramatic changes to the Phoenix water supply system" *(ibid,* p. 370). Here and in other cities in Arizona, supply side management including active management of groundwater and groundwater storage is combined with extensive demand side measures (Colby and Jacobs, 2007).

In Quito, where reduced freshwater supplies are projected with glacier retreat and other climate-related changes, local government has formulated a range of adaptation plans, including encouraging a culture of rational water use, reducing water losses and developing mechanisms to reduce water conflicts (Hardoy and Pandiella, 2009). However, community participation in planning and implementation has not been considered (*ibid.*). Participatory water planning has occurred elsewhere in Latin America: stakeholders in Hermosillo, Mexico, identified and prioritized specific adaptations such as rainwater harvesting and water-saving technologies (Eakin *et al.*, 2007).

Several cities actively encourage rainwater harvesting while others are considering its potential. Since 2004, in New South Wales, Australia, homeowners have been required to ensure that newly built houses use 40% less potable water than an established benchmark level of consumption, through water-saving measures like water-efficient shower heads, dual-flush toilets, rainwater tanks and grey water treatment systems (Warner, 2009). Many low-income Caribbean households rely on rainwater collection systems for domestic use. Extending existing communal collection and distribution systems would require community financing or governmental interventions, as well as overcoming resistance from higher-income residents (Cashman *et al.*, 2010). Rainwater harvesting has been promoted in several cities in India (Shaban and Sharma, 2007).

Waste and storm water management: More attention has been given to adaptations to help ensure sufficient water supplies than to increasing the capacity of sewer and drainage systems, or adapting them to allow for the impacts of heavier rainfall or sea-level rise. We noted earlier the very large deficiencies in provision for drainage for urban centres in low- and many middle-income nations.

In St. Maarten, Netherlands Antilles, the government, after a storm water modelling study, is developing a flood warning system and considering such institutional adaptations as a new decision-support framework, centralised GIS for infrastructure planning and public education, along with structural measures like draining areas with a high groundwater table (Vojinovic and Van Teeffelen, 2007). City management in Toronto, Canada, has prioritised an upgrade of storm water and wastewater systems (Kessler, 2011). Deak and Bucht (2011) analyse past hydrological structures in Lund, Sweden and use the concept of indigenous blue infrastructure to question current storm water management in the urban core. Cities in California have a range of flood management methods but Hanak and Lund (2012) suggest that they will also require forward-looking reservoir operation planning and floodplain mapping, less restrictive rules for raising local funds, and improved public information on flood risks.

Willems and Arnbjerg-Nielsen (2013) suggest that climate change adaptation for urban drainage systems requires a re-evaluation of the technical solutions implemented over the last 150 years. The objective is cities that interact with water (including storms) in a healthy, environmentally friendly, and cost-efficient way. This includes the incorporation of roads and parks into the active drainage system and the use of blue and green storm water infrastructure (see section 3.3.3.7). These authors also note that this implies changing roles for water scientists, water managers and water engineers as well as for water users, property owners, insurers, city planners and politicians (*ibid.*, also Willems *et al.* 2012). Many governments in the last 20 years have developed integrated water resource management (UNEP, 2012) with linkages between provisions for water, sanitation and drainage and other sectors, and a recognition of the need to work with a range of partners, consider broader development goals, identify tensions or trade-offs (Willems and Arnbjerg-Nielsen, 2013) and implement low-regret anticipatory solutions. For cities, this often includes management of groundwater use and water catchment in areas outside their jurisdiction and thus collaboration with other local governments (WMO, 2008). Most examples of this are in high-income nations (for an exception, see Bhat *et al.*, 2013).

Urban water systems usually depend on reliable electricity supplies and can be energy intensive – for instance, in conveying or treating water from distant or low-quality sources. Integrated planning (for instance, in concert with energy conservation, water catchment management and green infrastructure strategies) can minimize conflicts, support local industries, and ensure equitable access to water in cities.

8.3.3.5. Adapting Electric Power and Energy Systems

The heavy dependence of urban economies, infrastructure, services and residents on electricity and fossil fuels means far-reaching consequences if supplies are disrupted or unreliable (see 8.2.4.2). With mitigation concerns dominating the literature and urban energy policy discussions, there is less focus on adaptation issues (Carmin *et al.*, 2009; Mdluli and Vogel, 2010). The UNFCCC's estimates for investment to address climate change (UNFCCC, 2007) did not include the costs of adapting the energy sector (Fankhauser, 2010). Key issues relating to energy sector adaptation, including generation and distribution, are usually national or regional and are discussed in Chapter 10. But urban governments' and residents' responses are also important. Research has suggested that "private autonomous measures will dominate the adaptation response as people adjust their buildings, [or] change space-cooling and -heating preferences..." (Hammer *et al.*, 2011, p. 27). A few cities have adaptation initiatives underway for energy systems; others have begun to consider the steps needed (*ibid.*). Some relevant local urban concerns are the extent of the need for autonomous provision or back-up generating capacity, and the functioning of emergency services when energy supplies are disrupted or unreliable. The interrelations between energy and other sectors suggest the need for an integrated approach in understanding vulnerability and shaping appropriate responses (Gasper *et al.*, 2011).

Despite growing concern about the potential impact of climate change and extreme weather events for the oil industry in Canada, US and Mexico and how hurricanes, floods and sea level rise will disrupt oil, gas and petrochemical installations (Levina *et al.*, 2007; Savonis *et al.*, 2008), few adaptation studies have been undertaken.

8.3.3.6. Adapting Transport and Telecommunications Systems

Urban centres depend on transport and telecommunications systems for daily functioning and for vital regional, national and international supply chains. For instance, 80 percent of the food consumed in London is imported (Best Foot Forward, 2002). The Great Lakes–St. Lawrence route in the USA supports 60,000 jobs and US$ 3 billion worth annual movement of goods (Ruth, 2010). Most large and successful cities have also spread spatially, and well-functioning transport systems support the decentralization of the workforce and businesses. Many cities, for instance, depend on underground electric rail systems which require protection from the considerable risk from flooding – such as New York and London (Eichhorst, 2009). Adapting all these systems to the impacts of climate change (including hot days, storms and sea-level rise) poses many challenges (Mehrotra *et al.*, 2011b).

Transport systems: Four different aspects to adaptation strategies for transport can be highlighted: maintain and manage, strengthen and protect, enhance redundancy and, where needed, relocation. Cities that have developed adaptation plans usually include attention to more resilient transport systems (UN-Habitat, 2011a). Melbourne's adaptation plan notes that intense storms and wind may lead to blocked roads and disrupt traffic lights, trains, and trams and that these disruptions can be exacerbated by such compounding factors as power disruptions and emergency situations (Melbourne, 2009). Adaptation will require transport planners to take a whole-of-life approach to managing infrastructure, and constantly update risk assessments (Love *et al.*, 2010). Coordination at national, regional, and local levels is important for implementing adaptation strategies in the transport sector, since climate change impacts are widespread and extend across scales (Regmi and Hanaoka, 2011). Interdisciplinary approaches can include changing meteorological hazards as well as social and political values and the governance framework for more resilient transport systems (Jaroszweski *et al.*, 2010).

Adapting roads: Climate change may increase the costs of maintaining and repairing road transport networks (see Hayhoe *et al.* (2010) for discussion of changing conditions in Chicago). In Durban, revised road construction standards may be needed (Roberts, 2008). Coastal road adaptation may require strengthening barriers and designing roads or realigning them to higher locations to cope with sea-level rise (Regmi and Hanaoka, 2011).

Transport planners are beginning to reassess maintenance costs and traditional materials – for instance stiffer binding materials to cope with rising temperatures; softer bitumen for colder regions (Regmi and Hanaoka, 2011). But cost considerations may impede their use. The Chicago Department of Transportation decided not to use more permeable, adaptive road materials because of higher cost, although costs may fall with greater economies of scale as demand rises for such materials (Hayhoe *et al.*, 2010). Road maintenance costs vary widely, depending on local context, and future climate scenarios. In Hamilton, New Zealand, increases in rainfall in spring (within one scenario) or winter (in another) would increase road repair costs while decreases in rainfall in other seasons could decrease them; results depend upon the scenario and further investigation was recommended (Jollands *et al.*, 2007).

Adapting surface and underground railways: Underground transport systems are specific to cities and of great importance to the functioning of many major cities. They may have "particular vulnerabilities related to extreme events, with uniquely fashioned adaptation responses" (Hunt and Watkiss, 2011, p. 14). Heat impacts are often significant, as these systems gradually warm due to engine heat, braking systems, and increased passenger loads. To cope with increasing frequency of hot days, substantial investments in ventilation or cooling may be necessary (Love *et al.*, 2010). For New York City's subways, the system's age, fragmented ownership, overcapacity and in some cases floodplain location may augment the challenge of adaptation (Zimmerman and Faris, 2010, pp. 69-70). Storm surge flooding from Hurricane Sandy flooded eight under-river subway tunnels, severely impacting mobility and economic activity (Blake *et al.*, 2012).

Rail systems that struggle to cope with existing climate variability may require considerable investment to withstand higher temperatures and more extreme events (see Baker *et al.*, 2010). Railway systems may be more vulnerable to climate variability than the road system, which can more easily redirect traffic (Lindgren *et al.*, 2009). The costs of delays and lost trips due to extreme weather events, analysed in Boston (Kirshen *et al.*, 2008) and Portland (Chang *et al.*, 2010), were found to be small relative to the damage to infrastructure and other property. Floodplain restoration, use of porous pavements, and detention ponds may help address the projected increased flooding in Portland (*ibid.*).

In flood-prone cities, transport systems may require more stringent construction standards, design parameters, or relocation. Much of central Mumbai is built on landfill areas and prone to flooding, but they contain the main train stations and train lines as well as large populations and a large part of the city's economy. Rising sea levels may cause shifts at the sub-surface level of landfill areas and structural instabilities (de Sherbinin *et al.*, 2007).

Ports: 8.2 outlined the many ways in which ports can be impacted by climate change and the investments required to take account of these. Many ports remain largely unaware of the potential threats of climate change, or are slow to consider appropriate adaptation measures (Becker *et al.*, 2012). Rotterdam's Climate Proof Programme includes as key components flood safety and accessibility for ships and passengers (Rotterdam Climate Initiative, 2010; Vellinga and De Jong, 2012). A climate risk study for the Port of Muelles el Bosque (Cartagena, Colombia) analyzed projected changes in sea level rise, storm surge height, precipitation, temperature and wind patterns and their direct and indirect effects on port assets and operations, surrounding environment and communities, and on the trade of goods transported through the port and this helped catalyze adaptation investments (Stenek *et al.*, 2011).

There are also the deficits in basic infrastructure noted in 8.2 that inhibit adaptation including the lack of all-weather roads and paths in informal settlements that constrain rapid evacuation and limit access for emergency vehicles.

Telecommunications: A wide range of components and sub-systems for telecommunications systems that are within cities may need adaptation to the impacts of climate change – including telephone poles and exchanges, cables, mobile telephone masts and data centres (Chapman *et al.*, 2013; Engineering the Future, 2011).

8.3.3.7. Green Infrastructure and Ecosystem Services within Urban Adaptation

Ecosystem based adaptation has relevance for many chapters (see the cross-chapter box on Ecosystem-based Adaptation CC-EA). Ecosystem-based adaptation in urban areas as part of the climate change adaptation strategy seeks to move beyond a focus on street trees and parks to a more detailed understanding of the ecology of indigenous ecosystems, and how biodiversity and ecosystem services can reduce the vulnerability of ecosystems and people. Strategies to achieve biodiversity goals (developing corridors for species migration, enlarging core conservation areas, identifying areas for improved matrix management to enhance ecological viability) can have adaptation co-benefits. Recognizing that the adaptation deficit is both in the lack of conventional infrastructure and the loss of ecological infrastructure, the approach includes an interest in how ecosystem restoration and conservation can contribute to food security, urban development, water purification, waste water treatment climate change adaptation and mitigation (Roberts *et al.*, 2012). The growing attention to ecosystem services includes adaptations in urban, peri-urban and rural areas which use opportunities for the management, conservation and restoration of ecosystems to provide services and increase resilience to climate extremes. They can also deliver co-benefits (e.g. purifying water, absorbing runoff for flood control, cleansing air, moderating temperature, preventing coastal erosion) while helping contribute to food security and carbon sequestration (Foster *et al.*, 2011b; GLA, 2011; Newman, 2010; Roberts *et al.*, 2012; see also City of New York, 2011; Helsinki Region Environmental Services Authority, 2012; Institute for Sustainable Communities, 2010; Oliveira *et al.*, 2011; Tallis *et al.*, 2011; Wilson *et al.*, 2011). These approaches are particularly important in low- and many middle-income countries where livelihoods for some urban residents and much of the peri-urban population depend on natural resources. But there are considerable knowledge gaps in determining the limits or thresholds to adaptation of various ecosystems and where and how ecosystem based adaptation is best integrated with other adaptation measures. There is also some indication that the costs of ecosystem based adaptation in urban contexts might be higher than expected, in large part because costs are higher for land acquisition and ecosystem management (Cartwright *et al.*, 2013; Roberts *et al.*, 2012).

Box 8-2 describes how ecosystem-based adaptation is being developed in Durban. Another example is addressing flood risk through catchment management that includes community-based partnerships supported by full cost accounting and payment for ecosystem services – rather than the more conventional canalisation of rivers (Kithiia and Lyth, 2011; Roberts *et al.*, 2012).

_____ START BOX 8-2 HERE _____

Box 8-2. Ecosystem-based Adaptation in Durban

Durban has adopted an ecosystem-based adaptation approach as part of its climate adaptation strategy. This required a series of steps:

- A better understanding of the impacts of climate change on local biodiversity and the management Durban’s open space. The projected warmer and wetter conditions seem to favour invasive and woody plant species.
- Improved local research capacity that includes generating relevant local data.
- Reducing the vulnerability of indigenous ecosystems as a short term precautionary measure.

- Enhancing protected areas owned by local government and developing land-use management interventions and agreements to protect privately-owned land areas critical to biodiversity and ecosystem services. This can be supported by government incentives and regulation to stop development on environmentally sensitive properties, the removal of perverse incentives and support for affected landowners.
- The promotion of local initiatives that contribute jobs and promote skills and environmental education within ecosystem management and restoration programmes. Durban has initiated a large scale Community Reforestation Programme where community level 'tree-preneurs' produce indigenous seedlings and help plant and manage the restored forest areas as part of a larger strategy to enhance biodiversity refuges and water quality, river flow regulation, flood mitigation, sediment control and improved visual amenity. Advantages include employment creation, improved food security and educational opportunities.

Source: (Roberts *et al.*, 2012)

_____ END BOX 8-2 HERE _____

Although much of the early innovation in ecosystem services and green infrastructure was geared to address water shortages or flooding, its importance for climate change adaptation is increasingly recognized.

Green spaces in cities are beneficial for absorbing rainfall and moderating high temperatures. Urban forests and trees can provide shading, evaporative cooling and rainwater interception, storage and infiltration services for cities (Pramova *et al.*, 2012). Increasing tree cover is proposed as a way to reduce UHI. Cooling effects are especially high in large parks or areas of woodland but the land these are on face competition from developers, as well as management challenges *(ibid).* The rapid and often unregulated expansion of cities in low- and middle-income nations may also have left a much lower proportion of the urbanized area as parks and other green spaces.

There is also lack of detailed knowledge on the climatic effects of specific urban plants and vegetation structures (Mathey *et al.*, 2011) and on other important aspects such as the influence of green areas in local circulation patterns and impact on urban fluxes and urban metabolism (Chrysoulakis *et al.*, 2013). In addition, green infrastructure projects may select plant material for particular purposes that do not support habitat values or large ecosystem function and greater ecosystem services.

Some city governments have focused on green infrastructure within built up areas. In the USA, Portland and Philadelphia have encouraged green roofs, porous pavements and disconnection of downspouts) to reduce storm water at much lower cost than increasing storm water capacity (Foster *et al.*, 2011b). Some cities have invested in green infrastructure linked to both regeneration and climate change adaptation. The Green Grid for East London seeks to create "a network of interlinked, multi-purpose open spaces" to support the wider regeneration of the sub-region, enhancing the potential of existing and new green spaces to connect people and places, absorb and store water, cool the vicinity and provide a mosaic of habitats for wildlife (GLA, 2008, p. 80). New York has a well-established programme to protect and enhance its water supply through watershed protection. This includes city ownership of crucial natural areas and working with land owners and communities to balance protection of drinking water with facilitating local economic development and improving waste water treatment. There is also an ambitious green infrastructure plan, including porous pavements and streets, green and blue roofs and other measures to control stormwater. The programme is costly, compared to constructing and operating a filtration plant, but is the most cost-effective choice for New York (Bloomberg and Holloway, 2010; Foster *et al.*, 2011b).

The coastal city of Quy Nhon in Vietnam is reducing flood risks by restoring a 150-hectare zone of mangroves (Brown *et al.*, 2012). Singapore has used several anticipatory plans and projects to enhance green infrastructure including its Streetscape Greenery Master Plan, constructed wetlands or drains and community gardens (Newman, 2010). Authorities in England and the Netherlands are recognising the linkages between spatial planning and biodiversity, but without much direct response to climate change adaptation. Barriers to action include short-term planning horizons, uncertainty of climate change impacts, and problems of creating habitats due to inadequate resources, ecological challenges, or limited authority and data (Wilson and Piper, 2008).

In Mombasa, the Bamburi Cement Company rehabilitated 220 hectares of quarry land (Kithiia and Lyth, 2011). The resulting Haller Park attracts over 150,000 visitors per year, and has the potential to create adaptation co-benefits. Cape Town has initiated community partnerships to conserve biodiversity, including the Cape Flats Nature project with the para-statal South African National Biodiversity Institute. Participating schools and organisations explore ecosystem services (such as flood mitigation and wetland restoration), and the project facilitates "champion forums" to support conservation efforts (Ernstson *et al.*, 2010, p. 539).

Dedicated green areas within urban environments compete for space with other city-based needs and developer priorities. The role of strategic urban planning in mediating among competing demands is potentially useful for the governance of adaptation as demonstrated in London, Toronto, and Rotterdam (Mees and Driessen, 2011). The experience in Durban (see Box 8-2) also faces many challenges (Roberts *et al.*, 2012), including an assumption that ecosystem based adaptation is an easy alternative to the constraints that limit the implementation and effectiveness of "hard engineering" solutions (*ibid.*, Kithiia and Lyth, 2011). Experience in Durban shows that implementing an ecologically functional and well-managed, diverse network of bio-infrastructure requires data collection, expertise and resources, and to have direct and immediate co-benefits for local communities and ensure integration across institutional and political boundaries. There are substantial knowledge gaps such as determining where the limits or thresholds lie; many ecosystems have been degraded to the point where their capacity to provide useful services may be drastically reduced (TEEB, 2010).

Burley *et al.* (2012)'s review of the wetlands of South East Queensland, Australia indicates that adaptations focused on wetland and biodiversity conservation may impact urban form in coastal areas. A study of changes in tree species composition, diversity and distribution across old and newly established urban parks in Bangalore, India, aims to find ways to increase ecological benefits from these biodiversity hotspots (Nagendra and Gopal, 2011). When Leipzig applied a new approach to evaluating the impacts on local climate of current land uses and proposed planning policies, using evapotranspiration and land surface emissivity as indicators, green areas and water surfaces were found to have cooling effects, as expected, but some policies increased local temperatures (Schwarz *et al.*, 2011).

Some aspects of mitigating climate change in urban areas requires a dense urban form to maximize agglomeration economies in more efficient resource use and waste reduction and to reduce urban expansion, reliance on motorized transport and building energy use. But adaptation may require an urban form that favours green infrastructure and open space for storm water management, species migration and urban cooling (Hamin and Gurran, 2009; Mees and Driessen, 2011). Higher densities can prevent the maintenance of ecologically viable systems with high biodiversity and exacerbate the urban heat island, in turn generating the need for more cooling, increasing energy use and further escalating the urban heat island effect. This is the "density conundrum" (Hamin and Gurran, 2009, p. 242) at what point are densities too high to maintain ecologically viable systems with high biodiversity, especially given that urbanization has already compromised the ability of ecosystems to buffer urban development from hazards? This situation will be further exacerbated by new hazards (e.g. floods, fires) to which systems are or will be exposed as the result of climate change (Depietri *et al.*, 2012).

Green and white roofs: Green and white roofs, introduced in a range of cities, have the potential to create synergies between mitigation and adaptation. Rooftop vegetation helps decrease solar heat gain while cooling the air above the building (Gill *et al.*, 2007) thus improving the building's energy performance (Mees and Driessen, 2011; Parizotto and Lamberts, 2011). It can reduce cooling demand and often the use of air conditioning with its local contribution to heat gain and its implications for greenhouse gas emissions (Jo *et al.*, 2010; Zinzi and Agnoli, 2012). Rooftop vegetation can also retain water during storms, reducing stormwater run-off (Palla *et al.*, 2011; Schroll *et al.*, 2011; Voyde *et al.*, 2010) and promoting local biodiversity and food production. Studies have compared the performance of living roofs across different plant cover types, levels of soil water, and climatic conditions (see, e.g., Jim, 2012; Simmons *et al.*, 2008). Hodo-Abalo *et al.* (2012) confirm that a dense foliage green roof has a greater cooling effect on buildings in Togolese hot-humid climate conditions. Several field experiments combined with simulated modelling of impacts in the US also confirm the positive thermal behaviour of green roofs compared to alternative roof coverings (for example, Getter *et al.*, 2011; Scherba *et al.*, 2011; Susca *et al.*, 2011). Durban has a pilot green roof project on a municipal building; indigenous plants are being identified for the project and rooftop food production is being investigated (Roberts, 2010). New York's lack of space for street-level planting helped encourage the adoption of living roofs (Corburn, 2009). Under its Skyrise Greenery project, Singapore has provided subsidies and handbooks for rooftop and wall greening initiatives (Newman, 2010). Based on field tests in the UK, Castleton *et al.* (2010) find that older buildings with poor insulation benefit more from green roofs than newer structures built to higher insulation standards. Wilkinson and Reed (2009) suggest that the overshadowing caused by buildings in city centres may mean lower potential for green roof retrofits compared to installations in suburban areas and smaller towns with lower rise buildings. Benvenuti and Bacci (2010) highlight the availability of water as the main limiting factor in the realisation of green roofs.

A recent meta-analysis suggests that green roofs and parks may have limited effects on cooling. Findings on green roofs were mixed; some studies, but not all, showed lower temperatures above green sections. An urban park was found to be about 1◦C cooler than a non-green site and larger parks had a greater cooling effect. Yet studies were mainly observational, lacking rigorous experimental designs. It remains unclear whether there is a simple linear relationship between a park's size and its cooling impact (Bowler *et al.*, 2010) .

Cool roofs or white reflective roofs use bright surfaces to reflect short-wave solar radiation, which lowers the surface temperature of buildings compared to conventional (black) roofs with bituminous membrane (Saber *et al.*, 2012). There is also some work on roads and pavements with increased reflectivity (Foster *et al.*, 2011b) . Some studies have quantified the cooling benefits from white roofs in various urban settings - in Hyderabad (Xu *et al.*, 2012), in Sicily (Romeo and Zinzi, 2011) and in the North American climate (Saber et al. 2012). Comparisons between green and white roofs have also been undertaken. Ismail *et al.* (2011) investigated their cooling potential on a single-storey building in Malaysia and Zinzi and Agnoli (2012) explored the difference in a Mediterranean climate. Results suggest that local conditions play a dominant role in determining the best treatment. Hamdan *et al.* (2012), for instance, found a layer of clay on top of the roof as the most efficient for passive cooling purposes in Jordan, compared to two different types of reflective roofs.

8.3.3.8. Adapting Public Services and Other Public Responses

As city risk and vulnerability assessments become more common and detailed, they provide a basis for assessing how policies and services can adapt. Many sections of 8.2 noted health impacts that can arise or be exacerbated by climate change that will increase demands on health care systems – including those linked to air pollution, extreme weather, food or water contamination and climate sensitive disease vectors. For air quality, additional research is still needed to understand the complex links between weather and pollutants in the context of climate change (Harlan and Ruddell, 2011). Important synergies can be achieved through combining mitigation and adaptation strategies to improve air quality, reduce private transport and promote healthier lifestyles *(ibid.,* also Bloomberg and Aggarwala, 2008).

In responding to disasters, health care and emergency services (including ambulance, police and fire fighting) will have increased workloads while also ensuring that their systems can adapt. Their effectiveness can be enhanced by good working relationships with other key government sectors and with civil protection services including the army and the Red Cross/Red Crescent national societies. For cities without a robust early warning system or an emergency response network, adapting to climate change may require significant improvements in staffing, resources, and preparedness plans, for example, the data and personnel to deal with vulnerable residents during heat waves. Particular attention may be required to provide emergency services for informal settlements lacking adequate roads or infrastructure and when needed, evacuation plans for all those that have to move. There is little evidence of consideration to changes in services in response to climate change in the city case studies listed in Box 8-1.

Enhanced emergency medical services may help cope with extreme events while health officials can also improve surveillance, forecast the health risks and benefits of adaptation strategies, and support public education campaigns. Public health systems may need to increase attention to disease vector control (e.g. screening windows, eliminating breeding grounds for the mosquitoes that are vectors for malaria and dengue) and bolster food hygiene measures linking to increased flooding and temperatures. The costs of adapting health care systems may be considerable – for instance, modifying buildings and equipment, training staff, setting up comprehensive surveillance and monitoring systems that can capture the health risks of climate change, as well as other risks.

Schools and day-care centres may need risk and vulnerability assessments. School buildings can be designed and built to serve as safe shelters during floods or storms to which those at risk can move temporarily – although it is also important after a disaster to quickly re-establish functioning schools both for the benefit of children and their parents (Bartlett, 2008).

8.4. Putting Urban Adaptation in Place: Governance, Planning, and Management

This section discusses what we have learnt about introducing adaptation strategies into the decision-processes of urban governments, households, communities and the private sector. Many aspects of adaptation can only be implemented through what urban governments do, encourage, allow, support and control. This necessarily involves overlapping responsibilities and authority across other levels of government as well (Blanco *et al.*, 2011; Corfee-Morlot *et al.*, 2011; Dietz *et al.*, 2003; Kehew *et al.*, 2013; McCarney *et al.*, 2011; Ostrom, 2009). Approaches include new urban policies and incentives for action, as well as ensuring that existing policies reduce risk and vulnerability (Bicknell *et al.*, 2009; Brugmann, 2012; Urwin and Jordan, 2008). Transformation should be considered where fundamental change to economic, regulatory or environmental systems is seen as the most appropriate mechanism for reducing risk and where maintaining existing systems offers little scope for adaptation (Pelling and Manuel-Navarrete, 2011) for instance resettlement or abandonment of previously developed land.

City governments that have developed adaptation policies recognize the value of an iterative process responsive to new information, analyses or frameworks (National Research Council, 2010). In a range of cities, it has proved useful to have a unit responsible for this within city government, drawing together relevant data, informing key politicians and civil servants, encouraging engagement by different sectors and departments and consulting with key stakeholders (Brown *et al.*, 2012; Roberts, 2010).

The capacity of local authorities to work effectively, alone or with other levels, is constrained by limited funding and technical expertise, institutional mechanisms and lack of information and leadership (see Carmin *et al.*, 2013; Gupta *et al.*, 2007). Established development priorities and planning practices in functions like land-use, construction or infrastructure provision may not be aligned with the goals or practice of adaptation (Garschagen, 2013; Ostrom, 2009; Pelling, 2011a). Many national governments face comparable constraints and still do not recognize the importance of local governments in adaptation (OECD, 2010). Local adaptive capacity can benefit from disaster risk reduction (Schipper and Pelling, 2006; UNISDR, 2008). New national legislation and institutions on disaster risk reduction have helped in some cases to strengthen and support local government capacity (see 8.3.2.2), but as with other forms of adaptation, they require budgetary support and an increase in local professional capacities to be effective locally (Johnson, 2011).

8.4.1. Urban Governance and Enabling Frameworks, Conditions, and Tools for Learning

Enabling conditions and frameworks to support urban adaptation are grounded in institutional structures, values and local competence, interest, awareness and analytical capacity (Birkmann *et al.*, 2010; Moser and Luers, 2008). Preconditions for sound adaptation decision-making relate to principles of good urban government (what government does) and governance (how they work with other institutions and actors including the private sector and civil society) (Bulkeley *et al.*, 2011; Garschagen and Kraas, 2011; OECD, 2010). This includes science-policy deliberative practice and vulnerability assessment (Adger *et al.*, 2009; Corfee-Morlot *et al.*, 2011; Kehew, 2009; Moser, 2009; National Research Council, 2007; National Research Council, 2008; National Research Council, 2009; Renn, 2008). Civil society has important roles, for instance through community risk assessment, and the incorporation of local knowledge, preferences and norms (Fazey *et al.*, 2010; Krishnamurthy *et al.*, 2011; Shaw *et al.*, 2009; Tompkins *et al.*, 2008; van Aalst *et al.*, 2008). Human behaviour, values and social norms have a role and can evolve through dialogue and understanding (Dietz *et al.*, 2003; Moser, 2006; Ostrom, 2009) and engagement with stakeholders over time is key to effective adaptation (Bulkeley *et al.*, 2011; Kehew *et al.*, 2013). This has to allow consideration of dominant development trajectories and alternatives that can be approached by transformative adaptation. The capacity to act within urban settings varies with the organisational context for development (see 8.1

and Table 8-2), including the level of decentralization (Blanco *et al.*, 2011; Corfee-Morlot *et al.*, 2011; McCarney *et al.*, 2011).

8.4.1.1. Multi-Level Governance and the Unique Role of Urban Governments

A framework for urban governance emerges from the challenges that climate change brings to multilevel risk governance. Figure 8-4 summarises key actors and their relationships. Here, knowledge, policy and action are produced through the interaction, across scales, of three kinds of actors (based upon Corfee-Morlot *et al.*, 2011):

- knowledge producers (academic science, community, business and NGO produced research);
- knowledge actors or users (most important here is local government often in collaboration with partners);
- knowledge filters who can mediate between knowledge production and action (the media, lobby groups and boundary organisations that help in translation) (Ashley *et al.*, 2012; Carvalho and Burgess, 2005; Leiserowitz, 2006).

[INSERT FIGURE 8-4 HERE
Figure 8-4: The co-production of knowledge and policy for adaptation, mitigation, and development in urban systems. Source: Adapted from Corfee-Morlot *et al*., 2011.]

Urban governments, provided with authority for relevant policy decisions, are central to this process (Blanco *et al.*, 2011; Corfee-Morlot *et al.*, 2011; Kehew *et al.*, 2013; McCarney, 2012). Good practice also hinges in part upon the credibility, legitimacy and salience of science-policy processes, a strong local evidence base of historical and projected data on climate change, and on-going, open processes to support dialogue between government, civil society and expert advisors (Cash and Moser, 2000; Cash *et al.*, 2006; Kehew *et al.*, 2013; National Research Council, 2007; Preston *et al.*, 2011b; see also Ch.2). Timely and salient communication is important where a key role is played by the media, lobby groups and boundary organisations that "translate" scientific or expert information for local communities and sometimes also help to shape the questions of scientific inquiry (Gieryn, 1999; Jasanoff, 1998; Moser, 2006; Moser and Dilling, 2007; Moser and Luers, 2008). Good governance facilitates the mediation of policy and decision processes across these different actors, spheres of influence, sources of information and resources, to co-produce knowledge and support learning and action over time.

While urban governments have authority for many relevant adaptation decisions, they can be enabled, bounded or constrained by national, sub-national or supra-national laws, policies and funding and land use and infrastructure planning decisions (Arup/C40, 2012; Brown, 2011; Carter, 2011; Kehew *et al.*, 2013; Martins and da Costa Ferreira, 2011; OECD, 2010). This includes establishing formal mandates for urban adaptation action, without which adaptation becomes optional or discretionary, dependent on local-level interest and resources, and particularly vulnerable to leadership change. Where mandates for adaptation exist, they have been important in driving local level action (Kazmierczak and Carter, 2010). New mandates (formal or informal) may also require institutional changes (Kazmierczak and Carter, 2010; Lowe *et al.*, 2009; Roberts, 2008).

The level of complexity is raised in large metropolitan areas, especially when they are growing rapidly. Action has to be coordinated and harmonized across multiple urban jurisdictions; often dozens of them (e.g. Mexico City, Sao Paulo, London and Buenos Aires) and occasionally hundreds (e.g. Abidjan and Tokyo) (McCarney *et al.*, 2011; McCarney, 2012), for instance to implement flood protection of contiguous land areas (Hallegatte *et al.*, 2011b). Although there is some evidence of innovative responses at sub-national levels to plan for extreme weather events and climate change, limited capacity and experience at local government level suggests the need for support from higher levels of government (EEA, 2012; Gurran *et al.*, 2012; Norman and Nakanishi, 2011).

Policies and incentives need to be aligned to work coherently across multiple levels of government to define and deliver effective urban adaptation. This often involves institutions at different levels with different scopes of authority (Bulkeley and Kern, 2006; Cash *et al.*, 2006; Corfee-Morlot *et al.*, 2011; EEA, 2012; Kern and Gotelind, 2009; Mukheibir and Ziervogel, 2007; Urwin and Jordan, 2008; Young, 2002). Water authorities, for instance, may operate at water-basin level, representing both national and local interests while operating independently of urban authorities. Failing to ensure consistent alignment and integration in risk management can lock in outcomes that raise the vulnerability of urban populations, infrastructure and natural systems even where pro-active adaptation policies exist (Benzie *et al.*, 2011; OECD, 2009; Urwin and Jordan, 2008). Local government capacity is important, as well as the institutions that facilitate coordination across multiple, nested, poly-centric authorities with potential to mainstream adaptation measures and tailor national goals and policies to local circumstances and preferences. Horizontal coordination and networking across actors and institutions in different municipalities and metropolitan areas can accelerate learning and action (Aall *et al.*, 2007; Lowe *et al.*, 2009; Schroeder and Bulkeley, 2009).

Consultation and awareness-raising can help avoid the kind of public backlash that occurred when the French government sought to ban urban development and require strategic retreat in areas of risk to coastal flooding after the 2010 storm Xynthia (Laurent, 2010; Przyluski and Hallegatte, 2012). There can also be vested interests and trade-offs where near-term development conflicts with longer-term adaptation and resilience goals. Public engagement, openness and transparency can help ensure democratic debate to balance public interests and longer-term goals against the short-term benefits of unconstrained development. Urban governments are uniquely situated to understand local contexts, raise local awareness, respond to citizens' and civil society pressures and work to build an inclusive policy space (Brunner *et al.*, 2005; Brunner, 1996; Cash and Moser, 2000; Grindle and Thomas, 1991; Healey, 2006). Urban governments can also promote understanding of climate change risk and help to create a common vision for the future (Corfee-Morlot *et al.*, 2011; Moser, 2006; Moser and Dilling, 2007; Ostrom, 2009). The fact that preferences are more homogenous within smaller units (Ostrom, 2009) provides opportunities for leadership and innovation that may not exist at higher levels of governance. Urban governments, so often responsible for a substantial share of urban infrastructure (Arup/C40, 2012; Hall *et al.*, 2012), are also central to the interface between climate change and development, including provision for essential infrastructure and services (Bulkeley and Kern, 2006; Bulkeley, 2010). Urban planning structures, processes and plans can integrate and mainstream adaptation plans and risk management into urban and sectoral planning with a clear time frame, mandate and resources for implementation (Agrawala and Fankhauser, 2008; Bicknell *et al.*, 2009; Brugmann, 2012), even if functional authority is at national or sub-national regional levels (Hall *et al.*, 2012). Many urban governments show growing awareness and analytical capacity in adaptation planning but there is less evidence in implementation and influence on key sectors (Roberts, 2010).

Local government decisions can be driven by short-term priorities of economic growth and competitiveness (Moser and Luers, 2008) and addressing climate change can mean taking a longer-term perspective (Leichenko, 2011; Pelling, 2011a; Romero-Lankao and Qin, 2011; Viguié and Hallegatte, 2012). Tension also exists between economic growth and the needs of the large, often growing, numbers of ill-served urban poor (Bicknell *et al.*, 2009) whose resilience to climate change will depend on infrastructure and services. The challenges in low- and middle-income countries are exacerbated by relative inattention from international donors to urban policy and development concerns, as they have historically worked through national government planning processes, which may not capture the needs of urban populations (Mitlin and Satterthwaite, 2013). Donors may also prefer visible physical infrastructure projects over local institution and capacity building investments. Most national governments in high-income countries also have yet to fully embrace local adaptation initiatives (McCarney *et al.*, 2011).

8.4.1.2. Mainstreaming Adaptation into Municipal Planning

Mainstreaming adaptation into urban planning and land-use management and legal and regulatory frameworks is key to successful adaptation (Kehew *et al.*, 2013; Lowe *et al.*, 2009). It can help planners rethink traditional approaches to land use and infrastructure design based on past trends, and move towards more forward looking risk-based design for a range of future climate conditions (Kennedy and Corfee-Morlot, 2013; Kithiia, 2010; Solecki *et al.*, 2011), as well as reducing administrative cost by building resilience through existing policy channels (Benzie *et al.*, 2011; Blanco *et al.*, 2011; Urwin and Jordan, 2008). Mainstreaming through local government policies and planning ensures that investments and actions by businesses and households contribute to adaptation (Brown, 2011; Kazmierczak and Carter, 2010; Mees and Driessen, 2011; Sussman *et al.*, 2010). But this must avoid overloading already complex and inadequate planning systems with unrealistic new requirements (Kithiia, 2010; Roberts, 2008); particularly in many low- and middle-income countries, these systems are already stressed by lack of information, institutional constraints and resource limitations.

Mainstreaming may best be initiated by encouraging pilot projects and supporting experimentation by key sectors within local government. Assigning responsibility to specific departments can make the adaptation (and mitigation) message easier to understand by local governments and other stakeholders and the associated responsibilities and actions clearer and simpler to identify and assign (Roberts and O'Donoghue, 2013; Roberts, 2010; UN-Habitat, 2011a). Pilot projects and sectoral approaches ground adaptation in practical reality (Brown *et al.*, 2012; Roberts, 2010; Tyler *et al.*, 2010; UN-Habitat, 2011a). As actors in each sector in local government come to understand their roles and responsibilities, the basis for integration and cross-sectoral coordination is formed.

The literature suggests that opportunities to mainstream climate change into urban planning and development are still largely missed (Sánchez-Rodríguez, 2009). The planning agenda can already be full (Measham *et al.*, 2011). Challenges in information, institutional fragmentation and resources (Sánchez-Rodríguez, 2009; Wilson *et al.*, 2011) make it difficult to introduce the additional layer of climate change planning (Kithiia, 2010; Roberts, 2008) which may also be seen merely as “add-ons” (Kithiia and Dowling, 2010, p. 474).

Other challenges also limit progress – for instance the lack of leadership and of focal points on urban adaptation (see 8.4.3.4 for more detail). In times of economic hardship (e.g. the current recession), local authorities with already limited resources may prioritise conventional economic and development goals over ‘environmental’ issues including climate change adaptation (Shaw and Theobald, 2011; Solecki, 2012). A further challenge is getting the timely evaluation of emerging adaptation measures (Hedger *et al.*, 2008; Preston *et al.*, 2011).

Experience with adaptation programmes show they are often more cross-sectoral, cross-institutional and complex; they operate across a range of scales and timelines, are rooted in local contexts, involve many stakeholders and include high levels of uncertainty (Roberts and O'Donoghue, 2013; Roberts *et al.*, 2012). Standardised guidelines for action are less relevant and urban adaptation practitioners have identified instead the need for “clarity, creativity, and courage” (ICLEI Oceania, 2008, p. 62). In all instances, where progress on adaptation planning is observed, local leadership is a central factor (Carmin *et al.*, 2009; Carmin *et al.*, 2013; Measham *et al.*, 2011).

8.4.1.3. Delivering Co-Benefits

Important opportunities also exist to combine adaptation and mitigation goals in urban housing policies (and the energy sources they draw on), infrastructure investments and land use decisions - especially in high- and middle-income countries (Satterthwaite, 2011). Co-benefits for mitigation and for transformation require a reconsideration of dominant development pathways and of possible alternatives both within and beyond the urban core, influencing, for instance, local environments along with water-basin management and coastal defence regimes (OECD, 2010; Urwin and Jordan, 2008). Examples of positive and negative interactions between urban adaptation and mitigation strategies suggest that these strategies will need to be assessed and managed to achieve co-benefits (Kennedy and Corfee-Morlot, 2013; Viguié and Hallegatte, 2012). Viguié and Hallegatte (2012) demonstrate that despite trade-offs, careful planning can yield adaptation-mitigation co-benefits across greenbelt policies, flood zoning and transportation policies. Local governments may be able to address both adaptation and mitigation using pre-existing tools and policies such as building standards, transport infrastructure planning, and other urban planning tools (Hallegatte *et al.*, 2011a). It may be possible to avoid or limit trade-offs by developing institutional links between the different policy areas at the level of local planning (Kennedy and Corfee-Morlot, 2013; Swart and Raes, 2007; Viguié and Hallegatte, 2012).

Adaptation can produce development co-benefits in urban areas including safer, healthier, more comfortable urban homes and environments and reduced vulnerability for low-income groups to disruptions in their incomes and livelihoods (Anguelovski and Carmin, 2011; Bicknell *et al.*, 2009; Burch, 2010; Clapp *et al.*, 2010; Hallegatte *et al.*, 2011a; Kousky and Schneider, 2003; Roberts, 2010). Local development co-benefits may be particularly important to highlight in low and middle-income countries, where lack of policy buy-in accompanies limited local capacity (UN-Habitat, 2011a) and where current climate change challenges appear marginal compared with development deficits (Kithiia and Dowling, 2010; Kiunsi, 2013; Roberts, 2008). Urban authorities in India can see adaptation as a priority if it also addresses development and environmental health concerns (Sharma and Tomar, 2010).

Development and climate change adaptation are often seen as separate challenges in a sub-national planning context. A review in OECD countries showed only Japan and South Korea championing climate action as integral to sub-national development planning, although Finland and Sweden have innovative sub-national climate policies and action programmes funded by central government (OECD, 2010). For most OECD countries, urban development and adaptation are tackled separately. Yet policy research finds that successful adaptation is rooted within and harmonised with such development priorities as poverty reduction, food security and disaster risk reduction (Bicknell *et al.*, 2009; Measham *et al.*, 2011; Moser and Luers, 2008).

8.4.1.4. Urban Vulnerability and Risk Assessment Practices: Understanding Science, Development, and Policy Interactions

A critical aspect of urban climate risk governance is the integration of scientific knowledge into decision-making, building on exchange between scientists, policy-makers and those at risk (Government of South Africa, 2010; National Research Council, 2009; Rosenzweig and Solecki, 2010; Vescovi *et al.*, 2007). International policy advisory agencies with an interest in urban adaptation can augment this (ICLEI, 2010; Sonover *et al.*, 2007) , but will depend upon local capacity and engagement to produce, access and use climate change information and processes (Carmin *et al.*, 2013; Hallegatte *et al.*, 2011a). Local and regional boundary organisations can be influential in making scientific and technical information more salient to decision-makers (Bourque *et al.*, 2009; Corfee-Morlot *et al.*, 2011). In many instances, key boundary functions are carried out by nearby academic or research communities and these can also be a source of leadership for urban adaptation (Government of South Africa, 2010; Sánchez-Rodríguez, 2009).

Even where detailed vulnerability or risk assessments exist, their influence may be limited if decision-makers do not access and use this information. Urban master plans or strategic plans with a time horizon of ten or more years can incorporate climate risks and vulnerabilities, but assessments must be available to influence such plans. Moser and Tribbia (2006), exploring how decision makers access and use information, find that resource managers tend to rely more on informal sources (maps or in-house experts, media and internet) than on scientific journals. This reinforces the point made earlier in regard to producers of scientific and information and knowledge actors to needing to work closely with decision makers in the production and communication of scientific information (Cash *et al.*, 2003; Cash *et al.*, 2006; Corfee-Morlot *et al.*, 2011; Moser, 2006).

8.4.1.5. Assessment Tools: Risk Screening, Vulnerability Mapping, and Urban Integrated Assessment

Assessments of risk and vulnerability to the direct and indirect impacts of climate change are often the first step in getting government attention, especially when put in the context of development policy objectives (Hallegatte *et al.*, 2011a; Mehrotra *et al.*, 2011a, see also 8.2). Including risk management information in infrastructure design at the planning or design phase can mean lower retrofit costs later on (Baker, 2012; World Bank, 2012). A variety of planning and assessment tools can be helpful, including impact assessment, environmental audits, vulnerability mapping, disaster risk assessment and management tools, local agenda 21 plans, urban integrated assessment as part of public investment planning and as used by community organisations (Baker, 2012; Haughton, 1999; UN-Habitat, 2007). Governments can ensure that up-to-date climate information is available to the private sector to support adaptation (Agrawala *et al.*, 2011, see also 8.4.2.3). Some of these tools provide entry points and a means for participatory engagement, but often give little consideration to adaptation (Gurran *et al.*, 2012). More reliable, specific and downscaled projections of climate change and tools for risk screening and management can help engage relevant public sector actors and the interest of businesses and consumers (AGF, 2010a; UNEP, 2011).

Local climate change risk assessments, vulnerability and risk mapping can identify vulnerable populations and locations at risk and provide a tool for urban adaptation decisions (Hallegatte *et al.*, 2011a; Kienberger *et al.*, 2013; Livengood and Kunte, 2012; Ranger *et al.*, 2009). The LOCATE methodology (Local Options for Communities to Adapt and Technologies to Enhance Capacity), which integrates hazard and vulnerability mapping to inform choices about which populations, infrastructure and areas to prioritise for action (Annecke, 2010) is being tested in eight

African countries; in each, an NGO is working with communities on across-project design and implementation, monitoring, evaluation and learning.

Tools that organize and rank information on vulnerability in different locations often aim to identify relative and absolute differences in risk and resilience capacity (Hahn *et al.*, 2009; Manuel-Navarrete *et al.*, 2011; Milman and Short, 2008; Posey, 2009). They vary from quick screenings to a fuller risk analyses and evaluations of adaptation options (Hammill and Tanner, 2011). Preston *et al.* (2011), noting the wide variety of functions and methods in 45 vulnerability mapping studies, suggest that effectiveness is guided by identifying clear goals, robust technical methods and engagement of the appropriate user communities. Halsnæs and Trærup (2009) recommend the use of a limited set of indicators, engagement with representatives of local development policy objectives, and a stepwise approach to address climate change impacts, development linkages, and economic, social and environmental dimensions. Methods for application across scale (Kienberger *et al.*, 2013), considering the urban environment as a system, allow for better understanding of interconnections between root causes, risk production, cascading impacts and vulnerabilities (da Silva *et al.*, 2012; Kirshen *et al.*, 2008; United Nations, 2011).

Downscaling of climate scenarios, systems models and urban integrated assessment modelling at local scales integrate information in a forward-looking framework to support urban policy assessment (e.g. Dawson *et al.*, 2009; Hall *et al.*, 2010; Hallegatte *et al.*, 2011a; van Vuuren *et al.*, 2007; Viguié and Hallegatte, 2012; Walsh *et al.*, 2011). Integrated assessment modelling considers the driving forces of urban vulnerability and climate change impacts alongside possible policy responses and their outcomes. By integrating knowledge, this provides a tool for policy-makers to examine and better understand synergies and trade-offs across policy strategies (Dawson *et al.*, 2009; Viguié and Hallegatte, 2012). These modelling frameworks take time to build and to be incorporated into decision-making processes. While early results are promising, they also highlight the difficulty of producing tools that can be easily used by local governments (e.g. see also Hall *et al.*, 2012; Walsh *et al.*, 2013; Walsh *et al.*, 2011).

Despite growing attention, useful assessment of climate change at urban spatial scales is generally lacking (Hunt and Watkiss, 2011). A small number of cities, largely in high-income countries, have quantified local climate change risks; even fewer have quantified possible costs under different scenarios. Some exceptions exist – Durban has developed a benefit-cost model for adaptation options (Cartwright *et al.*, 2013), and there have been urban climate risk assessments in low- or middle-income developing countries as part of targeted development cooperation programmes, supported by external partners (World Bank, 2011; World Bank, 2013). Sea level rise and coastal flood risk, health and water resources are among the most studied sectors; energy, transport and built infrastructure get far less attention *(ibid.*, Hunt and Watkiss, 2011; Roy *et al.*, 2012). Science and climate change information is increasingly available, but socio-economic drivers of vulnerability and impacts, and opportunities and barriers to adaptation are less well studied and understood (Measham *et al.*, 2011; Romero-Lankao and Qin, 2011).

8.4.2. Engaging Citizens, Civil Society, the Private Sector, and Other Actors and Partners

8.4.2.1. Engaging Stakeholders in Urban Planning and Building Decision Processes for Learning

A common vision of a future resilient, safe and healthy city can be the first step to achieving it (Corfee-Morlot *et al.*, 2011; Moser, 2006; Moser and Dilling, 2007; UN-Habitat, 2011a). Participatory processes figure prominently in cities that have been leaders in urban adaptation (Brown *et al.*, 2012; Carmin *et al.*, 2012b; Rosenzweig and Solecki, 2010); see also below). The conceptual literature agrees that participatory decision-making is essential where uncertainty and complexity characterise scientific understanding of policy problems (Funtowicz and Ravetz, 1993; Liberatore and Funtowicz, 2003). Many have argued that the institutional features of the risk management decision-making process – participatory inclusiveness, equity, awareness raising, deliberation, argument and persuasion – will determine the legitimacy and effectiveness of action (Corfee-Morlot *et al.*, 2011; Dietz *et al.*, 2003; Lim *et al.*, 2004; Mukheibir and Ziervogel, 2007). Yet the review of 45 vulnerability mapping exercises found that only 40 percent included stakeholder participation, raising questions about the legitimacy and salience of contemporary approaches (Preston *et al.*, 2011). It also highlights the challenge local governments face to garner resources, including technical expertise and institutional capacity, to organise and use participatory processes to strengthen rather than delay adaptation decision-making (Carmin *et al.*, 2013).

In many urban settings, civil society and the private sector already have significant and positive roles in support of adaptation planning and decisions. Some studies show that despite limited information, adaptation at urban scale is moving ahead, particularly through initial planning and awareness-raising (Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011; Lowe *et al.*, 2009). Experience in a handful of cities– e.g. Cape Town, Durban, London, New York –shows that a wide number and variety of engaged stakeholders at early stages in a risk assessment creates political support and momentum for follow-up research and adaptation planning (Anguelovski and Carmin, 2011; Hunt and Watkiss, 2011; Rosenzweig and Solecki, 2010). In informal settlements with little or no formal infrastructure and services, stakeholder engagement is a means for participatory community risk assessment, where local adaptive capacity is built in part through local knowledge (Kiunsi, 2013; Livengood and Kunte, 2012). Over time, institutional mechanisms can be built that support innovation, collaboration and learning within and across sectors to advance urban adaptation action, but it takes time and resources (Anguelovski and Carmin, 2011; Burch, 2010; Mukheibir and Ziervogel, 2007; Roberts, 2010).

8.4.2.2. Supporting Household and Community-Based Adaptation

In well-governed cities, community groups and local governments are mutually supportive, providing information, capacity and resources in maintaining local environmental health and public safety, which in turn can support adaptation. Where local government has not yet formulated an adaptation strategy, community groups can raise political visibility for climate risks and provide front-line coping (Granberg and Elander, 2007; Wilson, 2006), and also begin to address gender disparities in urban risks (Björnberg and Hansson, 2013).

The full range of infrastructure and services needed for resilience is generally affordable only in middle- and upper-income residential developments in low- and lower-middle income countries. In most cities and neighbourhoods, where infrastructure coverage is incomplete and household incomes limited, community organisations – or community-based adaptation - offer a rich resource of adaptive capacity to cope and to prepare for future risk. A range of studies document the depth of knowledge and capacities held by local populations around reducing exposure and vulnerability (Anguelovski and Carmin, 2011; Dodman and Mitlin, 2011; Livengood and Kunte, 2012). For a high proportion of the households that live in informal urban settlements, household and community-based adaptation is their only means of responding to risk. They are well used to coping with environmental hazards (Adelekan, 2010; Jabeen *et al.*, 2010; Kiunsi, 2013; Livengood and Kunte, 2012; Wamsler, 2007). Some seek to modify hazards or reduce exposure, for example through ventilation and roof coverings to reduce high temperatures; barriers to prevent floodwater entering homes; keeping food stores on top of high furniture; and moving temporarily to safer locations (Douglas *et al.*, 2008). A study in Korail, one of Dhaka's largest informal settlements, showed the range of household responses to flood risk (see Figure 8-5). These include barriers across door fronts, increasing the height of furniture, building floors or shelves above the flood line and using portable cookers (Jabeen *et al.*, 2010). Provision for ventilation, creepers or other material on roofs and false ceilings helped to keep down temperatures. These are important near-term adaptations, and there are similar responses in many informal settlements (see for instance Adelekan, 2010; Kiunsi, 2013), but they do not generate capacity to adapt to future risk.

[INSERT FIGURE 8-5 HERE
Figure 8-5: Household adaptation - a cross section of a shelter in an informal settlement in Dhaka (Korail) showing measures to cope with flooding and high temperatures. CI: Corrugated iron. Source: Jabeen *et al*., 2010.]

There are multiple constraints on action for low-income households. Even where there are early warnings, a lack of trust in the security of their property and the right to return, along with fears for personal safety in shelters, are deterrents against evacuation (Hardoy *et al.*, 2011; Jabeen *et al.*, 2010). Tenants and those with the least secure tenure are often amongst the most vulnerable and exposed to hazards but also are usually unwilling to invest in improving the housing they live in and less willing to invest in community initiatives. Community-based responses are often reactive, addressing current more than future risks, though they may embody alternative development values and support local transformation. Shifting the burden of adaptation to the community level alone is unlikely to bring success. There are limits to what community action can do in urban areas. For instance, communities may build and maintain local water sources, toilets and washing facilities or construct or improve drainage (see for instance the programmes in cities in Pakistan described in Hasan, 2006) but they cannot provide the network infrastructure on which these depend (e.g. the water, sewer and drainage mains and water treatment) nor can they improve city-region governance (Bicknell *et al.*, 2009). Work on cities in the Caribbean and Latin America indicates the need for supportive links to community networks and/or local government for community-level adaptation to be effective (Mitlin, 2012; Pelling, 2011b).

There is some recognition that strengthening the asset base of low-income households helps increase their resilience to stresses and shocks, including those related to climate change (Moser and Satterthwaite, 2009). It has become more common for local governments to work with community-based organizations in upgrading their homes and settlements in disaster risk reduction (IFRC, 2010; Pelling, 2011b; United Nations, 2009; United Nations, 2011), and community-based adaptation is building on these experiences and capacities (Archer and Boonyabancha, 2011; Carcellar *et al.*, 2011). Communities can have close relationships with formal state and market institutions, shaping subsequent adaptive capacity for members. Most housing and infrastructure upgrading programmes mean that those living in low-income settlements become incorporated into 'the formal' city and this often means an increased expectation on the state to reduce vulnerability, including long-term and strategic adaptation investments through access to schools, health care, infrastructure and safety nets (Almansi, 2009; Boonyabancha, 2005; Ferguson and Navarrete, 2003; Fernandes, 2007; Imparato and Ruster, 2003; UN Millennium Project, 2005). There can still be obstacles. Where climate change or disaster risk is seen as distant or low probability, the immediate pressures of poverty tend to dominate local agendas (Banks *et al.*, 2011). In many informal settlements, the issue of land tenure is also difficult to resolve and impedes upgrading programmes (Almansi, 2009; Boonyabancha, 2005; Boonyabancha, 2009) and thus local-level adaptation action.

In a growing number of cities, residents' organizations supported by grassroots leaders and local NGOs are mapping and enumerating their informal settlements with eventual support and recognition from city governments (Patel and Baptist, 2012). This provides the data and maps needed to plan the installation or upgrading of infrastructure and services. Some of these enumerations also collect data on risks and vulnerabilities to extreme weather and other hazards (Carcellar *et al.*, 2011; Livengood and Kunte, 2012; Pelling, 2011b; UN-Habitat, 2007). For example, community surveys in the Philippines identified at-risk communities under bridges, in landslide-prone areas, on coastal shorelines and river banks, near open dumpsites and in flood-prone locations (Carcellar *et al.*, 2011). This mapping raises awareness among inhabitants of the risks they face, as well as getting their engagement in planning risk reduction and making early warning systems and emergency evacuation effective (Pelling, 2011b). Table 8-4 illustrates the contemporary limits of community-based action across key sites of coping and adaptation – highlighting where strategic partnerships, especially with a supportive municipal government, have key advantages.

[INSERT TABLE 8-4 HERE
Table 8-4: The possibilities and limitations of focused activity for community groups on climate change coping and adaptation.]

IFRC (2010) identifies three broad requirements for successful urban community-based disaster risk reduction that can be extended to assess coping and adaptive capacity: the motivation and partnership of stakeholders; community ownership, with flexibility in project design; and sufficient time, funding and management capacity. The effectiveness of community-based action also depends on how representative and inclusive the community leaders and organizations are (Appadurai, 2001; Banks, 2008; Houtzager and Acharya, 2011; Mitlin, 2012; Wamsler, 2007); their capacity to generate pressure for larger changes within government; and the relations between community organizations and government (Boonyabancha and Mitlin, 2012). Community-based adaptation can support transformation where it engages with key development agendas to reduce poverty and vulnerability (Sabates-Wheeler *et al.*, 2008), and can address local inequalities and adverse power relations at district, city, national and transnational levels (Mohan and Stokke, 2000). But urban governance regimes are often resistant to change and civil society organizations can be marginalized or co-opted, reducing the scope for transformative adaptation (Pelling and Manuel-Navarrete, 2011).

8.4.2.3. Private Sector Engagement and the Insurance Sector

Cities are attractive to private enterprises because so much business activity, private investment and demand are concentrated there. Private enterprises generally favour cities with functioning city infrastructure and a wide range of services. As noted earlier, much investment for sound adaptation will need to come from households and firms of all sizes (Agrawala and Fankhauser, 2008; Bowen and Rydge, 2011). Brugmann (2012) argues that effective adaptation depends on catalysing market-based investments. Beyond acting to protect their own interests, businesses are stakeholders in urban decision making, positioned to exploit new opportunities that arise from climate change (Chapter 14, also Khattri *et al.*, 2010). Private service providers and professional associations - including architects, engineers and urban planners – can influence the pace and quality of adaptation efforts where an understanding of climate change is part of professional training and knowledge (McBain *et al.*, 2010). Even when considering more political issues around the support of adaptation efforts (AGF, 2010b; AGF, 2010c), most studies conclude that the need for adaptation investments will far exceed available funds from public budgets (see Ch. 15; also Agrawala and Fankhauser, 2008; Hedger, 2011; World Bank, 2010d).

For markets to favour urban adaptation, the private sector will need to see financial justification for involvement, for example to ensure business continuity. A survey of companies on the most serious risks they faced (Aon, 2013) ranked weather/natural disasters 16th and climate change 38th although some higher ranked risks such as commodity prices (8th) or distribution/supply chain failure (14th) may be associated with climate change. Risk rankings differed by region (in Asia Pacific weather/natural disasters were 8th) and by sector (for agribusiness, weather/natural disasters were 2nd). Failure of climate change adaptation (as "governments and business fail to enforce or enact effective measures to protect populations and transition businesses impacted by climate change") was listed by World Economic Forum (2013, p. 46) as one of the most likely environmental risks over the next ten years and with having a high impact if the risk was to occur. Private sector actors may not be well positioned to consider the big adaptation questions, including changes in land use, development and infrastructure planning (Redclift *et al.*, 2011). For example, in Cancun, Mexico, close relationships between government and the corporate sector and the push for lucrative development have perpetuated an urban development model that generates climate change risk by increasing the hazard exposure of capital intensive, large-scale coastal development (Manuel-Navarrete *et al.*, 2011). Without transformative change in urban development planning, private sector investments in adaptation will remain limited, such as designing buildings to withstand hurricanes but not tackling where development occurs. In the Cancun case, most investment comes from the state, for example in beach replenishment and policies for rapid disaster recovery (Manuel-Navarrete *et al.*, 2011).

The Private Sector Initiative of the UNFCCC Nairobi Work Programme offers support for businesses to integrate climate change science into their business planning, including in urban infrastructure and technology developments (http://unfccc.int/adaptation/nairobi_work_programme/private_sector_initiative/items/6547.php). This shows that both public and private (including civil society) actors can have a role in providing regional data and projections of socio-economic trends, climate change, urban water supply and management practices, land use and building trends, and hazard mapping (UNEP, 2011). A review shows anecdotal evidence of large businesses investing in vulnerability assessments, yet few beginning to invest in adaptation (Agrawala *et al.*, 2011). While some private sector actors take action against climate change risks, many postpone upfront investments for longer-term benefits against uncertain risks. Eakin *et al.* (2010) and Chu and Schroeder (2010) suggest that the private sector becomes more prominent when local governments and civil society action is limited, but this raises the issue of what incentives are required, especially in regard to low-income countries and communities.

Particularly in wealthier countries and communities, insurance markets can share and spread financial risk from climate change, for example, to help limit damages and manage risks in urban flood-prone areas (Rosenzweig and Solecki, 2010; see also Ch. 10 and 14). Risk-differentiated property insurance premiums can incentivise individuals and businesses to invest in adaption and retrofitting property or to avoid building in high-risk areas (Fankhauser *et al.*, 2008; Mills, 2012; Mills, 2007). Relevant insurance instruments include health and life insurance for individuals; property and possession insurance for home and commercial property owners; and micro insurance or micro finance mechanisms to support those in low-income urban communities that are not covered by commercial insurance (see Box 8-3). Catastrophe bonds may be developed to cover some urban climate risks, but experience to date suggests they are quite narrowly written for specific events in specific locations, not providing the broad protection necessary to limit catastrophic risk in a changing climate and urban context (Brugmann, 2012; Keogh *et al.*, 2011). Multicat Mexico 2009 is a catastrophe bond used to reinsure the Natural Disaster Fund covering the Mexican territory against hurricanes and earthquakes. This provides resources to mitigate losses up to US$ 50 million for hurricanes (Aragón-Durand, 2012). The insurance industry can also help shape urban adaptation initiatives, collaborating with building owners, developers and governments to inform and encourage action.

Private investment or standard insurance markets will not protect low-income urban dwellers (Hallegatte *et al.*, 2010; Ranger *et al.*, 2009). For example, around half of Mumbai's population live in informal settlements mostly without protective infrastructure and at increasing risk of flooding under most climate change scenarios (Hallegatte *et al.*, 2010; McFarlane, 2008; Ranger *et al.*, 2011). This population (and most of those living in informal settlements in oither cities) will not be served by insurance because of the low ability to pay, high risks and the high transaction costs for companies of administering many small policies. Low-income groups rely instead on local solidarity and government assistance when disaster hits (Hallegatte *et al.*, 2010). In addition, where risk levels exceed certain thresholds, insurers will abandon coverage or set premiums unaffordable to those at risk. Insurance reduces the net risk and loss potential in urban areas, but can also increase inequality in security within neighbourhoods or across cities unless coupled with government action to help manage risk in low-income communities (da Silva, 2010).

In many informal settlements, informal savings groups give members (mostly women) quick access to emergency loans (Mitlin, 2008). Where access to formal banking is limited, but social capital is high, those living in informal settlements have also pooled their savings for collective investments that reduce risk in their settlements or allow them to negotiate land and support for new homes (d'Cruz and Mudimu, 2013; Manda, 2007; Satterthwaite and Mitlin, 2014).

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Box 8-3. Microfinance for Urban Adaptation

Microfinance schemes may contribute to pro-poor, urban adaptation through a variety of different instruments including micro-credit, micro-insurance and micro-savings to help households and small entrepreneurs without access to formal insurance or commercial credit markets. These have been applied mostly in rural areas, usually benefitting those with some property (and thus not the poorest of rural populations). As Hammill *et al.* (2008, p. 117) state: "*The value MFS holds for climate change adaptation is in its outreach to vulnerable populations through a combination of direct and indirect financial support, and through the long-term nature of its services that help families build assets and coping mechanisms over time, especially through savings and increasingly through micro insurance – products and sharing of knowledge and information to influence behaviours.*" Although typically more costly than commercial loans, micro-finance can support entrepreneurial undertakings by those unable to get bank loans, help diversify local economies and empower women in particular, which can in turn contribute to adaptive capacity in a local context (Agrawala and Carraro, 2010; Moser *et al.*, 2010). Microfinance also provides a means for donors to deliver support to low-income groups without creating an on-going dependence on aid. But there is a need to target it well to avoid encouraging growth in areas prone to climate risk (Agrawala and Carraro, 2010; Hammill *et al.*, 2008). A limitation of micro-finance for adaptation is that it typically provides credit to individuals, so it is not easily used to finance collective investments - for instance improving drainage - and it can be a route to indebtedness during disaster recovery. There has been some experience of pooling savings, e.g. in low-income communities to set up City Development Funds in Asia, from which they can draw loans for disaster rehabilitation among other things (Archer, 2012). Von Ritter and Black-Layne (2013) explore the possible role for microfinance and crowd funding to support local climate change action e.g. finance small decentralised energy solutions or "climate-proof" homes; they also suggest the new Green Climate Fund could support such activity through its private sector window.

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For the private sector to fulfil its potential to facilitate urban adaptation, public policy may need to establish enabling conditions in markets (see also 8.3), for example, targeting payment for provision of ecosystem services to deliver urban adaptation benefits that otherwise fall outside the market system. Such services include storm buffering and flood protection by paying for mangrove protection in coastal zones or urban green space along river-ways (Fankhauser *et al.*, 2008; Roberts *et al.*, 2012). In building construction, well-documented examples of market failure exist. Private investment in weather proofing new construction and retrofitting existing stock, may fail to occur without regulatory intervention. This is an area where municipal governments often have authority to act. Public policy and funding is also needed to protect the poorest and most vulnerable households, and to ensure or enable action by the private sector. This may include filling gaps in insurance markets (Fankhauser *et al.*, 2008; IPCC, 2012; Mills, 2007; UN-Habitat, 2011c), helping provide information about risks particularly where this is highly uncertain and encouraging pro-active engagement by the private sector, as in the UK where vulnerability assessment is required for infrastructure investments (Agrawala *et al.*, 2011). There are examples of urban governments leading by example, requiring the integration of adaptation considerations into public operations and infrastructure investments through procurement requirements, which in turn affects private sector providers. Thus, even where markets exist and are well-functioning, all levels of government may need to engage the private sector in adaptation. Public-private initiatives also have a role providing educational and skill development resources to ensure that the professional networks of private service providers are trained in the latest decision tools, assessment methods and practices (da Silva, 2012; McBain *et al.*, 2010). Where markets do not exist or do not function well, there will be an even larger role for policy and public investments to support urban adaptation.

8.4.2.4. Philanthropic Engagement and other Civil Society Partnerships

Philanthropic and other civil society support for urban adaptation is gaining momentum at all levels. The most diverse and numerous are local actions undertaken by community-based organisations, as described above. Philanthropic organisations demonstrate the enabling role that can be played by international civil society to support urban adaptation, particularly in cities and communities in low- and lower-middle income countries. The coming together of grassroots civil society organisations to form international collaborations and networks can also strengthen the framing role of civil society while retaining local accountability and focus to support adaptation. Some examples include:

- Rockefeller Foundation’s support for the Asian Cities Climate Change Resilience Network (ACCCRN) (Brown *et al.*, 2012; Moench *et al.*, 2011)
- The Asian Coalition for Community Action Program managed by the Asian Coalition for Housing Rights
- The Asian Disaster Reduction and Response Network (ADRRN)
- Philippines Homeless People’s Federation, working with local governments to identify and help those most at risk to natural disasters (Carcellar *et al.*, 2011)
- Shack/Slum Dwellers International (SDI), a network of community-based organizations and federations of the urban poor in 33 countries in Africa, Asia, and Latin America and their local support NGOs.

Many disaster events are small and local but taken together, have a widespread and cumulative impact on the development prospects of low-income households and communities, underscoring the need for enhanced civil society engagement and coordination (United Nations, 2009). Civil society organisations are well placed to address the local conditions and some of the structural root causes of vulnerability, necessary for successful urban adaptation. For example, the scale and range of recent disaster events in Asian cities suggest a growing need for new support mechanisms to facilitate action among local stakeholders – one that should include local government as well as local civil society organisations (Shaw and Izumi, 2011). Where urban civil society is well coordinated and has legitimacy, it can offer alternative models for urban governance and adapting to climate change to assist local governments (Mitlin, 2012). Elsewhere ad-hoc coalitions of civil society actors, or even uncoordinated activity in some cities, provide a de facto delivery mechanism for accessing basic infrastructure and rights as part of development and disaster response (Pelling, 2003), although the lack of coordination limits the scale and scope of adaptive capacity. Many civil society initiatives have developed models of infrastructure delivery that are not centered on urban adaptation but have relevance for it, in part through activities designed to reduce disaster risk and increase management capacity (see Hasan, 2006).

8.4.2.5. University Partnerships and Research Initiatives

Since AR4, interest in urban aspects of adaptation has grown in the research community and its funders, as is evident in the number of conferences on this topic, both within social and behavioural sciences and in engineering and city planning sciences. More professional societies are considering their roles and responsibilities. Some cities are tapping into relevant networks; for instance the Urban Climate Change Research Network (UCCRN) brings together researchers and city planners to exchange knowledge and build a coalition of awareness and policy (Rosenzweig *et al.*, 2010). Other examples include London's use of scenarios generated by UK Climate Impact Programme by University of Oxford's Environmental Change Institute (Carmin *et al.*, 2013); the Urbanization and Global Environmental Change Programme (UGEC) of the International Human Dimensions Programme on Global Environmental Change, the Earth System Science Partnership (ESSP) a pioneer in promoting social science and knowledge exchange; the Land-Ocean Interactions in the Coastal Zone programme; Integrated Research on Disaster Risk (IRDR) co-sponsored by the International Council for Science (ICSU), the International Social Science Council (ISSC), and the United Nations International Strategy for Disaster Reduction (UNISDR) and the research on urban adaptation in Africa supported by the International Development Research Centre (IDRC).

Individual academic institutes have also begun to support urban adaptation efforts. The Urban Observatory in Manila has become a regional hub for climate change science and urban adaptation; the Universiti Kebangsaan in Malaysia hosts a Malaysian Network for Research on Climate, Environment and Development (MyCLIMATE) focused on awareness and capacity in industry and civil society (Shaw and Izumi, 2011); the Climate and Disaster Resilience Initiative (Kyoto University, CITYNET and UNISDR) works with city managers and practitioners (Shaw and IEDM Team, 2009); Latin American networks such as FLACSO (Facultad Latinoamericana de Ciencias Sociales) provide leadership across the region in disaster risk reduction, management and climate change adaptation. Individual centers have also become more engaged in urban adaptation, for instance, UNAM (Universidad Nacional Autónoma de México) in Mexico and the International Centre for Climate Change and Development (ICCCAD) in Dhaka (Anguelovski and Carmin, 2011; Mehrotra *et al.*, 2009). There remains a challenge to reform university curricula to include urban adaptation and mitigation.

8.4.2.6. City Networks and Urban Adaptation Learning Partnerships

Opportunities for accelerating learning and action may stem from horizontal coordination and networking across actors, professions and institutions in different municipalities and metropolitan areas. The growing interest in urban adaptation is also seen in the growth of transnational networks and coalitions working across organisational boundaries to influence outcomes, both nationally and internationally (Bulkeley and Betsill, 2005; Bulkeley and Moser, 2007; Rosenzweig *et al.*, 2010) and providing an institutional foundation to concerted effort and collaboration at city level (Aall *et al.*, 2007; Kern and Gotelind, 2009; Romero-Lankao, 2007). ICLEI's Cities for Climate Protection has been extensively analyzed in the literature (Aall *et al.*, 2007; Betsill and Bulkeley, 2004; Betsill and Bulkeley, 2006; Lindseth, 2004) with a broad conclusion that they are influencing decision-making and offer an effective means of sharing experience and learning. Other examples include the Climate Alliance, the C-40 Large Cities Climate Leadership Group and the Urban Leaders Adaptation Initiative in the US (OECD, 2010). The United Cities and Local Governments (UCLG) network, representing local governments within the United Nations, also has a growing interest in adaptation. The Asian Cities Climate Change Resilience Network (ACCCRN), mentioned above, also encourages inter-city learning for officials and local researchers (Brown *et al.*, 2012). The Making Cities Resilient network, supported by the UN International Strategy for Disaster Risk Reduction (UNISDR) promotes a ten-point priority agenda for city governments, building on good risk reduction practices (UNISDR, 2008; see also Johnson and Blackburn, 2014). Another example of the influence of city networks is the signing of the Durban Adaptation Charter in December 2011 by 107 mayors representing over 950 local governments at COP17 (Roberts and O'Donoghue, 2013), signalling their intention to begin addressing climate change adaptation in a more concerted and structured way (Rosenzweig *et al.*, 2010). The initial focus of some city networks was on mitigation but attention and leadership on adaptation is growing (as in the US Urban Leaders Adaptation Initiative - Foster *et al.*, 2011a).

8.4.3. Resources for Urban Adaptation and their Management

Resources for urban adaptation action can come from public and private sectors, domestic and international. Table 8-5 summarizes the main funding sources and financial instruments. In high-income countries, local governments are responsible for an estimated 70 percent of public spending in urban areas and roughly 50 percent of public spending on environment infrastructure, often in partnership with other levels of government (OECD, 2010). The scale and source of funds contributing to adaptation varies widely by location and depends in part on the extent of to which local authorities can tax residents, property owners and businesses. A survey of 468 cities conducted by Carmin *et al.* (2012a) found that most (60%) are not receiving any financial support for their adaptation actions. Of the small percentage of cities receiving funding, the most common source of support is from national governments (24%). A smaller number of cities (9%) reported funding from sub-national governments while others (8%) reported support from private foundations and non-profit organizations; only 2-4% of the cities reported receiving financial support from international (bilateral and multilateral) financial institutions such as multilateral development banks and this varied widely by region (Carmin *et al.*, 2012a). Some of the environmental innovation in Latin America over the last 20 years is associated with decentralization that has strengthened fiscal bases for cities, along with more, elected mayors and more accountable city governments (Cabannes, 2004; Campbell, 2003); Latin American cities have also reported multilateral development banks as the most prevalent source of funding for adaptation representing about 21% of funding to date (Carmin *et al.*, 2012a). In Africa and Asia, a high proportion of urban governments still have very limited investment capacities as most of their revenues go to salaries and other recurrent expenditures (UCLG, 2011). UCLG data points to the large difference in annual expenditure per person by local governments, ranging from over US$6,000 in some high-income nations to less than US$20 in most low-income nations (UCLG, 2010).

[INSERT TABLE 8-5 HERE
Table 8-5: Main sources of funding and financial instruments for urban adaptation.]

As Table 8-5 indicates, large cities with strong economies and administrative capacity can best attract external funding (including transfers from higher levels of government) and raise internal funding for adaptation. Less prosperous and smaller urban centers and cities with fragmented governance structures or administrations lacking in capability have worse prospects. A key issue is 'unfunded mandates' – responsibilities assigned to cities with no increase in funding and capacity (UCLG, 2011)– and this can happen with new responsibilities around climate change (Kehew *et al.*, 2012; Tavares and Santos, 2013). Funding regimes and supportive legal frameworks need to integrate urban climate change risk management and adaptation into development.

8.4.3.1. Domestic Financing: Tapping into National or Sub-national Regional Sources of Funding and Support

For adaptation specifically, domestic public funding is one of the most significant and sustainable sources in many countries. Initiatives to green local fiscal policies are spreading, including congestion charges on motor vehicles and value-capture land taxes that make the cost of environmental externalities visible, and/or the benefits of infrastructure and services to property owners (e.g. transport, water and wastewater services). Such measures can promote private investment in risk management while mobilising local revenue sources. Local fiscal incentives can lead to mal-adaptation where urban government budgets and actions are financed by land sales, which in turn promote urban sprawl or development in areas at risk (Drejza *et al.*, 2011; Merk *et al.*, 2012). Greening local fiscal policies will need to identify and address these kinds of concerns.

Grants, loans and other revenue transfers from national or regional (sub-national) governments are also important sources, for instance to compensate local governments for the spillover environmental benefits of their expenditures (Hedger and Bird, 2011; Hedger, 2011; OECD, 2010). An example is municipal funding in Brazil, where the allocation of tax revenues is based on ecosystem management performance (see Box 8-3).

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Box 8-4. Environmental Indicators in Allocating Tax Shares to Local Governments in Brazil

In Brazil, part of the revenues from a value-added state government tax (ICMS) must be redistributed among municipalities. Three-quarters is defined by the federal constitution with the remaining 25% allocated by each state government. The state of Paraná introduced the ecological ICMS (ICMS-E) in 1992 against the background of state-induced land-use restrictions (protected areas) for several municipalities, which prevented them from developing land but provided no compensation. For example, 90% of the Piraquara municipality was designated as a protected watershed, supplying the Curitiba metropolitan region with water (May *et al.*, 2002).

States have different systems in place, but there are many commonalities. Revenues are allocated based on the proportion of a municipality's area set aside for protection, and protected areas are weighted according to different categories of conservation management (higher for biological reserves, for instance, than for areas of tourist interest). Paraná and some other states evaluate the protected areas based on physical and biological quality (fauna and flora), quality of water resources, physical representativeness and quality of planning, implementation and maintenance.

The ICMS-E, built on existing institutions and administrative procedures, has had very low transaction costs (Ring, 2008). Evaluations show it has been associated with improved environmental management and the creation of new protected areas (May *et al.*, 2002). It has also improved relations with the surrounding inhabitants as they start to see these areas as an opportunity to generate revenue, rather than an obstacle to development.

Source: Adapted from OECD, 2010.

_____ END BOX 8-4 HERE _____

Other innovative financial mechanisms for urban adaptation include revolving funds and the energy services company ("ESCO") model (OECD, 2010). Revolving funds can be developed from a variety of revenue streams such as Clean Development Mechanism projects (Puppim de Oliveira, 2009), and savings from energy efficiency investments in municipal buildings to feed public funds for investments that yield adaptation benefits. Local governments in high- and some middle-income countries may also have direct access to bond markets or loans from national (or regional) development banks or financial institutions (Merk *et al.*, 2012; OECD, 2010). Local access to capital markets can be facilitated through risk-sharing mechanisms or guarantees provided by development banks e.g. the German government's Development Bank KfW provides low-interest loans to local banks which then finance energy-efficient renovations in residential and commercial buildings (OECD, 2010; Pfliegner *et al.*, 2012).

A key challenge is determining how far adaptation funding should be geared to target associated policy realms. The very high costs of extreme weather events in many urban areas, and the fact that climate change usually increases these risks, indicates the need for increased funding and attention from national budgets for risk reduction, early warning and evacuation procedures within urban areas, alongside other adaptation measures (Hallegatte and Corfee-Morlot, 2011; World Bank, 2010a; World Bank, 2010e). The urban funding gap may be particularly wide for "soft" rather than "hard" infrastructure investments, yet both can be a motor for resilience.

8.4.3.2. Multilateral Humanitarian and Disaster Management Assistance

The international humanitarian community is increasingly active in urban contexts, with relevance for adaptation capacity (IFRC, 2010). Non-climate related disasters (including earthquakes and tsunamis) provide a learning opportunity, and the sector is beginning to review experience and develop appropriate tools and guidelines for urban contexts (e.g., ALNAP, 2012). In 2009, humanitarian groups formed a reference group on meeting humanitarian challenges in urban areas, setting a two-year action plan in 2010, and developing a database of urban-specific aid tools, the Urban Humanitarian Response Portal (http://www.urban-response.org/). Policies sensitive to the needs of internally displaced urban populations are a big challenge for the sector, especially where the resident population is chronically poor (Crawford *et al.*, 2010; Zetter and Deikun, 2010); so too are appropriate responses to increased urban food insecurity (Battersby, 2013).

The systematic programming of climate change adaptation into multilateral humanitarian, disaster response and management funding within development cooperation is in its infancy. Urban dimensions are under-developed although this is changing (see IFRC, 2010; United Nations, 2009; United Nations, 2011). The World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR) explicitly includes adaptation to climate change. Its Country Programmes for Disaster Risk Management and Climate Change Adaptation 2009-2011, and more recently 2014-2016, seek to deepen engagement in some priority countries (GFDRR, 2009; GFDRR, 2013; World Bank, 2013). The GFDRR, with UNISDR, has also advocated for more integrated policy and advisory services at the technical level (see Mitchell *et al.*, 2010). A 2009-11 survey of reports from 82 governments on disaster risk reduction and urban and climate change issues, found some progress in both areas (Figure 8-6, United Nations, 2011).

[INSERT FIGURE 8-6 HERE
Figure 8-6: Progress reported by 82 governments in addressing some key aspects of disaster risk reduction by countries' average per capita income. Source: United Nations, 2011.]

Despite progress, many urban governments lack the capacity to address disaster risk reduction and management. Almost 60 percent of the countries surveyed by the UN (80 percent of lower-middle income countries) reported that local governments have legal responsibility for disaster risk management, but only about a third had dedicated budget allocations, mostly in upper-middle and high-income countries (United Nations, 2011). Figure 8-6 highlights attention to investments in drainage infrastructure, but much less in urban and land-use planning in lower-middle and low-income countries. Progress in integrating climate change policies into disaster risk reduction was reported by over two thirds of governments in high, upper-middle and lower-middle income countries but under half of low-income countries.

8.4.3.3. International Financing and Donor Assistance for Urban Adaptation

The limited data available show attention to urban areas in the growing levels of international development financing available to support adaptation (e.g., OECD, 2013; World Bank, 2013). Development finance is a key source of support for adaptation in many low- and middle-income countries, but many vulnerable cities and municipalities are poorly positioned to access available funding (ICLEI, 2010; Paulais and Pigey, 2010), for their often very large deficits in risk-reducing infrastructure and services. In some local governments, international programmes offer the main source of institutional and financial support for mitigation and adaptation work at local level, but this can raise the danger of a "donor-driven model" (where the funding agency's agenda do not coincide with local priorities); experience shows that without strong and lasting local ownership, programmes are unsustainable once support is withdrawn (Hedger, 2011; OECD, 2012). More international funding for adaptation and mitigation is being committed, largely as Official Development Assistance (ODA), and governments are broadly on track delivering on their international promises (see for instance the Cancun Agreements) to scale up international climate finance (Buchner *et al.*, 2012; Clapp *et al.*, 2012). Less in evidence are sound institutional arrangements to make this support available to urban governments. SREX calls for arrangements that will allow adaptive urban management systems to evolve with changing social and environmental dynamics (IPCC, 2012) but international channels for development finance have yet to adjust to this call to action.

Recent data suggest that a small share of total flows of climate-related ODA targets adaptation (OECD, 2012; UNEP, 2011), and some this is supporting urban adaptation (e.g. see OECD, 2013; World Bank, 2013). OECD estimates bilateral ODA commitments targeting climate change to be in the range of US$11 – 20 billion per year on average in 2010-2011 for both adaptation and mitigation; of this roughly 20-40% targets adaptation (OECD, 2013). One in-depth assessment of five major donors, covering concessional and non-concessional finance, estimated adaptation to be 30% of their climate change portfolio, mostly targeted to water and sanitation (about 75%) (UNEP, 2011). The rest were for other relevant sectors (i.e. transport, policy loans, disaster risk reduction), but with energy and health largely overlooked (UNEP, 2011), see also Atteridge *et al.* (2010). Despite growing attention to climate change, many bilateral agencies have historically had very limited engagement with urban initiatives (Mitlin and

Satterthwaite, 2013). Some authors also note the difficulty in distinguishing adaptation from development finance, which limits the accuracy of such estimates (Buchner *et al.*, 2012; Tirpak *et al.*, 2010).

Despite the uncertainties in tracking adaptation ODA, OECD statistics (OECD, 2013) show that there is some attention to urban issues today.[2] Urban adaptation is estimated to represent about 20% of bilateral climate adaptation portfolios, equivalent to US$0.65 – 1.6 billion per year (on average over 2010- 2011). Slightly more than half of this goes to projects in urban centres with between 10,000 and 500,000 inhabitants while the rest goes to large cities with 500,000 or more inhabitants. The major sectors are water (about 38%, considering projects that had adaptation as principal or significant) and sanitation (another 6%) (OECD, 2013). The largest providers of urban adaptation ODA in these years were Japan (an average of $683 million a year in commitments), Germany ($333 million), France ($111 million) and South Korea, European Union Institutions, Spain and Denmark (between $48 and $80 million). The largest recipients were Vietnam ($232 million), Bangladesh ($146 million), China ($100 million) and the Philippines, Peru, Indonesia and Kenya ($52-76 million).

[FOOTNOTE 2: Data and information as found in the OECD DAC-CRS 2013, www.oecd.org/dac/stats/rioconventions.htm [last accessed: 7 September 2013]. These estimates derive from data and project descriptions in the OECD DAC-Creditor Reporting System. It is based on a project-by-project review of qualitative information in the 2013 version of the database describing official development finance from bilateral agencies and the EU institutions. This sub-set of “urban” adaptation activities describes those projects that identify the geography of benificiaries as urban and which include a verifiable location (e.g. metropolitan Lima); data were organized by key characteristic of each urban location (i.e.population size and recipient country). Only urban areas with populations of 10,000 or more are included here. Projects are marked with climate adaptation “Rio marker”; this data set includes all projects marked as targeting climate adaptation, either as a principal objective as well as those with it as a significant objective.]

Around 70 percent of urban adaptation aid is dedicated to “hard” infrastructure while about 10% goes to “soft” measures to support capacity building related to urban infrastructure planning and adaptation. So OECD data suggest that urban adaptation is a recent but significant objective in climate aid activities but it is still only a small part of overall ODA portfolios (OECD, 2013).

Conventional channels for development finance appear to have the biggest role in adaptation financing in low- and middle-income countries, though new vertical funds are also emerging. The proliferation of multiple, single purpose funding mechanisms runs contrary to long-standing harmonization principles of sound development cooperation (Hedger, 2011; OECD, 2012). This more complex funding architecture makes it difficult for smaller actors like local authorities to access sources for timely adaptation investments.

Development assistance can be better targeted if reconciled with bottom-up, locally-based planning processes that take climate risks into account, and programmes aiming to be mainstreamed into urban development over time (Brugmann, 2012). Research shows the lack of well-defined priorities in partner countries, combined with a donor tendency to “control” funds for short-term results and a large variety of different funding instruments results in fragmented delivery systems and unclear outcomes (Brown and Peskett, 2011). Even where climate strategies exist to guide action – as in Bangladesh, an “early mover” on adaptation planning – the plan is often not costed nor sequenced, making it an inadequate framework for finance delivery (Hedger, 2011). A key to improving effectiveness of international public finance will be building the capacity for country-led planning processes identifying priority actions for targeting adaptation funds. National Adaptation Plans of Action (NAPAs) have become a principal way of organising adaptation priorities in Least Developed Countries, but the majority of plans do not explicitly include urban projects and do not reflect local government perspectives (UN-Habitat, 2011c).

A number of authors conclude that international development finance is failing to tackle urban adaptation financing needs (ICLEI, 2011; Parry *et al.*, 2009; Paulais and Pigey, 2010; UN-Habitat, 2011c). Some suggest that national governments could set up funds supported by international finance (governmental, philanthropic or both) and on which urban governments and community-based organisations can draw (Paulais and Pigey, 2010; Satterthwaite and Mitlin, 2014). In some middle-income countries, such as Indonesia, a more effective and sustainable strategy than a focus on external funding may be national policy reforms and incentives to steer investment to priority needs

(Brown and Peskett, 2011). There is also a need to mobilise domestic public and private investment to ensure delivery of adaptation at national and urban levels (Hedger and Bird, 2011; Hedger, 2011; OECD, 2012). Accessing all these sources of development finance for urban adaptation will require institutional mechanisms to support multilevel planning and risk governance (Carmin *et al.*, 2013; Corfee-Morlot *et al.*, 2011).

8.4.3.4. Institutional Capacity and Leadership, Staffing, and Skill Development

Leadership is critical for generating interest in urban adaptation, championing awareness and institutional change to bring action (Anguelovski and Carmin, 2011; Carmin *et al.*, 2012a). Creating a climate change and environmental focal point or office in a city can help coordinate climate action across government departments or agencies (Anguelovski and Carmin, 2011; Brown *et al.*, 2012; Hunt and Watkiss, 2011; OECD, 2011; Roberts, 2008; Roberts, 2010). Yet there may be downsides when this function is housed in the environmental line department – see Durban (Roberts, 2008), Boston (Boston, 2011), and Sydney (Measham *et al.*, 2011) - since they are typically among the weakest parts of city government with limited influence (Roberts, 2010).

Although there is growing evidence of urban adaptation leadership (Anguelovski and Carmin, 2011; Foster *et al.*, 2011b; Lowe *et al.*, 2009), there are also important political constraints at the local level. Powerful vested interests may oppose attention to adaptation and promote development on sites at risk. As noted earlier, concerns about employment and competitiveness make it difficult for local governments to focus on the more distant implications of climate change. This is especially so during periods of economic hardship (Shaw and Theobald, 2011; Solecki, 2012). A key step forward is institutionalising different types of behaviour and norms.

Beyond goal setting and planning, the literature also suggests the need for regulatory frameworks to require relevant behaviour and investment. Governments can institute small changes, such as job descriptions that require actions and provide incentives to act in new ways (e.g. for line managers and sector policymakers) or by providing training and clear guidance to staff (Carmin *et al.*, 2013; Moser, 2006; Tavares and Santos, 2013). Budgetary transparency and metrics to measure progress on adaptation can also help to institutionalize changes in planning and policy practice (OECD, 2012).

8.4.3.5. Monitoring and Evaluation to Assess Progress

Adaptation leaders and funding institutions need tools for monitoring and evaluating urban adaptation actions to justify investments but these are not well developed yet nor widely implemented in urban areas (Kazmierczak and Carter, 2010). This requires indicators that show if adaptation is taking place, at what pace, and in what locations. Relevant evaluation criteria include cost, feasibility, efficacy, co-benefits (direct and indirect), and institutional considerations (Jacob *et al.*, 2010). Assessment methods can capture outcomes of adaptation decisions, or the decision-making processes themselves – ideally both. Monitoring is challenging for adaptation, especially urban, given the lack of standard metrics, the differences in local contexts and the often localized nature of adaptation (Lamhauge *et al.*, 2012; Spearman and McGray, 2012).

City authorities, NGOs and researchers have begun to design adaptation monitoring and evaluation frameworks. Box 8-5 presents the experience of New York City. Development of standard tools offers scope for international benchmarking and coordination across scales of assessment, for example by associating local indicators of resilience with those in the Hyogo Framework for Action (that prioritize disaster risk reduction) and the post-2015 development agenda (IFRC, 2011).

_____ START BOX 8-5 HERE _____

Box 8-5. Adaptation Monitoring: Experience from New York City

The adaptation monitoring approach developed for New York City has four indicator elements: (1) physical climate change variables; (2) risk exposure, vulnerability and impacts; (3) adaptation measures; and (4) new research in each of these categories. Examples of indicators arising from these categories include: the percentage of building permits issued in a given year in current Federal Emergency Management Agency (FEMA) coastal flood zones, and in projected 2080 coastal flood zones; a tally of building permits with measures to reduce precipitation runoff; an index based on insurance data that measures the insurer's perception of the city's infrastructure-coping capacity; an index that measures the rating of city-issued bonds or infrastructure operators for capital projects with climate change risk exposure; the detailed trend of weather-related emergency/disaster losses (whether insured or uninsured, relative to the total asset volume); and the number of days with major telecommunication outages (wireless versus wired), correlated with weather-related power outages. Data criteria were decided through a scientist-stakeholder consensus with designated groups to evaluate prospective indicators and their values. This case study shows the need for interdisciplinary, longitudinal data collection and analysis systems along with an inclusive, transparent process for stakeholder engagement to interpret the data (Jacob *et al.*, 2010).

_____ END BOX 8-5 HERE _____

Monitoring and evaluation focusing on the effectiveness of donor aid on climate adaptation is a growing area of research (Chaum *et al.*, 2011; Lamhauge *et al.*, 2012; Spearman and McGray, 2012). Recent work shows the urgent need for consistent and internationally harmonised data collection to support monitoring. This is a concern for both adaptation and wider disaster risk reduction spending, suggesting a systemic challenge to the architecture of international finance (Kellett and Sparks, 2012). Steps are being made through multi-site assessment programmes, in some instances including treatment of urban issues. For example, the World Bank recently included an adaptive capacity index as part of an analysis of risk and adaptation options for five cities in Latin America and the Caribbean. The methodology was previously applied in Guyana, where it demonstrated a gap between national and city level adaptive capacity (Pelling and Zaidi, 2013).

Monitoring also needs to consider the delivery and use in cities of international climate finance to ensure that funds are being effectively directed (Chaum *et al.*, 2011; Hedger, 2011). This is especially important for cities at an early stage of planning, implementing and monitoring of adaptation, as they can learn from one another's experiences. There is some evidence that international agencies overburden partner organizations and countries (including in some cases city authorities) with monitoring requirements; with limited local capacities, this can detract from further programme design and implementation.

8.5. Annex: Climate Risks for Dar es Salaam, Durban, London, and New York City

This annex has four city profiles of current and indicative future climate risks: Dar es Salaam, Durban, London and New York. Each summarizes the present, near-term (2030-2040) and long-term (2080-2100) climate risks and the potential for risk reduction through adaptation. As noted earlier, data should not be compared between cities but trends in adaptive capacity and impact can be drawn out.

[INSERT TABLE 8-6 HERE
Table 8-6: Current and Indicative future climate risks for Dar es Salaam, Durban, London, and New York City.]

Frequently Asked Questions

FAQ 8.1: Do experiences with disaster risk reduction in urban areas provide useful lessons for climate-change adaptation? *[to be inserted in Section 8.3.2.2]*
There is a long experience with urban governments implementing disaster risk reduction that is underpinned by locally-driven identification of key hazards, risks and vulnerabilities to disasters and that identifies what should be done to reduce or remove disaster risk. Its importance is that it encourages local governments to act before a disaster – for instance for risks from flooding, to reduce exposure and risk as well as being prepared for emergency responses prior to the flood (eg temporary evacuation from places at risk of flooding) and rapid response and building back afterwards. In some nations, national governments have set up legislative frameworks to strengthen and support local government capacities for this (see 8.3.2.2). This is a valuable foundation for assessing and acting

on climate-change related hazards, risks and vulnerabilities, especially those linked to extreme weather. Urban governments with effective capacities for disaster risk reduction (with the needed integration of different sectors) have institutional and financial capacities that are important for adaption. But while disaster risk reduction is informed by careful analyses of existing hazards and past disasters (including return periods), climate change adaptation needs to take account of how hazards, risks and vulnerabilities will or might change over time. Disaster risk reduction also covers disasters resulting from hazards not linked to climate or to climate change such as earthquakes.

FAQ 8.2: As cities develop economically, do they become better adapted to climate change?
[to be inserted in Section 8.3.3.1]
Cities and nations with successful economies can mobilize more resources for climate change adaptation. But adaptation also needs specific policies to ensure provision for good quality risk-reducing infrastructure and services that reach all of the city's population and the institutional and financial capacity to provide, and manage these and expand them when needed. Poverty reduction can also support adaptation by increasing individual, household and community resilience to stresses and shocks for low-income groups and enhancing their capacities to adapt. These provides a foundation for building climate change resilience but additional knowledge, resources, capacity and skills are generally required, especially to build resilience to changes beyond the ranges of what have been experienced in the past.

FAQ 8.3: Does climate change cause urban problems by driving migration from rural to urban areas?
[to be inserted in Section 8.3.3.2]
The movement of rural dwellers to live and work in urban areas is mostly in response to the concentration of new investments and employment opportunities in urban areas. All high-income nations are predominantly urban and increasing urbanization levels are strongly associated with economic growth. Economic success brings an increasing proportion of GDP and of the workforce in industry and services, most of which are in urban areas. While rapid population growth in any urban centre provides major challenges for its local government, the need here is to develop the capacity of local governments to manage this with climate change adaptation in mind. Rural development and adaptation that protects rural dwellers and their livelihoods and resources has high importance as stressed in other chapters – but this will not necessarily slow migration flows to urban areas, although it will help limit rural disasters and those who move to urban areas in response to these.

FAQ 8.4: Shouldn't urban adaptation plans wait until there is more certainty about local climate change impacts? *[to be inserted in Section 8.4.1.5]*
More reliable, locally specific and downscaled projections of climate change impacts and tools for risk screening and management are needed. But local risk and vulnerability assessments that include attention to those risks that climate change will or may increase provide a basis for incorporating adaptation into development now, including supporting policy revisions and more effective emergency plans. In addition, much infrastructure and most buildings have a lifespan of many decades so investments made now need to consider what changes in risks could take place during their lifetime. The incorporation of climate change adaptation into each urban centre's development planning, infrastructure investments and land-use management is well served by an iterative process within each locality of learning about changing risks and uncertainties that informs an assessment of policy options and decisions.

Cross-Chapter Box

Box CC-UR. Urban-Rural Interactions –
Context for Climate Change Vulnerability, Impacts, and Adaptation

[John Morton (UK), William Solecki (USA), Purnamita Dasgupta (India), David Dodman (Jamaica), Marta G. Rivera-Ferre (Spain)]

Rural areas and urban areas have always been interconnected and interdependent, but recent decades have seen new forms of these interconnections: a tendency for rural-urban boundaries to become less well-defined, and new types of land-use and economic activity on those boundaries. These conditions have important implications for understanding climate change impacts, vulnerabilities, and opportunities for adaptation. This box examines three critical implications of these interactions:

1) Climate extremes in rural areas resulting in urban impacts – teleconnections of resources and migration streams mean that climate extremes in non-urban locations with associated shifts in water supply, rural agricultural potential, and the habitability of rural areas will have downstream impacts in cities;
2) Events specific to the rural-urban interface – given the highly integrated nature of rural-urban interface areas and overarching demand to accommodate both rural and urban demands in these settings, there is a set of impacts, vulnerabilities and opportunities for adaptation specific to these locations. These impacts include loss of local agricultural production, economic marginalization resulting from being neither rural or urban, and stress on human health; and,
3) Integrated infrastructure and service disruption – as urban demands often take preference, interdependent rural and urban resource systems place nearby rural areas at risk, because during conditions of climate stress, rural areas more often suffer resource shortages or other disruptions in order to sustain resources to cities. For example, under conditions of resource stress associated with climate risk (e.g., droughts) urban areas are at an advantage because of political, social, economic requirements to maintain service supply to cities to the detriment of relatively marginal rural sites and settlements.

Urban areas historically have been dependent on the lands just beyond their boundaries for most of their critical resources including water, food, and energy. While in many contexts, the connections between urban settlements and surrounding rural areas are still present, long distance, teleconnected, large-scale supply chains have been developed particularly with respect to energy resources and food supply (Güneralp et al., 2013). Extreme event disruptions in distant resource areas or to the supply chain and relevant infrastructure can negatively impact the urban areas dependent on these materials (Wilbanks et al., 2012). During the summer of 2012, for instance, an extended drought period in the central United States led to significantly reduced river levels on the Mississippi River which led to interruptions of barge traffic and delay of commodity flows to cities throughout the country. Urban water supply is also vulnerable to droughts in predominantly rural areas. In the case of Bulawayo, Zimbabwe, periodic urban water shortages over the last few decades have been triggered by rural droughts (Mkandla et al., 2005).

A further teleconnection between rural and urban-areas is rural-urban migration. There have been cases where migration and urbanization patterns have been to attributed to climate change or its proxies such as in parts of Africa (Morton 1989, Barrios et al., 2006). However, as recognized by Black *et al.* (2011), life in rural areas across the world typically involves complex patterns of rural-urban and rural-rural migration, subject to economic, political, social and demographic drivers, patterns which are modified or exacerbated by climate events and trends rather than solely caused by them.

Globally, an increased blending of urban and rural qualities has occurred. Simon *et al*. (2006:4) assert that the simple dichotomy between 'rural' and 'urban' has "long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South". One approach to reconciling this is through the increasing application of the concept of "peri-urban areas" (Simon *et al*., 2006; Simon, 2008). These areas can be seen as rural locations that have "become more urban in character" (Webster 2002: 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be "largely rural landscapes" (Learner and Eakin 2010: 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). The inhabitants of "core" urban areas within cities have also increasingly turned to agriculture, with production of staple foods, higher-value crops and livestock (Bryld, 2003; Devendra et al., 2005; Lerner and Eakin, 2010; Lerner et al., 2013). Bryld (2003) sees this as driven by rural-urban migration and by structural adjustment (e.g. withdrawal of food price controls and food subsidies). Lerner and Eakin (2011, also Lerner et al., 2013) explored reasons why people produce food in urban environments, despite high opportunity costs of land and labour: buffering of risk from insecure urban labour markets; response to consumer demand; and the meeting of cultural needs.

Livelihoods and areas on the rural-urban interface suffer highly specific forms of vulnerability to disasters, including climate-related disasters. These may be summarised as specifically combining: urban vulnerabilities of population concentration, dependence on infrastructure, and social diversity limiting social support with rural traits of distance, isolation and invisibility to policy-makers (Pelling and Mustafa, 2010). Increased connectivity can also encourage land expropriation to enable commercial land development (Pelling and Mustafa, 2010). Vulnerability may arise from the co-existence of rural and urban perspectives, which may give rise to conflicts between different social / interest groups and economic activities (Darly and Torre 2013, Masuda and Garvin 2008, Solona-Solona 2010).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Iaquinta and Drescher 2000). Rapid declines in traditional informal institutions and forms of collective action, and their imperfect replacement with formal state and market institutions, may also increase vulnerability (Pelling and Mustafa, 2010).

Peri-urban areas and livelihoods have low visibility to policy-makers at both local and national levels, and may suffer from a lack of necessary services, and inappropriate and uncoordinated policies. In Tanzania and Malawi, national policies of agricultural extension to farmer groups for example, do not reach peri-urban farmers (Liwenda et al., 2012). In peri-urban areas around Mexico City (Eakin et al., 2013), management of the substantial risk of flooding is led *de facto* by agricultural and water agencies, in the absence of capacity within peri-urban municipalities and despite clear evidence that urban encroachment is a key driver of flood risk. In developed country contexts suburban areas, suburban-exurban fringe areas often are overlooked in the policy arena that traditionally focuses on rural development and agricultural production, or urban growth and services (Hanlon et al., 2011). The environmental function of urban agriculture, in particular, in protection against flooding, will increase in the context of climate change. (Aubry et al., 2012).

However, peri-urban areas and mixed livelihoods more generally on rural-urban interfaces, also exhibit specific factors that increase their resilience to climate shocks (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education. The expansion of local labour markets and wage labour in these areas can strengthen adaptive capacity through providing new livelihood opportunities (Pelling and Mustafa, 2010). Maintaining mixed portfolios of agricultural and non-agricultural livelihoods also spreads risk (Lerner et al., 2013).

In high-income countries, practices attempting to enhance the ecosystem services and localized agriculture more typically associated with lower density areas have been encouraged. In many situations these practices are focused increasingly on climate adaptation and mitigating the impacts of climate extremes such as those associated with heating and the urban heat island effect, or wetland restoration efforts to limit the impact of storm surge wave action (Verburg et al., 2012).

The dramatic growth of urban areas also implies that rural areas and communities are increasingly politically and economically marginalized within national contexts, resulting in potential infrastructure and service disruptions for such sites. Existing rural-urban conflicts for the management of natural resources (Castro and Nielsen, 2003) such as water (Celio et al., 2011) or land-use conversion in rural areas (e.g. wind farms in rural Catalonia (Zografos and Martínez-Alier, 2009); industrial coastal areas in Sweden (Stepanova and Bruckmeier, 2013); or conversion of rice land into industrial, residential and recreational uses in the Philippines (Kelly, 1998) or Spain have been documented, and it is expected that stress from climate change impacts on land and natural resources will exacerbate these tensions. For instance, climate induced reductions in water availability may be more of a concern than population growth or increased per-capita use for securing continued supplies of water to large cities (Darrel Jenerette and Larsen, 2006), both of which requires an innovative approach to address such conflicts (Pearson et al., 2010).

Box CC-UR References

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Table 8-1: The distribution of the world's urban population by region, 1950–2010 with projections to 2030 and 2050. Source: Derived from statistics in United Nations, 2012.

Urban population (millions of inhabitants)						
Major area, region, country or area	**1950**	**1970**	**1990**	**2010**	**Projected for 2030**	**Projected for 2050**
World	745	1,352	2,281	3,559	4,984	6,252
More developed regions	442	671	827	957	1,064	1,127
Less developed regions	304	682	1,454	2,601	3,920	5,125
Least developed countries	15	41	107	234	477	860
Sub-Saharan Africa	20	56	139	298	596	1,069
Northern Africa	13	31	64	102	149	196
Asia	245	506	1,032	1,848	2,703	3,310
China	65	142	303	660	958	1,002
India	63	109	223	379	606	875
Europe	281	412	503	537	573	591
Latin America and the Caribbean	69	163	312	465	585	650
Northern America	110	171	212	282	344	396
Oceania	8	14	19	26	34	40
Percent of the population in urban areas						
World	29.4	36.6	43.0	51.6	59.9	67.2
More developed regions	54.5	66.6	72.3	77.5	82.1	85.9
Less developed regions	17.6	25.3	34.9	46.0	55.8	64.1
Least developed countries	7.4	13.0	21.0	28.1	38.0	49.8
Sub-Saharan Africa	11.2	19.5	28.2	36.3	45.7	56.5
Northern Africa	25.8	37.2	45.6	51.2	57.5	65.3
Asia	17.5	23.7	32.3	44.4	55.5	64.4
China	11.8	17.4	26.4	49.2	68.7	77.3
India	17.0	19.8	25.5	30.9	39.8	51.7
Europe	51.3	62.8	69.8	72.7	77.4	82.2
Latin America and the Caribbean	41.4	57.1	70.3	78.8	83.4	86.6
Northern America	63.9	73.8	75.4	82.0	85.8	88.6
Oceania	62.4	71.2	70.7	70.7	71.4	73.0
Percent of the world's urban population						
World	100.0	100.0	100.0	100.0	100.0	100.0
More developed regions	59.3	49.6	36.3	26.9	21.4	18.0
Less developed regions	40.7	50.4	63.7	73.1	78.6	82.0
Least developed countries	2.0	3.0	4.7	6.6	9.6	13.8
Sub-Saharan Africa	2.7	4.1	6.1	8.4	11.9	17.1
Northern Africa	1.7	2.3	2.8	2.9	3.0	3.1
Asia	32.9	37.4	45.2	51.9	54.2	52.9
China	8.7	10.5	13.3	18.6	19.2	16.0
India	8.5	8.1	9.8	10.6	12.2	14.0
Europe	37.6	30.5	22.0	15.1	11.5	9.5
Latin America and the Caribbean	9.3	12.1	13.7	13.1	11.7	10.4
Northern America	14.7	12.6	9.3	7.9	6.9	6.3
Oceania	1.1	1.0	0.8	0.7	0.7	0.6

*Chapter 26 on North America includes Mexico; in the above statistics, Mexico is included in Latin America and the Caribbean.

Table 8-2: The large spectrum in the capacity of urban centers to adapt to climate change. One of the challenges for this chapter is to convey the very large differences in adaptive capacity between urban centres. This table seeks to illustrate differences in adaptive capacity and the factors that influence it. For a more detailed assessment of adaptation potentials and challenges for specific cities, see the Tables for Dar es Salaam, Durban, London, and New York in Section 8.5.

Indicator Clusters	**Very little adaptive capacity or resilience/ 'bounce-back' capacity**	**Some adaptive capacity and resilience/ 'bounce-back' capacity**	**Adequate capacity for adaptation and resilience/ 'bounce-back' but needs to be acted on**	**Climate resilience and capacity to bounce forward**	**Transformative adaptation**
The proportion of the population served with risk-reducing infrastructure (paved roads, storm and surface drainage, piped water ….) and services relevant to resilience (including health care, emergency services, policing/rule of law) and the institutions needed for such provision	0-30% of the urban centre's population served; most of those unserved or inadequately served living in informal settlements	30-80% of the urban centre's population served; most of those unserved or inadequately served living in informal settlements	80-100% of the urban centre's population served; most of those unserved or inadequately served living in informal settlements	Most/all of the urban centre's population with these and with an active adaptation policy identifying current and probable future risks and with an institutional structure to encourage and support action by all sectors and agencies. In many cities, also upgrade ageing infrastructure	Urban centres that have integrated their development and adaptation policies and investments within an understanding of the need for mitigation and sustainable ecological footprints
The proportion of the population living in legal housing built with permanent materials (meeting health and safety standards)				Active programme to improve conditions, infrastructure and services to informal settlements and low-income areas. Identify and act on areas with higher/increasing risks. Revise building standards.	Land use planning and management successfully providing safe land for housing, avoiding areas at risk and taking account of mitigation
Proportion of urban centres covered	Most urban centres in low-income and many in middle-income nations	Many urban centres in many low-income nations; most urban centres in most middle-income nations	Virtually all urban centres in high-income nations, many in middle-income nations	A small proportion of cities in high-income and upper-middle income nations	Some innovative city governments thinking of this and taking some initial steps
Estimated number of people living in such urban centres	One billion	1.5 billion	1 billion	Very small	
Infrastructure deficit	Much of the built up area lacking infrastructure	Most or all the built up area with infrastructure (paved roads, covered drains, piped water…..)			
Local government investment capacity	Very little or no local investment capacity	Substantial local investment capacity			
Occurrence of disasters from extreme weather*	Very common	Uncommon (mostly due to risk-reducing infrastructure, services and good quality buildings available to almost all the population)			

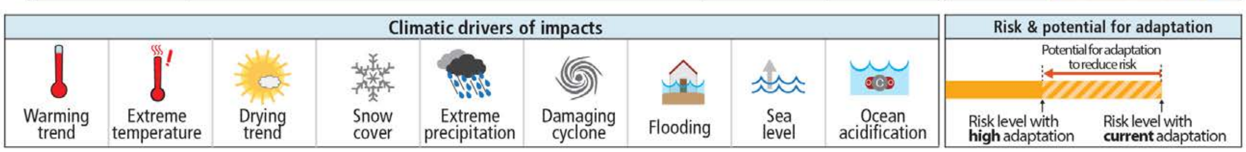
Indicator Clusters	**Very little adaptive capacity or resilience/ 'bounce-back' capacity**	**Some adaptive capacity and resilience/ 'bounce-back' capacity**	**Adequate capacity for adaptation and resilience/ 'bounce-back' but needs to be acted on**	**Climate resilience and capacity to bounce forward**	**Transformative adaptation**
Examples	Dar es Salaam, Dhaka	Nairobi, Mumbai	Most cities in high-income nations	Cities such as New York; London, Durban and Manizales with some progress	
Implications for climate change adaptation	Very limited capacity to adapt. Very large deficits in infrastructure and in institutional capacity. Very large numbers exposed to risk if these are also in locations with high levels of risk from climate change	Some capacity to adapt, especially if this can be combined with development but difficult to get city governments to act. Particular problems for those urban centres in locations with high levels of risk from climate change	Strong basis for adaptation but needs to be acted on and to influence city government and many of its sectoral agencies.	City government that is managing land-use changes as well as having adaptation integrated into all sectors	City government with capacity to influence and work with neighbouring local government units. Also with land-use changes managed to protect eco-system services and support mitigation
NB: For cities that are made up of different local government areas, it would be possible to apply the above at an intra-city or intra-metropolitan scale. For instance, for many large Latin American, Asian and African cities, there are local government areas that would fit in each of the first three categories					

* See text in regard to disasters and extensive risk (United Nations, 2011).

Sources: This table was constructed to provide a synthesis of key issues, so it draws on all the sources cited in this chapter. However, it draws in particular on Solecki (2012), Kiunsi (2013), and Roberts and O'Donoghue (2013).

Table 8-3: Urban areas: current and indicative future climate risks. Key risks are identified based on an assessment of the literature and expert judgments by chapter 8 authors, with the evaluation of evidence and agreement presented in supporting chapter sections. Each key risk is characterized as very low to very high. For the near-term era of committed climate change (2030-2040), projected levels of global mean temperature increase do not diverge substantially across emission scenarios. For the longer-term era of climate options (2080-2100), risk levels are presented for global mean temperature increases of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Modal Urban (*medium confidence*)	Climate change will have profound impacts on urban infrastructure systems and services, the built environment and ecosystem services and hence on urban economies and populations. This could exacerbate existing social, economic and environmental drivers of risk, especially for vulnerable groups who lack essential services. An appropriate urban governance frame and coordinated urban adaptation focused on the built environment, improved infrastructure and services and risk reduction, has significant potential for reducing key climate risks in the medium term and especially in the long term.		8.2, 8.3, 8.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Coastal zones systems (*medium confidence*)	Coastal cities with extensive port facilities and large scale industries are vulnerable to increased flood exposure. High growth cities located on low-lying coastal areas are also at greater risk. There is possibility of non-linear increase in coastal vulnerability over the next two decades.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Terrestrial ecosystems & ecological infrastructure (*medium confidence*)	Ecosystem services will be impacted by altered ecosystem functions such as temperature and precipitation regimes, evaporation, humidity and soil moisture levels, indicating close links with sustainable water management. Knowledge gaps exist with respect to thresholds to adaptation of various ecosystems.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Water supply systems (*high confidence*)	Adaptation response requires changes to network infrastructure as well as demand side management, to ensure sufficient water supplies, increased capacities to manage reduced freshwater availability, flood risk reduction and water quality.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Waste water system (*high confidence*)	Managing waste water flows improves water supply and ecosystem services. Reducing vulnerability of infrastructure may be easier in new areas, well-funded local bodies or as part of scheduled interventions.		8.2, 8.3, 8.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Green built infrastructure (*medium confidence*)	Green infrastructure not utilised sufficiently in most cities. Climate change impacts can bring attention to the dual benefits of green infrastructure for climate change mitigation and impact management.		8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Energy systems (*high confidence*)	Most urban centres are energy intensive, with energy related climate policies focused only on mitigation measures. A few cities have adaptation initiatives underway for critical energy systems. There is great potential for non-adapted, centralised energy systems to magnify and cascade impacts to national or transboundary consequences from localised extreme events.		8.2, 8.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high
Food systems and security (*high confidence*)	Urban food sources are dependent upon local, regional and often global supplies. Climatic drivers can exacerbate food insecurity, especially of the urban poor. Enhanced social safety nets can support adaptation measures. Urban and peri-urban agriculture, local markets and green roofs hold good prospects as adaptive measures, but are under-utilised in rapidly growing cities.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low / Medium / Very high



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Transportation systems (*medium confidence*)	A difficult sector to adapt due to large existing stock, especially in developed country cities leading to potentially large secondary economic impacts with regional and potentially global consequences for trade and business. Emergency response requires well-functioning transport infrastructure.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Communication systems (*medium confidence*)	Resilient communication systems are a critical component of emergency response, and therefore adaptation. The rise of decentralised and networked mobile communications offer great potential for real-time and easily accessed information dissemination and communication systems, information quality control is a key element in realising the potential of communications systems for early warning and adaptation.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Urban risks associated with housing (*high confidence*)	Poor quality, inappropriately located housing is often most vulnerable to extreme events. Adaptation options include enforcement of building regulations and upgrading. Some city studies show the potential to adapt housing and promote mitigation, adaptation, and development goals simultaneously. Rapidly growing cities, or those rebuilding after a disaster, especially have the opportunities to increase resilience, but this is rarely realized. Without adaptation, risks of economic losses from extreme events are substantial in cities with high-value infrastructure and housing assets, with broader economic effects possible.		8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Human health (*high confidence*)	Health is a higher order risk impacted by key developmental issues including water supply,water and air quality, waste management, housing quality, sanitation, food security and provision of health care servicesand insurance. Certain groups of people are particularly vulnerable, such as the elderly, the chronically ill, the poor and the very young, and require targeted social care interventions. Longer term developmental improvements need considerable financial resources and coherent intergovernmental action, limiting prospects for near-term adaptation.		8.2, 8.3, 8.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Human security & Emergency response (*medium confidence*)	Security is linked to key developmental issues such as income, housing, health care, education and food security. Moderate prospects as city governments can enhance emergency response services, to significantly reduce vulnerability for those who are most at risk. Where security and emergency forces have limited public trust, and especially with regard to gender issues,scope for supporting adaptation and risk management is considerably constrained.		8.3, 8.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*)	Large diversity across cities in terms of key economic sectors and adaptive capacity to disruptions in city services. Cities reliant on climate-sensitive tourism or agriculture may require economic diversification. Good prospects for advancing co-benefits through 'green' and 'waste' economy.		8.2, 8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Livelihoods (*medium confidence*)	Informal economy is more vulnerable, and often less adaptive in the short term. Social protection measures, in the specific context of urban livelihoods, are required.		8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Poverty & Access to basic services (*high confidence*)	Reducing basic service deficit could reduce hazard exposure, especially of the poor and vulnerable, alongside upgrading of informal settlements, improved housing conditions and enabling the agency of low income communities. Significant prospects where adaptation is already being implemented as part of human development or social protection.		8.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high

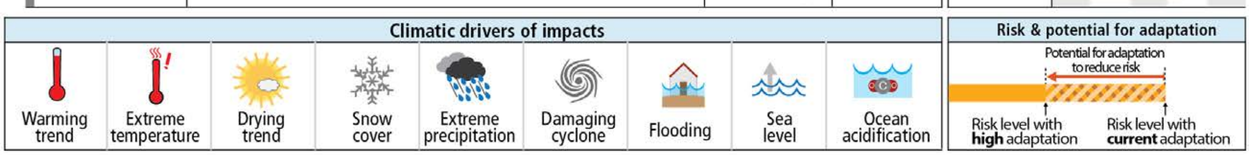


Table 8-4: The possibilities and limitations of focused activity for community groups on climate change coping and adaptation.

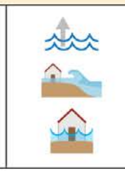
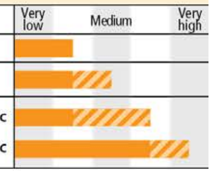
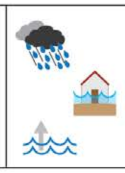
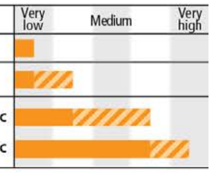
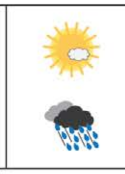
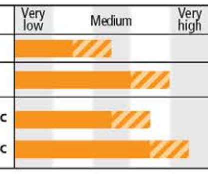
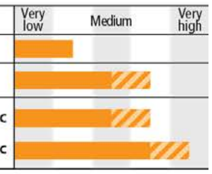
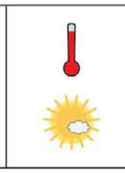
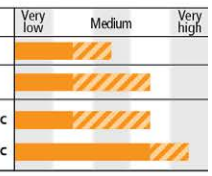
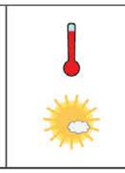
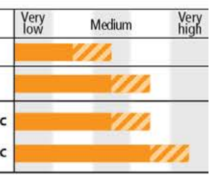
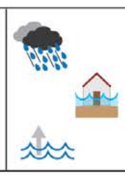
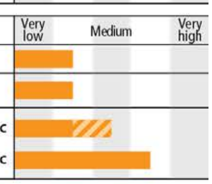
Capacity/Focus of Action	Coping (drawing on existing resources to reduce vulnerability and hazardousness and contain impacts from current and expected risk)	Adaptation (using existing resources and especially information to reorganize future asset profiles and entitlements to better position the household in the light of anticipated future risk, and to prepare for surprises)
Physical – buildings and critical community-level infrastructure	**Often possible to improve these although tenants will have little motivation to do so**	**Limits in how much risk reduction is possible within settlement (i.e. without trunk infrastructure to connect to)**
Physical – land and environment	**Local hazard reduction through drain cleaning, slope stabilization etc. is a common focus of community-based action (although there are less incentives where the majority of residents are short-term tenants or threatened with eviction)**	**External input required to design local hazard reduction works in ways that will consider the impacts of climate change 20 years or more in the future**
Social – health, education	**Many examples of community based action to improve local health and education access and outcomes, often with strong NGO and/or local government support**	**Health care and education are amenable to supporting adaptation by providing long-term investments in capacity building. They are rarely framed in climate change adaptation terms**
Economic – local livelihoods	**Livelihoods routinely assessed as part of household assessments of coping capacity in urban areas. More rarely is there a local livelihood focus for community based coping**	**Livelihoods and wider economic entitlements are key to individual adaptive profiles, but are seldom considered as part of urban community based adaptation programmes**
Institutional – community organization	**Local community strengthening is a common goal of interventions aimed at building coping capacity. Risk mapping, early warning, risk awareness, community health promotion and shelter training are common foci increasingly applied to urban communities. Local savings groups may have important roles**	**Local community strengthening is a core element of planning for adaptation but there are few assessments of the medium/long-term sustainability of outcomes. Where these have been undertaken, close ties to wider civil society networks or supportive local government is evident for community organizations and actions to persist**
Institutional – external influence	**It is unusual for coping programmes to include an element of external advocacy aimed at changing policy or practices in local government**	**Despite being core to determining future adaptation, there are very few examples of urban community based adaptation projects that include a targeted focus or parallel activity aimed at shifting priorities and practices in local government and beyond to support community capacity building**

Key: green = many cases of activity, amber = few cases of activity, red = very few cases of activity

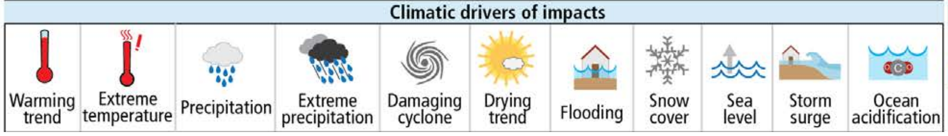
Table 8-5: Main sources of funding and financial instruments for urban adaptation.

Sources of funding	Types	Instruments	What can be funded (with some examples of funds)	Urban capacity required to access funding
Local – public	Local revenue raising policies: taxes, fees and charges, or use of local bond markets	♦ Local taxes (eg on property, land value capture, sales, businesses, personal income, vehicles….) ♦ User charges (eg for water, sewers, public transport, refuse collection) ♦ Other charges or fees (eg parking, licenses)	♦ Urban infrastructure and services ♦ Urban adaptation programmes and planning processes ♦ Urban capacity building	Cities with well-functioning administrative and institutional capacity and adequate funding from local revenue generation and inter-governmental transfers
Local – public-private	Public-Private-Partnerships (PPP) contracts and concessions	♦ Concessions and private finance initiatives to build, operate and/or maintain key infrastructure ♦ Energy performance contracting	♦ Medium to large-scale infrastructure with strong private goods (to allow rents for private sector)	Cities with strong capacity for legal oversight and management
Local or national - Private or Public	National or local financial markets	♦ Commercial loans, ♦ Private bonds ♦ Municipal bonds	♦ Basic physical infrastructure (need for collateral)	Well-functioning local or national financial markets that city governments can access
National - public	National (or state/provincial) revenue transfers or incentive mechanisms	♦ Revenue transfers from central or regional government ♦ Payment for ecosystem services or other incentive measures	♦ Urban Payment for Environmental Services in Brazil ♦ Sweden's KLIMP Climate Investment programme	Cities with good relations with national governments, strong administrative capacity to design and implement policies and plans
International – private	Market-based investment	♦ Foreign Direct Investment, Joint Ventures	♦ Industrial infrastructure ♦ Power generation infrastructure	Cities with strong national enabling conditions and policies for investment
International sources	Grants, concessional financing (e.g. Adaptation Fund)	♦ Grants, concessional loans and loan guarantees through bilateral and multilateral development assistance ♦ Philanthropic grants	♦ Urban capacity building ♦ Urban infrastructure adaptation planning	Typically requires strong multi-level governance – cities with good relations with national governments. Cities with low levels of administrative and financial market capacity

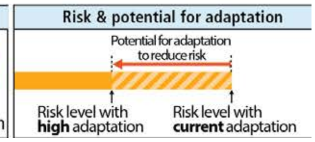
Table 8-6: Current and Indicative future climate risks for Dar es Salaam, Durban, London, and New York City.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Dar es Salaam					
Coastal zones systems (*medium confidence*)	Construction of coastal protection structures such as sea walls and groynes to minimize coastal erosion and land inundation in Dar es Salaam. Medium prospects due to high costs.		8.3.3.3, 8.3.3.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Terrestrial ecosystems & ecological infrastructure (*low confidence*)	Demarcation and protection of green areas, provision of more drainage systems and protection of urban wetlands and ground water resources. Low prospects due to poor development control including land-use management.		8.3.3.7, Table 8-2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Water supply systems (*high confidence*)	Improvement in Dar es Salaam's water resources management and increased coverage and efficiency in water supply systems. Medium prospects as some of these measures are already being implemented.		8.2.4.1, 8.3.3.4, Table 8-2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Waste water system (*high confidence*)	Increase in spatial coverage of sewerage and improvement of on-site excreta disposal systems. Low prospects for extending sewer coverage; higher prospects for expanding onsite disposal systems.		8.2.4.1, 8.3.3.4, Table 8.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Energy systems (*very high confidence*)	Reduced dependence on hydropower as the main source of energy by replacing it with natural gas. Very high prospects as the country has vast resources of natural gas.		8.2.4.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Food systems and security (*high confidence*)	Urban and peri-urban agriculture and new adaptation policies to take into account impacts of climate change on food costs and supply chain. . Enhanced social safety nets can support adaptation measures.		8.3.3.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Transportation and communication systems (*medium confidence*)	New design standards in context of climate change and enforcement of development controls. Low prospects as climate change issues are yet to be mainstreamed in the sector.		8.2.4.3, 8.3.3.6	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

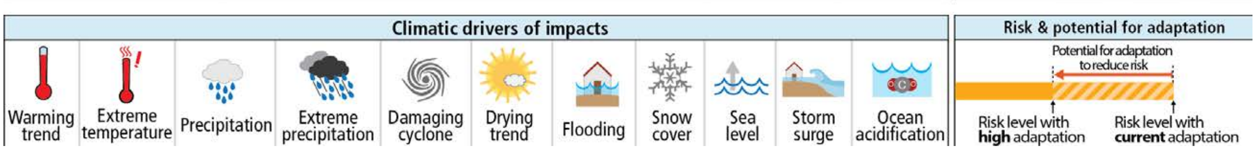
Climatic drivers of impacts



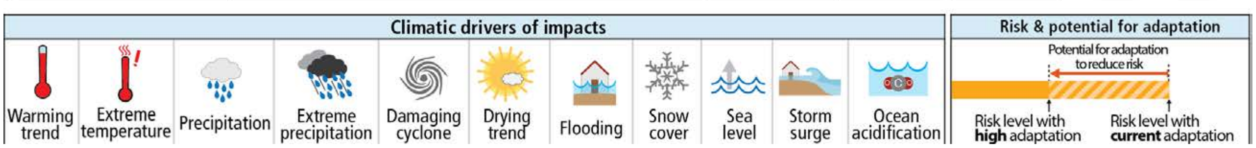
Risk & potential for adaptation



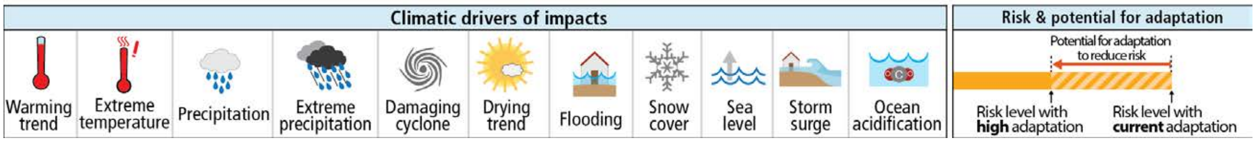
Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Dar es Salaam (continued)					
Housing (*high confidence*)	Climate change adaptation plans, new building codes, effective development control and upgrading of informal settlements. High prospects as some of these measure are already being taken into account.		8.2.4.4, 8.3.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Human health (*medium confidence*)	Improvement of water supply, solid waste management, housing conditions, land use planning and food security and provision of health insurance. Medium prospects as these are key development issues that require a lot of financial resources.		8.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*)	Improvement of storm water infrastructure and transport networks. Use of natural gas as main source for power generation, relocating of key economic activities and infrastructure along coastal buffer areas. A mixture of high and low prospects due to availability of natural gas and high requirements of financial resources.		8.3.3.1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Poverty & Access to basic services (*high confidence*)	Formalizing informal economic sector, upgrading of informal settlements, improving of housing conditions and empowering local communities in tackling problems related to climate change. High prospects as this is already being implemented as a development issue.		8.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Durban					
Coastal zones systems (*medium confidence*)	Maintaining and restoring Durban's coastal ecosystems. Use of coastal protection structures such geofabric sand bags, retaining walls, groynes and a beach nourishment scheme to minimize coastal erosion and infrastructure damage. Use of a development setback line and in some instances strategic retreat to protect infrastructure. High prospects as systems for coastal protection exist and are being improved, but may be overwhelmed by the increase in severity and frequency of storm surges over time.		8.3.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Terrestrial ecosystems and ecological infrastructure (*medium confidence*)	Design and implementation of a fine scale systematic conservation plan to protect a representative and persistent system of local biodiversity and related ecosystem services. Remove non-climate threats e.g. by managing alien invasive species. Medium prospects due to lack of human and financial resources to protect and manage system and poor enforcement of contraventions.		8.3.3.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Water supply systems (*high confidence*)	Demand and supply side management required. Reduce non-revenue water losses. Use of ecological infrastructure to improve level of assurance. Medium prospects as measures are already being implemented or considered.		8.3.3.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Waste water system (*high confidence*)	Increase in spatial coverage of Durban's waterborne sewerage system and use of appropriate alternative services in areas too costly to serve with water-borne systems. Recycling of waste water to potable standards. Medium prospects as measures are already being implemented or investigated.		8.3.3.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Durban (continued)					
Energy systems (*medium confidence*)	No integration of energy policy with adaptation policy or practice. Need to avoid maladaptation e.g. increased electricity use for cooling in response to rising temperatures. Low prospects as institutional structures not yet in place to drive this integration.		8.3.3.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Food systems and security (*high confidence*)	Need to change planting dates and to provide increased crop irrigation. Need to take into account the impacts of climate change on the full food supply chain. Low prospects as climate change not yet considered a serious threat.		8.3.3.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Transportation and communications systems (*medium confidence*)	New design standards in context of climate change and enforcement of development control. Medium prospects as climate change issues are beginning to be considered in the transportation sector.		8.3.3.6	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Housing (*high confidence*)	New building codes, effective development control, upgrading of informal settlements and retrofitting of existing housing stock. Changes in stormwater policy, preparation of master drainage plans, use of attenuation facilities and calculation of new floodlines. Promotion of higher densities to reduce pressure on ecological infrastructure. Medium prospects as measures are already being implemented or being investigated.		8.3.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Human health (*high confidence*)	Improvement of basic services, housing conditions, land use planning and food security. Extend coverage of primary health care and health insurance. Maintain and extend vector control. Ensure ability to deal with the impacts of large scale disasters through inter-sectoral co-ordination. Low to medium prospects due to limited human and financial resources.		8.3.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*)	Durban is a logistics, manufacturing and tourist centre. Need to protect and properly locate vulnerable infrastructure in coastal areas – particularly port-related infrastructure. High prospects because of the national economic significance of the port and petro-chemical sectors and local economic significance of tourism.		8.3.3.1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Poverty and access to basic services (*high confidence*)	Formalizing informal economic sector, upgrading informal settlements, provision of interim services to informal settlements, improving housing conditions and increasing the adaptive capacity of local communities (especially through ecosystem based adaptation). Use of climate change adaptation interventions to create employment opportunities. Medium prospects because of the scale of the problem and related costs.		Box 8-2, 8.3.3.7	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
London					
River/coastal zones systems (*high confidence*)	London is currently well protected from tidal flooding and has utilised an 'adaptation pathways' approach to ensure it identifies and delivers a flexible long-term tidal flood risk management plan to maintain a high standard of protection through the century.		8.3.3.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
London (continued)					
Terrestrial ecosystems & ecological infrastructure (*medium confidence*)	Adaptation is compromised primarily by habitat fragmentation and can be exacerbated, especially in wetland habitats, by invasive species. The city is taking an approach which promotes the multifunctional benefits of ecologically-designed urban green spaces to benefit adaptation with restoring ecological function.	Warming trend; Precipitation	8.3.3.7	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Water supply systems (*high confidence*)	London faces increasing water security issues during droughts created by higher relative per capita consumption, ageing infrastructure, a rapidly growing population and projected diminishing resources. Resilience is being increased through programmes to reduce consumption and increase the diversity of supply.	Precipitation; Extreme precipitation	8.3.3.4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Waste water system (*high confidence*)	Much of London is served by a combined rain and foul water drainage system that regularly overflows into the River Thames. Population growth, urban creep and projected more intense rainfall will further challenge the system. The city is working with the relevant drainage partners to manage this increasing risk through a combination of grey and green infrastructure.	Extreme precipitation; Flooding	8.3.3.4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Energy systems (*medium confidence*)	The city's energy security is threatened by a reduction in national generation capacity and the resilience of local distribution systems not matching the increasing demand. The city is responding through increasing energy efficiency and local energy production to improve resilience. Some concern over amplifications effects of energy system failure during heat or cold shocks.	Extreme temperature; Precipitation	8.3.3.5	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Food systems and security (*low confidence*)	London's food supply is globalised and access is strongly influenced by global food prices relative to income, as well as regional and national agricultural productivity.	Warming trend; Drying trend	8.3.3.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Transportation and communication systems (*medium confidence*)	London is served by a complex communications and public transport network, which whilst vulnerable in parts has sufficient redundancy to be resilient at the strategic level. Detailed risk assessments are informing an investment programme in the transport network that will deliver increasing resilience to climate impacts.	Warming trend; Precipitation; Snow cover	8.3.3.6	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Housing (*high confidence*)	London has an extensive historic housing stock that demonstrates poor thermal performance in summer and winter, poor water efficiency and significant numbers of which are at risk of flooding. There is improving integration between mitigation and adaptation policy implementation at the regional level, but insufficient funding and levers to implement widespread adaptation.	Warming trend; Extreme precipitation	8.3.3.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Human health (*high confidence*)	Health observations systems and care delivered through the National Health Service respond well but need to integrate better with social care provision to be more proactive, especially for vulnerable groups such as the elderly.	Warming trend	8.2.2.1, 8.2.3.1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
London (continued)					
Key economic sectors and services (*medium confidence*)	London's economy is dominated by service sector activities, particularly finance and including global businesses that expose it to failure in external markets that may be associated with climate change impacts or management. Business continuity is routinely integrated into business plans. Failure of essential infrastructure, including transport and energy networks has short-term impacts.	Extreme temperature; Extreme precipitation	8.3.3.1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Poverty & access to basic services (*high confidence*)	A significant proportion of the population struggles to pay their energy and water bills. Pockets of deprivation create areas of high vulnerability to climate risks, compounded by low levels of community capacity / social networks.	Extreme temperature; Extreme precipitation	8.3.3.8	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
New York City					
Coastal zones systems (*very high confidence*)	New York City is highly vulnerable to coastal storm events and sea level rise associated flooding. Integration of infrastructure and policy changes with opportunity to enhance ecosystem service services is possible.	Damaging cyclone; Storm surge	8.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Terrestrial ecosystems & ecological infrastructure (*high confidence*)	Promotion of ecosystem restoration efforts consistent with the current degraded state of most of NYC's ecosystem function. A need exists for continued land use protection of the City's water supply region.	Extreme temperature; Extreme precipitation; Flooding	8.2.4.5; 8.3.3.4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Water supply systems (*medium confidence*)	New York City maintains an extremely extensive and resilient water supply infrastructure. Long term adaptation could potentially include heightened drought management and interagency coordination with other water supply demand entities in region.	Drying trend	8.3.3.4, 8.3.3.7	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Waste water system (*medium confidence*)	NYC maintains an extremely extensive and resilient wastewater infrastructure. Gray and green infrastructure adaptation to limit effects of extreme precipitation events and combined sewer overflows will be necessary.	Extreme precipitation; Storm surge; Flooding	8.2.3.3, 8.2.4.1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Energy systems (*medium confidence*)	NYC is served by an extensive energy generation and distribution system most of which is operated by private companies or semi-public authorities. Peak load demand adaptation especially for cooling demand will be necessary, as will adaptation for distribution disruptions associated with extreme events including ice storm events and coastal storm surge.	Extreme temperature; Snow cover; Storm surge	8.2.4, 8.2.4.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Food systems and security (*medium confidence*)	NYC is connected to a regional, national, and global food distribution system. Adaptation will be necessary to ensure that food processing and distribution systems within the City can be resilient in the face of potential extreme event impacts.	Storm surge; Flooding	8.3.3.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high

Climatic drivers of impacts

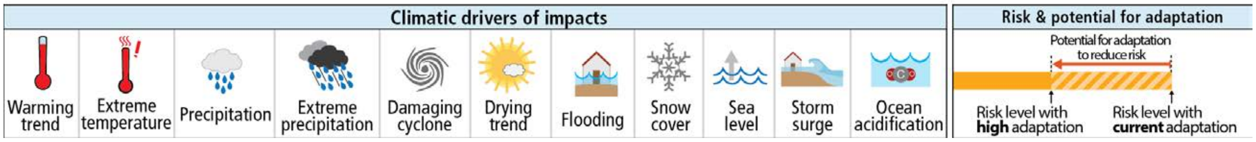
Warming trend | Extreme temperature | Precipitation | Extreme precipitation | Damaging cyclone | Drying trend | Flooding | Snow cover | Sea level | Storm surge | Ocean acidification

Risk & potential for adaptation

Potential for adaptation to reduce risk

Risk level with **high** adaptation — Risk level with **current** adaptation

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
New York City (continued)					
Transportation systems (*high confidence*)	NYC is served by a complex and redundant transportation and communications infrastructure. Numerous vulnerabilities to extreme events are present which result in short term disruption. Long term SLR and increased flood frequency can result in increased disruption and will require adaptation strategies.		8.2.2.2, 8.3.3.6	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Housing (*high confidence*)	NYC includes approximately 1 million buildings and similar structures. These maintain a broad range of vulnerabilities to climate change particularly associated with flooding and extreme heat events. Adaptation strategies could include retrofit construction practices especially in coastal zone locations or areas affected by urban heat island conditions.		8.1.3, 8.2.4, 8.3.3.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Human health (*high confidence*)	Great diversity of health conditions of the 8.3 plus million residents are associated with a wide range of human health vulnerabilities to climate change. The very young, aged, and otherwise health- compromised face heightened risk and require adaptation strategies, particularly focused on heat stress and disease.		8.2.3.1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Key economic sectors and services (*medium confidence*)	NYC has a diverse economic base focused on the service related industries with regional, national, and global connections. Adaptation will be necessary to limit vulnerability and enhance resilience in the face of large scale extreme events such as Hurricane Sandy.		8.3.3.1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Poverty & Access to basic services (*medium confidence*)	NYC has an extensive public service provision capacity. Adaptation will be necessary to ensure that more frequent or more intense extreme events will not limit this capacity.		8.3.3.8	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high



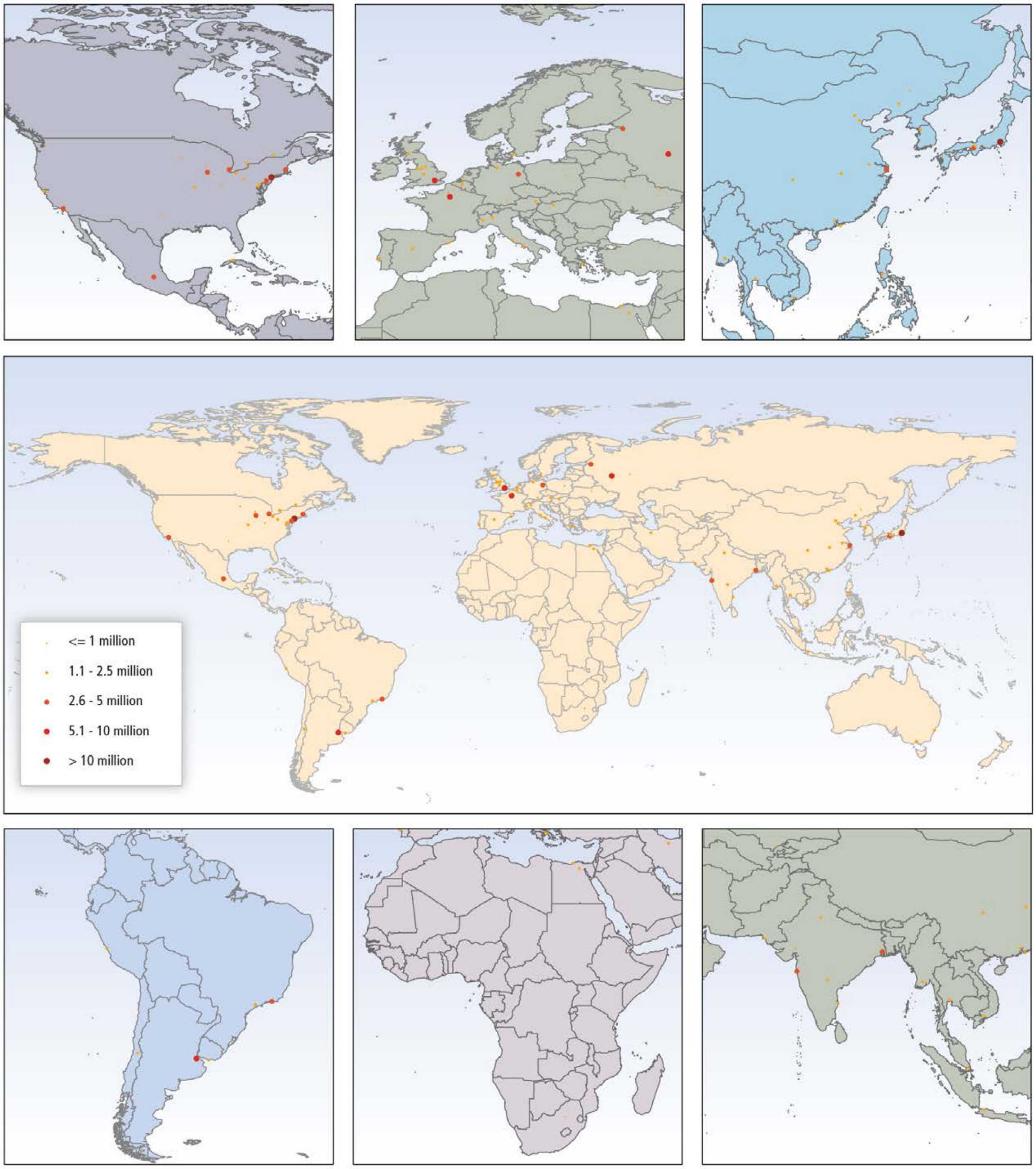


Figure 8-1: Global and regional maps showing the location of urban agglomerations with 750,000 plus inhabitants in 1950. Source: Derived from statistics in United Nations, 2012.

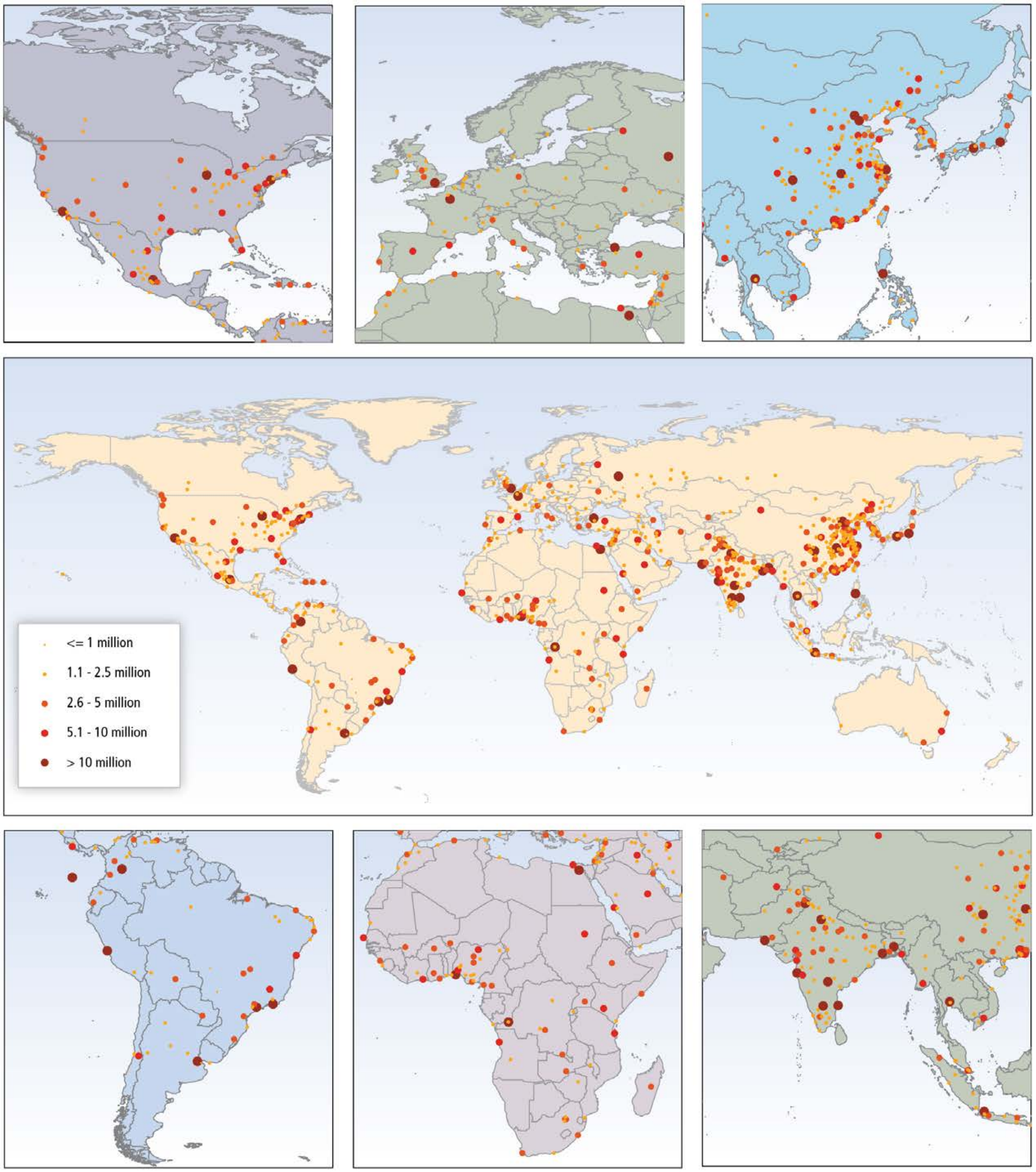
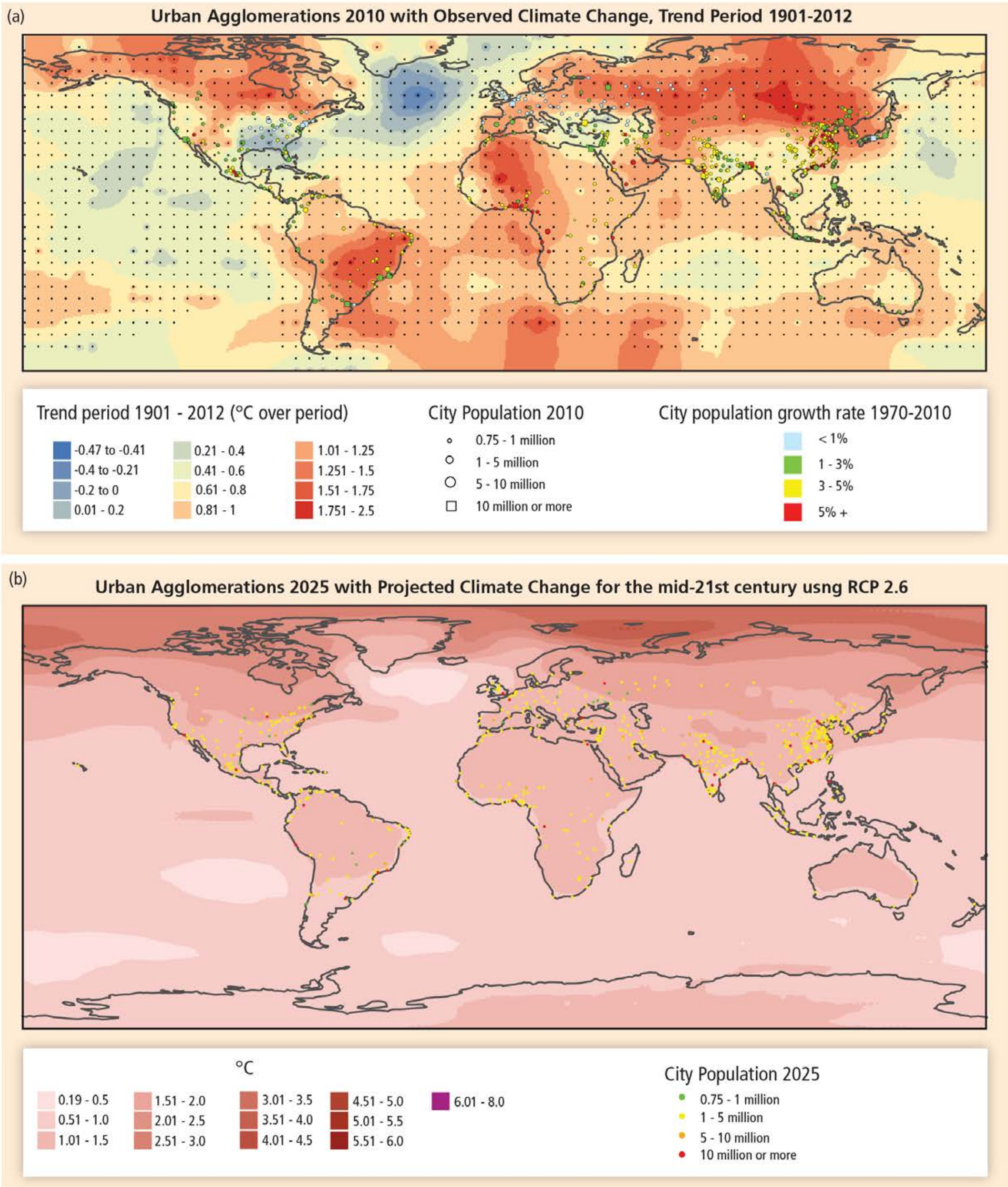


Figure 8-2: Global and regional maps showing the location of urban agglomerations with 750,000 plus inhabitants projected for 2025. Source: Derived from statistics in United Nations, 2012.


(a)
Urban Agglomerations 2010 with Observed Climate Change, Trend Period 1901-2012
Trend period 1901 - 2012 (°C over period)
-0.47 to -0.41
-0.4 to -0.21
-0.2 to 0
0.01 - 0.2
0.21 - 0.4
0.41 - 0.6
0.61 - 0.8
0.81 - 1
1.01 - 1.25
1.251 - 1.5
1.51 - 1.75
1.751 - 2.5
City Population 2010
0.75 - 1 million
1 - 5 million
5 - 10 million
10 million or more
City population growth rate 1970-2010
< 1%
1 - 3%
3 - 5%
5% +
(b)
Urban Agglomerations 2025 with Projected Climate Change for the mid-21st century usng RCP 2.6
°C
0.19 - 0.5
0.51 - 1.0
1.01 - 1.5
1.51 - 2.0
2.01 - 2.5
2.51 - 3.0
3.01 - 3.5
3.51 - 4.0
4.01 - 4.5
4.51 - 5.0
5.01 - 5.5
5.51 - 6.0
6.01 - 8.0
City Population 2025
0.75 - 1 million
1 - 5 million
5 - 10 million
10 million or more

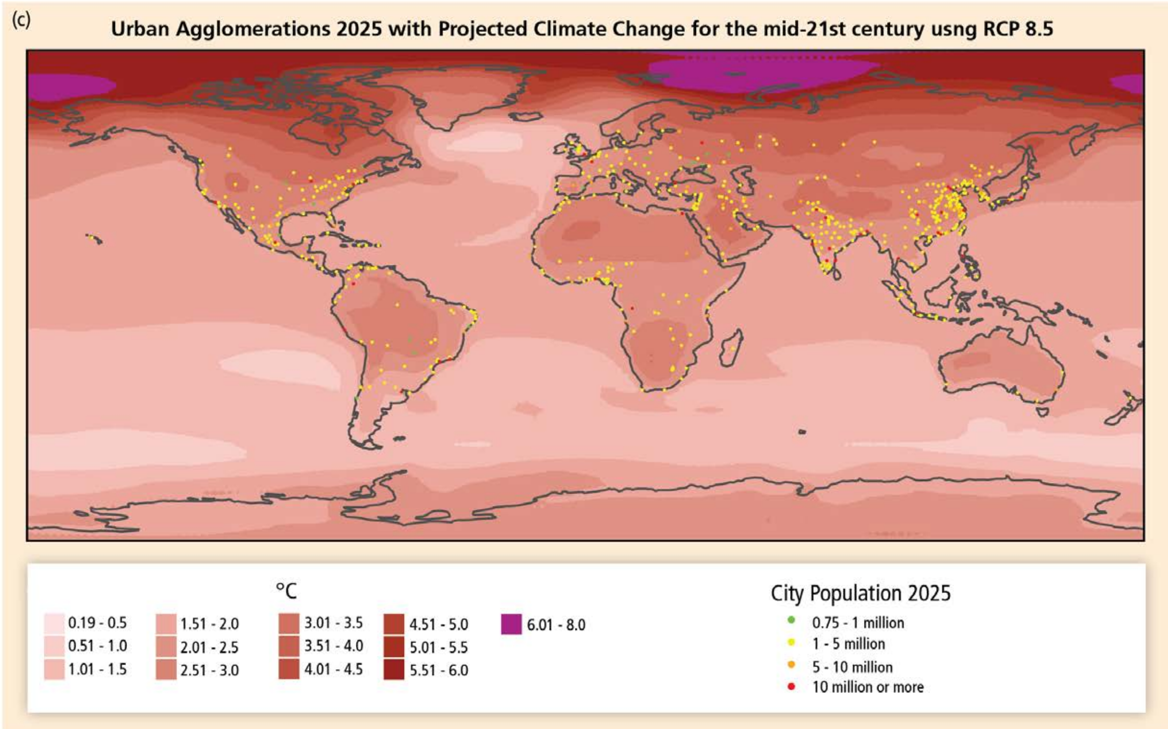


Figure 8-3: Large urban agglomerations and temperature change. Sources: Maps drawn from IPCC, 2013; urban agglomeration population and population growth data from United Nations, 2012.

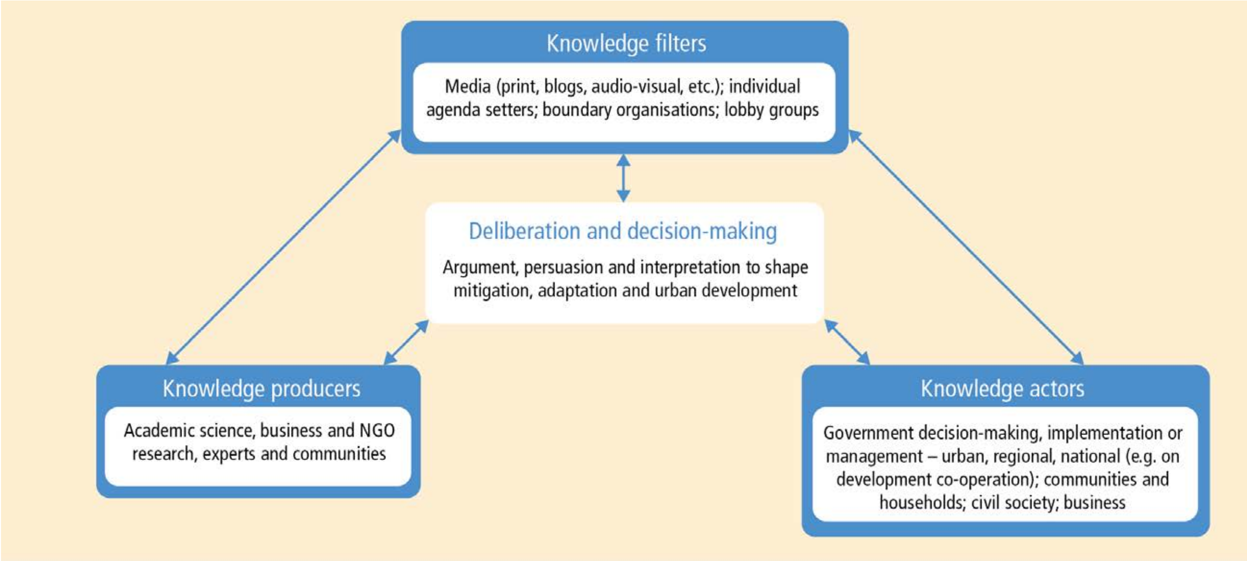


Figure 8-4: The co-production of knowledge and policy for adaptation, mitigation, and development in urban systems. Source: Adapted from Corfee-Morlot *et al*., 2011.

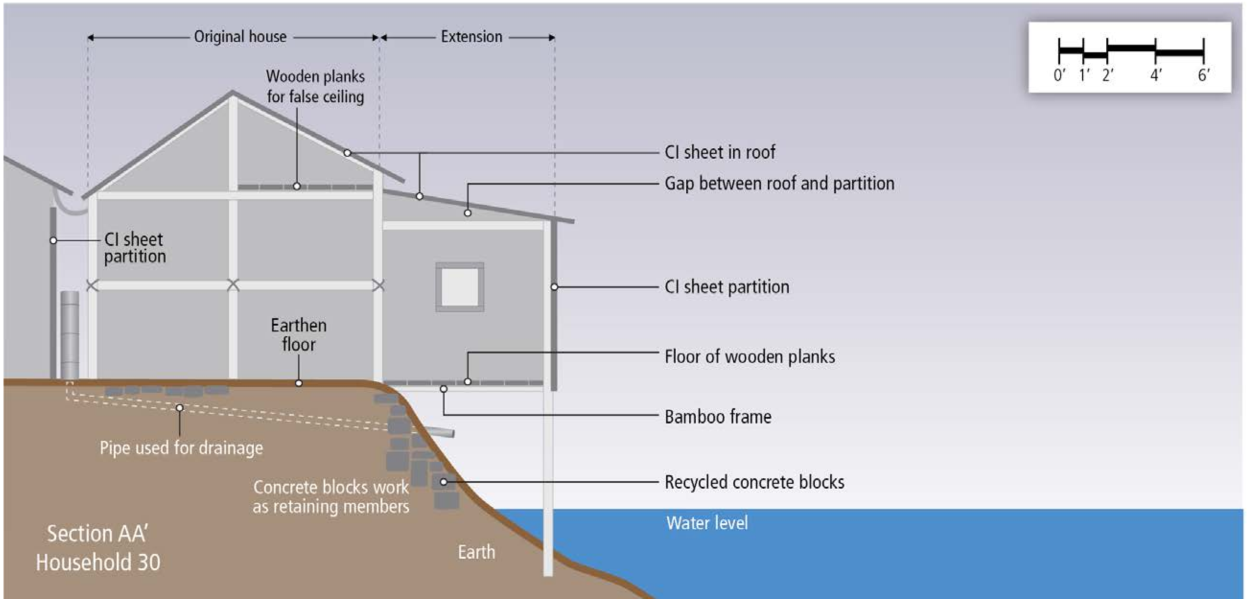


Figure 8-5: Household adaptation - a cross section of a shelter in an informal settlement in Dhaka (Korail) showing measures to cope with flooding and high temperatures. CI: Corrugated iron. Source: Jabeen *et al*., 2010.

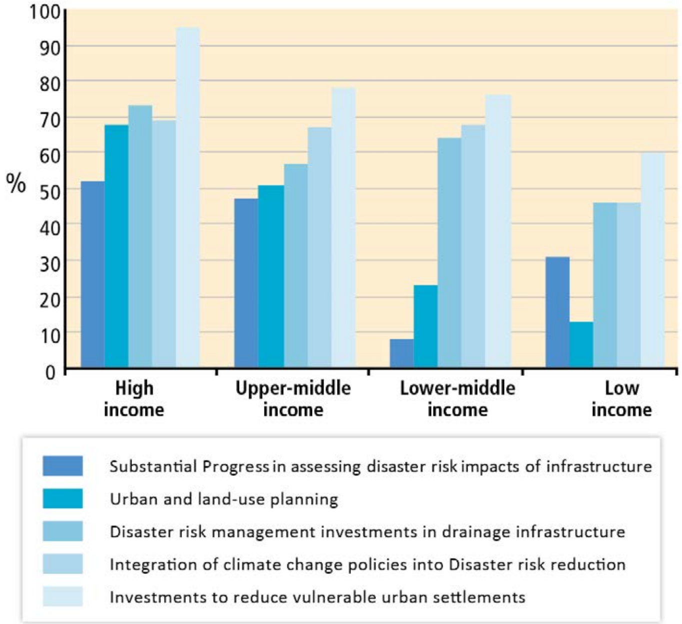


Figure 8-6: Progress reported by 82 governments in addressing some key aspects of disaster risk reduction by countries' average per capita income. Source: United Nations, 2011.

Chapter 9. Rural Areas

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Executive Summary

Rural areas still account for almost half the world's population, and about 70% of the developing world's poor people. [9.1.1] There is a lack of clear definition of what constitutes rural areas, and definitions that do exist depend on definitions of the urban. [9.1.2] Across the world, the importance of peri-urban areas and new forms of rural-urban interactions are increasing (*high agreement, limited evidence*). [9.1.3] Rural areas, viewed as a dynamic, spatial category, remain important for assessing the impacts of climate change and the prospects for adaptation. [9.1.1]

Climate change in rural areas will take place in the context of many important economic, social and land-use trends (*very high confidence*). In different regions, absolute rural populations have peaked or will peak in the next few decades. [9.3.1] The proportion of the rural population depending on agriculture is extremely varied across regions, but declining everywhere. Poverty rates in rural areas are higher than overall poverty rates, but also falling more sharply, and the proportions of population in extreme poverty accounted for by rural people are also falling: in both cases with the exception of sub-Saharan Africa, where these rates are rising [Fig 9-2]. Accelerating globalization, through migration, labour linkages, regional and international trade, and new information and communication technologies, is bringing about economic transformation in rural areas of both developing and developed countries. [9.3.1]

Rural people in developing countries are subject to multiple non-climate stressors, including under-investment in agriculture (though there are signs this is improving), problems with land and natural resource policy, and processes of environmental degradation (*very high confidence*). In developing countries, the levels and distribution of rural poverty are affected in complex and interacting ways by processes of commercialization and diversification, food policies, and policies on land tenure. In developed countries, there are important shifts towards multiple uses of rural areas, especially leisure uses, and new rural policies based on the collaboration of multiple stakeholders, the targeting of multiple sectors and a change from subsidy-based to investment-based policy. [9.3.1, Table 9-3]

Impacts of climate change on the rural economic base and livelihoods, land-use and regional interconnections are at the latter stages of complex causal chains (*high confidence*). These flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. [9.3.3] This increases both the uncertainty associated with detection and attribution of current impacts [9.3.2], and with projections of specific future impacts. [9.3.3]

Structural features of farm households and communities affect their vulnerability to climate change in complex ways (*high confidence*). There is *low agreement* on some of the key factors associated with vulnerability or resilience in rural areas [9.3.5.1], including rainfed as opposed to irrigated agriculture [9.3.5.1.1], small-scale and family-managed farms, and integration into world markets. [9.3.5.1.2]. There is *high agreement* on the importance for resilience of access to land and natural resources, flexible local institutions [9.3.5.1.3], and knowledge and information [9.3.5.1.6], and on the association of gender inequalities with vulnerability. [9.3.5.1.5] Specific livelihood niches such as pastoralism, mountain farming systems, and artisanal fisheries are vulnerable and at high risk of adverse impacts (*high confidence*), partly due to neglect, misunderstanding or inappropriate policy towards them on the part of governments. [9.3.5.2]

Cases in the literature of observed impacts on rural areas often suffer from methodological problems of attribution, but evidence for observed impacts, both of extreme events and other categories, is increasing (*medium confidence*). Impacts attributable to climate change include some direct impacts of droughts, storms, and other extreme events on infrastructure and health (*low confidence* globally, but *medium confidence* in certain regions), as well as longer-term declining yields of major crops, from which impacts on income and livelihoods can be inferred with *low confidence*. There is *high confidence* in geographically-specific impacts, such as glacier melt in the Andes. [9.3.2]

Major impacts of climate change in rural areas will be felt through impacts on water supply, food security [9.3.3.1] and agricultural incomes [9.3.4.1] (*high confidence*). Shifts in agricultural production, of food and non-food crops, are projected for many areas of the world (*high confidence*). [9.3.3.1] Price rises, which may be induced by climate shocks as well as other factors [9.3.3.3.2], have a disproportionate impact on the welfare of the poor in rural areas, such as female headed households and those with limited access to modern agricultural inputs, infrastructure and education. [9.3.3.1] The time scale for impacts varies across regions and sectors, and by the nature of the specific climatic impact.

Climate change will impact international trade volumes in both physical and value terms (*medium agreement, limited evidence*). Importing food can help countries adjust to climate-change induced domestic productivity shocks while short-term food deficits in low-income countries may have to be met through food aid. Options exist for adaptations within international agricultural trade (*medium confidence*). Deepening agricultural markets and improving the predictability and the reliability of the world trading system through trade reform, as well as investing in additional supply capacity of small-scale farms in developing countries, could result in reduced market volatility and manage food supply shortages caused by climate change. [9.3.3.3.2]

Migration patterns will be driven by multiple factors of which climate change is only one (*high confidence*). [9.3.3.3.1] Given these multiple drivers of migration (economic, social, political, demographic and environmental) and the complex interactions which mediate migratory decision-making by individuals or households, establishment of a relation between climate change and intra-rural and rural-to-urban migration, observed or projected, remains a major challenge.

Climate policies, such as increasing energy supply from renewable resources, encouraging cultivation of biofuels, or payments under REDD, will have significant secondary impacts, both positive (increasing employment opportunities) and negative (landscape changes, increasing conflicts for scarce resources), in some rural areas (*medium confidence*). [9.3.3.4] There is a need to understand how implementation of these policies will impact on rural livelihoods. These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including the need to promote participation of rural stakeholders.

Most studies using valuation methodologies conclude that climate change impacts will be substantial, especially for developing countries, due to their economic dependence on agriculture and natural resources, low adaptive capacities, and geographical locations (*very high confidence*). [9.3.4] Valuation of climate impacts needs to draw upon both monetary and non-monetary indicators. The valuation of non-marketed ecosystem services

[9.3.4.5] and the limitations of economic valuation models which aggregate across multiple contexts [9.3.4] pose challenges for valuing impacts in rural areas (*high confidence*).

There is a growing body of literature on adaptation practices in both developed and developing country rural areas [9.4.1], including documentation of practical experience in agriculture, water, forestry and biodiversity and, to a lesser extent, fisheries [9.4.3] (*very high confidence*). Public policies supporting decision-making for adaptation exist in developed and, increasingly, in developing countries, and there are also examples of private adaptations led by individuals, companies and NGOs (*high confidence*). [9.4.2] Constraints on adaptation come from lack of access to credit, land, water, technology, markets, knowledge and information, and perceptions of the need to change; and are particularly pronounced in developing countries *(high confidence)*. [9.4.4] Gender and institutions affect access to adaptation options and the presence of barriers to adaptation (*very high confidence).* [9.4.4]

9.1. Introduction

9.1.1. Rationale for the Chapter

This chapter assesses the impacts of climate change on, and the prospects for adaptation in, rural areas. Rural areas include diverse patterns of settlement, infrastructure and livelihoods, and relate in complex ways with urban areas. The chapter shows that rural areas experience specific vulnerabilities to climate change, both through their dependence on natural resources and weather-dependent activities, and through their relative lack of access to information, decision-making, investment and services. Adaptation strategies will need to address these vulnerabilities. Some of the key starting points, which affect the scope and coverage of literature assessed in this chapter, will be as follows.

- Rural areas, even after significant demographic shifts, still account for 3.3 billion people or almost half (47.9%) of the world's total population (UN-DESA Population Division 2012).
- The overwhelming majority of the world's rural population (3.1 billion people, or 91.7% of the world's rural population, or 44.0% of the world's total population) live in less developed or least developed countries (UN-DESA Population Division 2012).
- Rural dwellers also account for about 70% of the developing world's poor people. IFAD (2010) states that around 70% of the extreme poor in developing countries lived in rural areas in 2005. Ravallion *et al*. (2007) using 2002 data and poverty lines of $US1.08 or $US2.15, in each case with urban poverty lines adjusted upwards to recognize additional non-food spending, give a figure of around 75% of people, under either poverty line, being rural.
- Rural areas are a spatial category, associated with certain patterns of human activity, but with those associations being subject to continuous change.
- Rural areas are largely defined in contradistinction to urban areas, but that distinction is increasingly seen as problematic.
- Rural populations have, and will have, a variety of income sources and occupations, within which agriculture and the exploitation of natural resources have privileged, but not necessarily predominant, positions.

The chapter will complement the treatment of issues also dealt with in Chapter 7 "Food Production Systems and Food Security" and Chapter 4 "Terrestrial and Inland Water Systems", but will primarily look at how biophysical impacts of climate change on agriculture and on less-managed ecosystems translate into impacts on human systems, and in this regard will complement sections of Chapter 12 "Human Security", Chapter 13 "Poverty and Livelihoods", and other sectoral and regional chapters. The important impacts of climate change on human health are covered in Chapter 11. In accordance with the proportion of the rural population found in developing countries, literature on these countries is given prominence, but issues of impact, vulnerability and adapatation in developed countries are also assessed.

9.1.2. Definitions of the Rural

"Rural" refers generally to areas of open country and small settlements, but the definition of "rural areas" in both policy-oriented and scholarly literature are terms often taken for granted or left undefined, in a process of definition which is often fraught with difficulties (IFAD, 2010). Ultimately, in developing countries as well as developed countries, the rural is defined as the inverse or the residual of the urban (Lerner and Eakin, 2010). Human settlements in fact exist along a continuum from 'rural' to 'urban', with 'large villages', 'small towns' and 'small urban centres' not clearly fitting into one or the other. The variations in definitions from country-to-country can best be described through several examples (from both developed and developing countries of different sizes) shown in Table 9-1.

[INSERT TABLE 9-1 HERE
Table 9-1: Definitions of the "rural" and the "urban" in selected countries.]

Researchers have increasingly recognized that the simple dichotomy between 'rural' and 'urban' has is extremely problematic (Simon et al., 2006:4). Additional categories such as "peri-urban areas" (Simon et al., 2006; Simon, 2008; Webster 2002; Lerner and Eakin 2010; Bowyer-Bower, 2006), and *desakota* (Desakota Study Team 2008; McGee 1991; Moench and Gyawali 2008), allow more nuanced analysis of the permeable boundaries of rural and urban areas and the diversified economic systems that exist across the urban-rural spectrum – see Box CC-UR.

While remaining aware of issues of definition, this chapter will in general assess literature on rural areas using whatever definitions of the rural are used in that literature. Global statistics collated by international organizations and cited here are generally aggregations of national statistics compiled under each national definition.

9.2. Findings of Recent Assessments

The Fourth Assessment Report (AR4) of the IPCC contains no specific chapter on "rural areas". Material on rural areas and rural people is found throughout the AR4, but rural areas are approached from specific viewpoints and through specific disciplines. Table 9-2 summarizes key findings on rural areas from AR4 (particularly Easterling *et al*., 2007 on agriculture, Wilbanks *et al.*, 2007 on industry, settlement and society, and Klein *et al.* 2007 on links between adaptation and mitigation), and relevant findings from the International Assessment of Agricultural Knowledge, Science and Technology for Development (McIntyre *et al.*, 2009). All these sources stress uncertainty, the importance of non-climate trends, complexity and context-specificity, in any findings on rural areas and climate change.

[INSERT TABLE 9-2 HERE
Table 9-2: Relevant findings on rural areas from the IPCC Fourth Assessment Report and the International Assessment of Agricultural Science and Technology for Development.]

9.3. Assessing Impacts, Vulnerabilities, and Risks

9.3.1. Current and Future Economic, Social, and Land-Use Trends in Rural Areas

Climate change in rural areas will take place against the background of the trends in demography, economics and governance which are shaping those areas. While there are major points of contact between the important trends in developing and developed countries, and the analytical approaches used to discuss them, it is easier to discuss trends separately for the two groups of countries. In particular there is a close association in developing countries between rural areas and poverty. Table 9-3 summarizes and compares the most important trends across the two groups of countries. Figure 9-1, Table 9-4, and Figure 9-2 focus on two specific trends in developing countries: demographic trends and trends in poverty indicators.

[INSERT TABLE 9-3 HERE
Table 9-3: Major demographic, poverty-related, economic, governance, and environmental trends in rural areas of developed and developing countries.]

[INSERT FIGURE 9-1 HERE
Figure 9-1: Trends in rural (blue), urban (black), and total (red) populations by region. Solid lines represent observed values and dotted lines represent projections. Source: United Nations, Department of Economic and Social Affairs/Population Division (2012).]

[INSERT TABLE 9-4 HERE
Table 9-4: Poverty indicators for rural areas of developing countries.]

[INSERT FIGURE 9-2 HERE
Figure 9-2: Demographic and poverty indicators for rural areas of developing countries, by region. R: rural people as percentage of population; A/R: agricultural population as percentage of rural; P: incidence of poverty; RP: incidence of poverty in rural areas; EP: incidence of extreme poverty; ERP: incidence of extreme poverty in rural areas; R/EP: rural people as percentage of those in extreme poverty. Source: Adapted from IFAD (2010).]

9.3.2. Observed Impacts

Documentation of observed impacts of climate change on rural areas involves major questions of detection and attribution (see chapter 18). Whilst having potential, there are complications with using traditional knowledge and farmer perceptions to detect climate trends (Box 18-4, Rao *et al.*, 2011). Implied equivalence between local perceptions of climate change, local decadal trends, extreme events and global change is common, and often used without systematic discussion of the challenges (Ensor and Berger, 2009; Paavola, 2008; Castro *et al.*, 2012). This is not a problem in the context of detailed social-scientific analysis of vulnerability, adaptive capacity and their determinants, but becomes more problematic to use as evidence for observed impact. Detection and attribution of extreme events to climate change is no less challenging (Seneviratne *et al.* 2012). Exposure to non-climate trends and shocks further complicates the issue (Nielsen and Reenberg, 2010, Section 3.2.7).

The impacts of climate change on patterns of settlement, livelihoods and incomes in rural areas will be the result of multi-step causal chains of impact. Typically, those chains will be of two sorts. One sort will involve extreme events, such as floods and storms, as they impact on rural infrastructure and cause direct loss of life. The other sort will involve impacts on agriculture or on ecosystems on which rural people depend. These impacts may themselves stem from extreme events, from changing patterns of extremes due to climate change, or from changes in mean conditions. The detection and attribution of extreme events is discussed by the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (Seneviratne *et al.*, 2012). The detection and attribution of impacts on ecosystems and on agriculture are dealt with in Chapters 4 and 7 of this report. Both exercises are complex.

Seneviratne *et al.* (2012) give a detailed and critical assessment of the detection and attribution of observed patterns of extreme events, which shows greatly varying levels of confidence in the attribution to climate change of global and regional trends, and that "attribution of single extreme events to anthropogenic climate change is challenging" (2012:112). They state that it is *likely* there has been a worldwide increase in extreme high-water events during the late 20th century, with a *likely* anthropogenic influence on it. They have *medium confidence* in detecting trends towards more intense and frequent droughts in some parts of the world (Southern Europe and West Africa) since 1950. They note that opposite trends exist elsewhere, and that there is *low confidence* in any trend in drought in, for example, East Africa. WG I AR5 Chapter 2 similarly ascribes *low confidence* in a global observed trend in drought in the later 20th century, with a *likely* increase in frequency and intensity of drought in the Mediterranean and West Africa and a likely decrease in central North America. Lyon and DeWitt (2012) see a "recent and abrupt decline in the East African long rains" since 1999. Seneviratne *et al.* (2012) assign *low confidence* to any observed long-term increases in tropical cyclone activity, as does WGI AR5 Chapter 2, and to attribution of any changes in cyclone activity to anthropogenic influence. WGI AR5 Chapter 2 states that an observed increase in the frequency and intensity of North Atlantic cyclones is virtually certain. It also describes varying regional trends towards heavy precipitation events, *very likely* in central North America. Section 3.2.7 ascribes *medium confidence* to observed increased likelihood of flooding at the scale of some regions.

Handmer *et al.* (2012) discuss both observed and projected impacts of extreme events on human systems and ecosystems, with numerous examples of diverse, widespread negative impacts (see also Chapter 18). Important categories of extreme events causing negative impacts in rural areas include tropical storms and droughts: Hurricane Stan in October 2005 affected nearly 600,000 people on the Chiapas coast as a consequence of flooding and sudden river overflows (Saldaña-Zorrilla, 2008). Droughts in rural areas produce severe economic stresses, including employment reduction and migration (Gray and Mueller, 2012). Agricultural livelihoods are affected by droughts. Ericksen *et al.* (2012) review a variety of livestock mortality rates for recent droughts in the Horn of Africa, ranging up to 80% of livestock in Southern Kenya in 2009.

Climate change impacts on agriculture and ecosystems run through rising temperature and changes in rainfall variability and seasonality as well as through extreme events. Changes in temperature caused reduction in global yields of maize and wheat by 3.8 and 5.5% respectively from 1980 to 2008 relative to a counterfactual without climate change, which offset in some countries some of the gains from improved agricultural technology (Lobell et al., 2011, section 7.2.1.1). Badjeck *et al.* (2010) discuss current and future impacts on fisherfolk across the world. Many local-level studies are subject to the attribution problems mentioned above, but Wellard *et al.* (2012) cautiously note a convergence of climate data with the perceptions of farmers and officials to the effect that over the last 30 years the rainfall in Malawi has become less predictable, that the rainy season is arriving later in the year causing delays in planting of the main crops, and that damaging dry spells during the rainy season have become more likely.

Glacial retreat in Latin America is one of the best evidenced current impacts on rural areas (see Section 27.3.1.1). In highland Peru there have been rapid observed declines since 1962 in glacier area and dry-season stream flow, on which local livelihoods depend, which accord well with local perceptions of changes that are necessitating adaptation (Orlove, 2009). Other studies of the area focus both on observed changes in water availability and on glacial lake outburst floods, which are attributable to climate change (Bury *et al.*, 2011; Carey, 2010, Carey *et al.* 2012). There is also a rich specialized literature on the impacts of shrinking sea-ice and changing seasonal patterns of ice formation and melt on indigenous peoples in the Arctic (Ford, 2009; Beaumier and Ford, 2010, Section 28.2.5.1.7).

Migration associated with weather-related extremes or longer-term climate trends is discussed in Chapter 12, Table 12-3, with empirical examples of migrations linked to droughts, coastal storms, floods and sea level rise. The Asian Development Bank (ADB, 2012) gives a figure of 42 million people displaced by extreme weather events in Asia and the Pacific over 2010-2011. Attribution of migration to climate change is extremely complex, as recognized by Black *et al.* (2011a), because life in rural areas across the world typically involves complex patterns of rural-urban and rural-rural migration, subject to economic, political, social and demographic drivers, patterns which are modified or exacerbated by climate events and trends rather than solely caused by them (see also Section 12.4.1).

9.3.3. Future Impacts

This section will examine the major impacts of climate change identified or projected for rural areas, under the headings of: economic base and livelihoods; infrastructure; spatial and regional interconnections, including migration, trade, investment and knowledge; and second-order impacts of climate policy. Section 9.3.4, assesses literature on impact through a different and specific lens, that of economic valuation. The biophysical impacts of climate change on food crops are dealt with primarily in Chapter 7; but also here and in section 9.3.4 insofar as they affect rural economies. Biophysical impacts on non-food cash crops, are discussed below. As with the observed impacts in section 9.3.2, the future impacts of climate change described here, and quantified in section 9.3.4, are at the latter stages of complex causal chains that flow through changing patterns of extreme events and/or effects of climate change on biophysical processes in agriculture and less-managed ecosystems. Lal *et al.* (2011) show the regional specificity of projected socio-economic impacts across the rural United States, with different regions affected through agriculture, water stress and energy costs. Anderson *et al.* (2010) discuss the complexity of projected impacts across dryland regions of developing countries. These considerations increase the uncertainty associated with any particular impact on the economic base, on land-use or on regional interconnections.

9.3.3.1. Economic Base and Livelihoods

9.3.3.1.1. General considerations

Climate change will affect rural livelihoods, or "the capabilities, assets (stores, resources, claims and access) and activities required for a means of living" (Chambers and Conway, 1992). Many, though by no means all, rural livelihoods are dependent on natural resources (e.g. agriculture, fishing and forestry), and their availability will vary in a changing climate. This will have effects on human security and wellbeing (Kumssa and Jones, 2010, see also Chapter 12). Climate change impacts on smallholder and subsistence farmers will be compounded by environmental and physical processes affecting production at a landscape, watershed or community level; and other impacts, including those on human health and on non-agricultural livelihoods (Morton, 2007) and also trade and food prices (Anderson *et al*,. 2010). Despite the growing importance of non-farm livelihoods in rural areas worldwide (Ellis, 2000; Reardon *et al*., 2007), and households pursuing interdependent agricultural and non-agricultural livelihoods in peri-urban areas as a risk management strategy (Lerner and Eakin, 2010; Lerner *et al.*, 2013), there is a relative scarcity of literature on the interactions of these with climate variability and climate change.

Climate variability and change interacts with, and sometimes compounds, existing livelihood pressures in rural areas, such as economic policy, globalization, environmental degradation and HIV/AIDS, as has been shown in Tanzania (Hamisi *et al.*, 2012), Ghana (Westerhoff and Smit, 2009), South Africa (O'Brien *et al*., 2009; Ziervogel and Taylor, 2008; Reid and Vogel, 2006), Malawi (Casale *et al.*, 2010), Kenya, (Oluoko-Odingoa, 2011), Senegal (Mbow *et al*., 2008) and India (O'Brien *et al.*, 2004). Economic heterogeneity of farm households within communities, in terms of farm and household size, crop choices and input use, will be important in determining impacts (Claessens *et al.* (2012), as will social relations within households that affect production (Morton, 2007).

Projected impacts on yields and production of food crops are assessed in Section 7.4.1 and Figure 7-7. Local warming in excess of 1°C is projected to have negative impacts in both temperate and tropical regions without adaptation (though individual locations may benefit). There is *medium confidence* in large negative impacts of local increases of 3-4°C, on productivity, production and food security, globally and particularly in tropical countries, that go beyond adaptive capacity. The impacts of climate change on the agricultural sector in Africa, dominated by smallholder farming and very largely rainfed are considered to be very significant to economies and livelihoods (Müller *et al.*, 2011; Kotir, 2011; Collier et al., 2008; Hassan, 2010). These results emerge across a range of scenarios. Several other studies also map declines in net revenues from crops and the associated links with food security and poverty (Molua, 2009; Thurlow et al., 2009; Reid et al., 2008; Thurlow and Wobst, 2003).

Post-harvest aspects of agriculture – storage on-farm and commercially, handling and transport – have been relatively neglected in discussions of climate change, but will be affected by changes in temperature, rainfall, humidity, and by extreme events. Many adaptation opportunities are already understood by postharvest service providers, but getting postharvest knowledge into use at scale is a significant challenge (Stathers *et al.*, 2013, also Tefera, 2012). Future impacts on production and storage will affect prices. Food crises in Africa triggered by moderate declines in agricultural production have been exacerbated by "exchange entitlement failures" – food price spikes and asset price collapses (Devereux, 2009). Rising food prices negatively affect many rural people who are net food buyers (see Table 7-1), and the poorest of the poor in rural areas - female-headed households (which tend to be poorer than male-headed households) and those who have limited access to land, modern agricultural inputs, infrastructure and education (Ruel *et al.*, 2009).

The remainder of this section will discuss issues around climate impacts on agricultural livelihoods, other than food crop production: water as an input to agriculture, non-food crops, livestock and fisheries.

9.3.3.1.2. Water

Water supply will be impacted through climate change (Ch 3). In rural areas groundwater extraction and irrigation water availability is crucial for agricultural livelihoods but is typically not included in modelled projections of future crop yields, as discussed by Lobell and Field (2012). At the same time, non-climate trends including population growth and lack of adequate regulatory frameworks will greatly affect demand for water by agriculture and other, competing, uses, as discussed by Macdonald, 2010 for the Southwestern USA, by Juana et al., 2008 for South Africa, and multiple authors for the Middle East (Chenoweth *et al.*, 2011; Rochdane *et al.*, 2012; Iglesias *et al.*, 2010; Hanafi *et al.*, 2012, Sowers *et al.*, 2011; Verner, 2012: 166).

At the continental level in Africa, analysis of existing rainfall and recharge studies suggests that climate change will not lead to widespread catastrophic failure of improved rural groundwater supplies, but it could affect a population of up to 90 million people, as they live in rural areas where annual rainfall is between 200 and 500mm per year, and where decreases in annual rainfall, changes in intensity or seasonal variations may cause problems for groundwater supply (Macdonald *et al*., 2009). At higher resolution groundwater resources are threatened (e.g. in South Africa, Knüppe, 2011), and multiple water crises are expected to result from the increasing demand, further affecting people in rural areas (Nkem *et al*., 2011). Climate change is expected to impact water resources in the Asian region in a major way. Immerzeel *et al*. (2010) in a study of the Indus, Ganges, Brahmaputra, Yangtze and Yellow River basins conclude that different river basins would experience different impacts on water availability and food security due to climate change. They further argue that the Brahmaputra and Indus basins would be more susceptible to changes in water availability affecting the food security of 60 million people. In Southern Europe, declines in rainfall and meltwater from glacial ice and snow would increase the costs of production and living (Falloon and Betts, 2010). Drought could threaten biodiversity and traditional ecosystems particularly in Southern Europe with problems exacerbated by declining water quality. Decline in economic activity may increase rural depopulation and harm the development of rural communities in Southern Europe (Westhoek *et al*., 2006).

9.3.3.1.3. Non-food crops and high-value food crops

Non-food crops and high-value food crops, such as cotton, wine grapes, beverage crops and other cash crops, which represent an important source of livelihood in many rural areas, have received less attention than staple food crops when assessing the impacts of climate change. Literature on biofuels such as jatropha focuses on the impacts of biofuels on climate change rather than on the effects of climate on yields and other relevant variables in these agricultural systems. Where crops have dual use as food and biofuel (for example oilseeds, sugarcane, sugar beet, maize and wheat) impacts can be inferred from studies that focus on their use for food.

The findings of Easterling *et al.*, (2007), that cotton yields would decrease as changes in temperature and precipitation overcome potential benefits of increasing carbon dioxide have been corroborated in other findings, such as those of Haim *et al.* (2008: 433) that cotton cultivation in Israel will decline by 52% and 38% by 2070-2100 under the A2 and B2 scenarios, and that the net revenue will also decrease by 240% and 173% in both scenarios. Few systematic assessments have been done on other fibre crops such as jute, kenaf, and flax.

Climate change impacts on wine grapes have been extensively studied and documented. Climate impacts such as increasing number of hot days and decreasing frost risk may benefit some varieties. Lobell *et al*. (2006) assess the impacts of climate change on yields of six perennial crops in California by 2099, and report that the production of wine grapes will experience relatively small changes compared to other commodities during the concerned period. The uncertainty analysis shows the yield variations are limited within 10% although Gatto *et al*. (2009) argue that the revenue of the industry in Napa, California could decline by 2034. Jones *et al*. (2005) indicate that future climate change will exceed climatic thresholds affecting ripening for existing varieties grown at the margins of their climatic limits. Warmer conditions could also lead to more poleward locations becoming more conducive to grape growing and wine production.

Lobell and Field (2012) model impacts on 20 perennial crops in California under the A2 and B1 scenarios; of the four crops with the most reliable models cherry yields are projected to decline by nearly 20%, strawberries and table grapes to experience smaller declines, and almonds a slight positive trend. These projections do not incorporate adaptation options, nor possible decline in irrigation water supply, which would limit production. Yields of several cash crops in the Middle East such as olives, apples and pistachios may decline if winter temperatures are too high (Verner, 2012).

The case of tropical beverage crops, in particular coffee, is discussed in Box 9-1, and projected changes in area suitable for all three tropical beverage crops are set out in Table 9-5.

____ START BOX 9-1 HERE ____

Box 9-1. Impacts of Climate Change on Tropical Beverage Crops

The major traded beverage crops coffee, tea and cocoa support the livelihoods of several million small-scale producers in over 60 countries of the tropics of Africa, Asia and Latin America. Coffee production has long been recognized as sensitive to climate variability with global production and prices sensitive to occasional frosts in Brazil – the world's largest producer (Varangis *et al.*, 2003). Likewise the livelihoods of millions of small producers are dependent both on stability of production and stability in world prices. During the last crash in coffee prices from 2000-2003 poverty levels in the coffee growing regions of Nicaragua increased, while they fell in the rest of the country (World Bank, 2003); subsequently during the drought associated with El Nino in 2005 coffee productivity fell to between a third and half of normal similarly leading to severely reduced income for small producers (Haggar, 2009).

Gay *et al.* (2006), analysing the effects of recent climate change on coffee producing areas in Veracruz, Mexico, have developed econometric models of the relationship between coffee productivity and fluctuations in temperature and precipitation, which gave an R-squared of 0.69 against historical data. Extrapolating the historical tendencies in temperature and precipitation to 2020 and applying their econometric model they predict that coffee production is *likely* to decline by 34%, and this decline in production takes producers from making net profits of on average around US$200 per acre, to less than $20 per acre. This has led to a series of studies projecting the effects of climate change on the distribution of Arabica coffee growing areas of the coming decades summarized below and in Table 9-5.

For Brazil, Assad *et al.* (2004) and Pinto *et al.* (2007) have mapped the changes in area suitable for coffee production in the four main coffee producing states. A 3^{o}C increase in temperature and 15% increase in rainfall (taken from the general prediction of climate change for Southern Brazil in the IPCC Third Assessment Report of 2001) would lead to major changes in the distribution of coffee producing zones. In the main coffee producing states of Minas Gerais and Sao Paulo the potential area for production would decline from 70-75% of the states to 20-25%, production in Gioas would be eliminated, but the area would only be reduced by 10% in Parana. New areas suitable for production in Santa Catarina and Rio Grande do Sul will only partially compensate the loss of area in other states (Pinto and Assad, 2008). The economic impacts of a rise in temperature of 3^{o}C would cause a 60% decline in coffee production in the state of Sao Paulo equal to nearly US$300 million income (Pinto *et al.*, 2007).

Models developed by CIAT predict the distribution of coffee under the A2a climate scenario using a statistical downscaling of the climate change data from 20 different GCM models used in the IPCC Fourth Assessment. They use WorldClim data to characterize the current distribution of coffee using 19 climatic variables and then use the climate data downscaled to 1, 5 and 10 km resolution to map where those conditions may occur in the future (2020 or 2050). This method has been applied to coffee distribution in Kenya (CIAT 2010), Central America and Mexico (Laderach *et al.*, 2010, Glenn *et al* 2013), tea production in Kenya (CIAT, 2011a) and Uganda (CIAT, 2011b), and cocoa production in Ghana and Ivory Coast (CIAT, 2011c) (Table 9-5). The suitability for coffee crops in Costa Rica, Nicaragua and El Salvador will be reduced by 40% (Glenn *et al.*, 2013) while the loss of climatic niches in Colombia will force the migration of coffee crops towards higher altitudes by mid-century (Ramirez-Villegas *et al.*, 2012). In the same way, increases in temperature will affect tea production, in particular at low altitudes (Wijeratne, et al., 2007). Only one similar study has been done for Robusta coffee (Simonett, 2002), in Uganda, which shows similarly drastic changes in both distribution and total area suitable for coffee production.

Effects are also expected on the incidence of pests and diseases in these crops. Increased generations under climate change for the coffee nematode have been predicted for Brazil (Ghini *et al*., 2008). Jaramillo *et al.* (2011) conclude that Coffee Berry Borer (*Hypothenemus hampei*) distribution in East Africa has expanded due to rising temperatures, and predicts (based on A2A and B2B scenarios of HADCM3 model) that it will spread to affect the main coffee producing areas of Ethiopia, Kenya, Uganda, Rwanda and Burundi by 2050.

At a minimum climate change will cause considerable changes in the distribution of these crops disrupting the livelihoods of millions of small-holder producers. In many cases the area suitable for production would decrease considerably with increases of temperature of only 2-2.5ºC. Although some local areas may experience improved conditions for coffee production, e.g. high altitude areas of Guatemala, the overall predictions are for a reduction in area suitable for coffee production by 2050 in all countries studied (Laderach *et al.* 2010).

____ END BOX 9-1 HERE ____

[INSERT TABLE 9-5 HERE
Table 9-5: Projected changes in areas suitable for production of tropical beverage crops by 2050.]

9.3.3.1.4. Livestock

The impacts of climate change on livestock – which form a part of a variety of farming systems (Devendra *et al.* 2005) – are seen by Thornton *et al.* (2009), as a neglected research area complicated by other drivers of change, rapid change in livestock systems, spatial heterogeneity and social inequality between livestock-keepers. They review various pathways of impact on livestock. Impacts through drought will be significant, as will heat stress, particularly of *Bos taurus* cattle. Impacts through animal health and disease will be even harder to predict than other categories of impact (Thornton *et al.*, 2009). Franco *et al.* (2011) reveal significant declines in forage for ranching in California under SRES scenarios B1 and A2.

Pastoralists, who are dependent on livestock grazed in arid, semi-arid or mountainous areas, represent a specific case, display very specific combinations of adaptive capacity, especially through mobility, and vulnerability, as discussed in 9.3.5 below. Ericksen *et al.* (2012), with particular reference to East Africa, discuss possibilities of loss of rangeland productivity, changes in rangeland composition towards browse species, and changes in herd dynamics through more frequent droughts as possible impacts. In the Middle East, rangelands will be under substantial climate stress which may reduce their carrying capacity, in light of the growing demand for meat products and the region's growing livestock population (Verner, 2012: 166). Little *et al.* (2001) discuss impacts of floods, directly and through disease, on pastoral herds. Similarly in the Ferlo Region in Northern Senegal, modest reduction in rainfall of 15% in combination with a 20% increase in rainfall variability could have considerable effects on livestock stocking density and profits, reducing the optimal stocking density by 30%, based on six GCMs (Hein *et al.* 2009).

As extensive livestock production is associated with semi-arid areas marginal for cropping, some authors project shifts toward livestock production under climate change. Modeled data from across Africa on the net income per unit of land from crops and different livestock species, show that farmers are more likely to keep livestock, compared to crop cultivation, as temperatures increase and as precipitation decreases. Within livestock production, beef production will decline and sheep and goat production increase (Seo and Mendelsohn, 2007a). Large-scale commercial beef cattle farmers are most vulnerable to climate change, particularly since they are less likely to have diversified (Seo and Mendelsohn, 2007b). Kabubo-Mariara (2009) shows for non-pastoral areas of Kenya the non-linear relationship of livestock production to climate change, whereby increased mean precipitation of 1% could reduce revenues from livestock by 6%. Jones and Thornton (2009) identify major transition zones across Africa where increased probability of drought up to 2050 will create conditions for shifts from cropping to livestock.

9.3.3.1.5. Fisheries

Impacts of climate change on aquatic ecosystems will have adverse consequences for the world's 36 million fisherfolk, through multiple pathways including changes in fish stock distribution and abundance, and destruction of fishing gear and infrastructure in storms and severe weather events (Badjeck *et al*., 2010; 5.4.3.3, 6.4.1.1, 7.4.2, 30.6.2.1). An indicator approach (assessing climate change impacts together with the high share of fisheries as a source of income) showed that economies with the highest vulnerability of capture fisheries to climate change were in Central and Western Africa (e.g. Malawi, Guinea, Senegal, and Uganda), Peru and Colombia in north-western South America, and four tropical Asian countries (Bangladesh, Cambodia, Pakistan, and Yemen) (Allison *et al*., 2009). In China, Japan and South Korea changes in climate and social systems could have a negative impact on fisheries adversely affecting livelihoods and food security of the region (Kim, 2010).

9.3.3.2. Infrastructure

Assessments of the impacts of climate change on infrastructure take a general or urban perspective and do not focus on rural areas, though rural impacts can be inferred. River flooding and sea level rise will produce temporary loss of land and land activities, and damage to transportation infrastructure particularly on coastal areas (Kirshen *et al*., 2008), with specific evidence from North America (Hess *et al.*, 2008). Flooding events may cause sediment transport and damage roads and bridges (Nearing *et al.*, 2004) as well as to affect reservoir storing capacity. Importantly, in rural areas usually there are few alternatives once a road is blocked and that may increase vulnerability of rural areas when facing extreme hydroclimatological events that impact transportation infrastructure (NRC, 2008). Climate change will affect the operation of existing water infrastructures (Kundzewicz *et al.*, 2008). Some documented impacts on dams, reservoirs and irrigation infrastructure are: reduction of sediment load due to reductions in flows (associated with lower precipitation), positively affecting infrastructure operation (Wang et al., 2007); impacts of climate variability and change on storage capacity that creates further vulnerability (Lane *et al.*, 1999); and failures in the reliability of water allocation systems (based on water use rights) due to reductions of streamflows under future climate scenarios (Meza *et al.*, 2012).

In Arctic Canada and Alaska, infrastructure built for very cold weather will deteriorate as the air and ground warm. Larsen *et al.* (2008) estimate, using the AOGCM model inter-comparison project and an A1B scenario, increases in public infrastructure costs of 10-20 percent through 2030 and 10% through 2080 for Alaska, amounting to several billion dollars, much of it to be spent outside of urban centers. Lemmen *et al.* (2008) reports that foundation fixes alone in the largely rural Northwest Territories could cost up to CAN$420 million, and that nearly all of Northern Canada's extensive winter road network, which supplies rural communities and supports extractive industries which bring billions of dollars to the Canadian economy annually, is at risk (Furgal and Prowse 2008) from a 2-4℃ change in ground surface temperatures, which would imply a cost of replacement with all-weather roadways of CAN$85,000/km, over several decades.

9.3.3.3. Spatial and Regional Interconnections

In both developing and developed countries, rural areas have been increasingly integrated with the rest of world. The main channels through which this rapid integration process takes place are migration (permanent and cyclical), commuting, transfer of public and private remittances, regional and international trade, inflow of investment and diffusion of knowledge through new information and communication technologies (IFAD, 2010), as well as the spatial intermingling of rural and urban economic activities (see Box CC-UR).

9.3.3.3.1. Migration

It is difficult to establish a causal relationship between environmental degradation and migration (see Section 12.4.1). Many authors argue that migration will increase during times of environmental stress (e.g. Afifi, 2011; Gray and Mueller, 2012; Kniveton *et al*., 2011; Brown and Crawford, 2008), and will lead to an increase in abandonment of settlements (McLeman, 2011). Climate variability has been associated with rural-urban migration (Mertz *et al.*, 2011; Parnell and Walawege, 2011). Another body of literature argues that migration rates are no higher under conditions of environmental or climate stress (Black *et al.*, 2011a and b; van der Geest, 2011; van der Geest and de Jeu, 2008; Tacoli, 2009; McLeman and Hunter, 2010; Gemenne, 2011; Foresight, 2011; Cohen, 2004; Brown, 2008). For Tacoli (2009) the current alarmist predictions of massive flows of so-called “environmental refugees” or “environmental migrants”, are not supported by past experiences of responses to droughts and extreme weather events and predictions for future migration flows are tentative at best. Analogies with past migration experiences are used frequently in such studies (McLeman and Hunter 2010). For example, in Ghana the causality of migration was established to be relatively clear in the case of sudden-onset environmental perturbations such as floods, whereas in case of slow-onset environmental deterioration, there was usually a set of overlapping causes - political and socioeconomic factors – which come into play (van der Geest, 2011). Similarly, a recent survey by Mertz *et al*. (2010) has argued that climate factors played a limited role in past adaptation options of Sahelian farmers. Given the multiple drivers of migration (Black *et al.*, 2011a and b) and the complex interactions which mediate migratory decision-making by individual or households (Raleigh, 2008; McLeman and Smit, 2006; Kniveton *et al.*, 2011; Black *et al.*, 2011a and b), the projection of the effects of climate change on intra-rural and rural-to-urban migration remains a major challenge.

9.3.3.3.2. Trade

Agricultural exports accounted for around one sixth of world agricultural production in 2012, while this proportion was higher for some commodities such as oilseeds, sugar and fish (OECD-FAO, 2013). Global agricultural exports grew at an average annual rate of 9% in 2000-2005 and 11% in 2005-2011 (WTO, 2013: 63-72). Apart from a major price hike and high price volatility since 2007-2008, several structural and cyclical factors – such as droughts in major producers, expansion of area under biofuel crop production, financial speculation, export restrictions – have led to volatility and unpredictability in the trading environment (Chapter 7 this report, FAO, 2008; Cooke and Robles, 2009; Abbott 2008, Timmer, 2010; Schmidhuber and Matuschke, 2010; Karapinar and Haberli, 2010; Wright, B.D. 2011; Headey , 2011; Anderson and Nelgen, 2012; Nazlioglu, 2013). In the absence of extensive literature and reliable data on within-country trade, this section focuses on international trade in the specific context of climate change.

There is *medium agreement* and *limited evidence* that climate change will affect trade patterns and it will increase international trade volumes in both physical and value terms by altering the comparative advantage of countries and regions, and given its potential impacts on agricultural prices (Nelson et al., 2009b; 2010; 2013b; Tamiotti et al., 2009). For example, simulation based results from variants of the NCAR and CSIRO climate models (A2 scenario) suggest that climate change might lead to increases in export volumes (of rice, wheat, maize, millet, sorghum, and other grains) from developed to developing countries by 0.9 million mt to 39.9 million mt by 2050. Higher export volumes are expected if future scenarios consider CO_2 fertilization effects as they produce lower world prices than scenarios without CO_2 effects. Many regions including South Asia, East Asia and Pacific, Middle East, North Africa and Sub-Saharan Africa are projected to increase their imports substantially over this period. (Nelson *et al*., 2009b; 2010).

The recent literature highlights the potential role of trade in adaptation to climate impacts on global crop yields, while cautioning policy makers about the possible negative consequences of increased trade (Verburg *et al*., 2009; Lotze-Campen *et al*. 2010; Schmitz *et al.*, 2012; Huang *et al.*, 2011). Importing food might help countries adjust to climate-change induced domestic productivity shocks and mitigate related welfare losses (Tamiotti *et al.*, 2009; Reimer and Li, 2009). Countries might also capitalize on new export opportunities arising from higher achievable yields, for example in Argentina (Asseng *et al.*, 2013) or increasing heterogeneity of climate impacts on yields in neighbouring countries, for example in Tanzania (Ahmed *et al.*, 2012). Increased trade would lower the cost of food and thus help alleviate food insecurity, however if it is driven by an expansion of agricultural areas (especially to marginal land and to forests), it would also lead to negative environmental consequences in the form of loss of biodiversity, deforestation and additional carbon emissions (Verburg *et al.*, 2009; Schmitz *et al.*, 2012; Lotze-Campen *et al.*, 2010).

If climate change affects crop yields negatively, and results in increased frequency of extreme events (Chapter 3, IPCC, 2012), especially in low-income developing countries, the consequent short-term food deficits might need to be supplied, fully or partly, through food aid (Alderman, 2010). Hence food aid agencies, such as the United Nations World Food Programme, might face additional operational challenges (Barrett and Maxwell, 2006; Harvey *et al.*, 2010). Local or regional procurement of food aid, targeted distribution of food and safety net programs through direct income transfers could be part of an overall strategy to address climate-induced shocks to food security (see also Chapter 7) (Alderman, 2010; Harvey *et al.*, 2010).

The potential impacts of climate change on agricultural trade and the role that trade could play in adaptation will inevitably depend on countries' trade policies. There is *medium agreement* and *medium evidence* that deepening agricultural markets through trade reform, improved market access, avoiding export controls and developing institutional mechanisms to improve the predictability and the reliability of the world trading system as well as investing in additional supply capacity of small-scale farms in developing countries could help reduce market volatility and offset supply shortages which might be caused by climate change (Reimer and Li, 2009; Tanaka and Hosoe, 2011; Karapinar, 2011, 2012; Ahmed *et al.*, 2012, UNEP, 2009; Tamiotti et al., 2009).

9.3.3.3.3. Investment

Climate change may also affect investment patterns in rural areas. On the one hand, countries, regions and sectors that are expected to be affected adversely by climate change may have difficulty attracting investment. On the other hand, ecological zones that will become favourable due to climate change are expected to see increasing inflow of investment. The recent price hikes in agricultural commodities have led to new initiatives of foreign direct investment (FDI) in large-scale crop production (Anseeuw *et al.*, 2012; World Bank, 2010b), with capital-endowed countries with high food imports investing in large production projects in low-income countries endowed with low-cost labour forces, land and water resources. Climate change will lead to similar investment patterns. However, there is a risk that these new investments might not be integrated into local structures and that local populations will become increasingly vulnerable as they lose access to vital assets such as land and water (Anseeuw *et al.*, 2012).

9.3.3.3.4. Knowledge

Rural areas are increasingly exposed to diffusion of knowledge through migration, trade and investment flows, technology transfers, and improved communication and transport facilities (IFAD, 2010), although differentials on knowledge access and diffusion (e.g. access to high speed internet) between rural and urban areas remain, even in high-income countries. Future impacts of climate change on these channels of integration will affect the pace and intensity of knowledge transfers. If trade, migration and investment flows will be intensified as a result of climate change, this will have a positive impact on knowledge transfer both from and to rural areas.

Traditional Knowledge (TK) developed to adapt to past climate variability and change, can both be affected by climate change and used and transformed in adaptation (Nyong, *et al.*, 2007). Ettenger (2012) discusses how seasonal hunting camps among the Cree of Northern Quebec that were the occasion for intergenerational knowledge transfer have been disrupted by changing bird migrations, while new technologies such as the internet, GPS and satellite phones have been integrated into livelihood strategies. Climate-change induced migration can threaten TK transfer (Valdivia *et al.*, 2010; Gilles *et al.*, 2013). Disaster management by central government may undermine decentralization efforts, disfavouring TK transfer (Dekens, 2008).

9.3.3.4. Second-Order Impacts of Climate Policy

Policy responses for mitigation and adaptation affect rural people, their livelihoods and environments. Working towards increasing energy supply from renewable resources may result in landscape changes (Dockerty *et al.*, 2006; Prados 2010); increasing employment opportunities (del Río and Burguillo, 2008); or increasing conflicts for scarce resources, such as water (Gold and Bass, 2010; Blair *et al.*, 2011; McIntyre and Duane, 2011; Phadke, 2011).

Planning applications for wind energy schemes in the UK have been subject to local opposition when they are perceived as having negative impacts on rural landscape qualities (van der Horst, 2007, Jones and Eiser, 2010, Wolsink 2007). Governance of energy distribution is thus an important issue (Vermeylen, 2010; Devine-Wright, 2011). Steps towards energy self-sufficiency can reinforce rural autonomy in isolated rural communities, including indigenous groups (Love and Garwood, 2011).

Social responses to such changes are expected (Molnar, 2010). The promotion of biofuel crops has been an extremely controversial issue during the last decade, as they have potential socioeconomic impacts related to their asserted ability to act as stimulus for rural economies, promote changes in land ownership and affect food security (German *et al.*, 2011). Delucchi (2010) concludes that biofuels produced from intensive agriculture will aggravate stresses on water supplies, water quality and land use, and impact rural areas (through land-use change) and agriculture (see also Box CC-WE). Concerns about the impact of biofuel production on food security relates to increases in food prices, land concentration (and landgrabs), and competition for water (Eide, 2008; Müller *et al*., 2008, (German *et al.*, 2011)). Gurgel *et al*. (2007), who modeled potential production and implications of a global biofuels industry by the end of the century under a reference scenario and a high-mitigation scenario, recognized the need for a high land conversion rate to achieve moderate objectives. Delucchi (2010) suggests developing biofuels programs with low inputs of fossil fuels and chemicals, that do not require irrigation, and on land with little or no economic or ecological opportunity cost (Plevin *et al.*, 2010). This implies analysing each case in its context, including production for both local and global markets, and factoring in concerns for social, cultural, and economic costs of biofuel production (i.e. impact of biofuel production on indigenous livelihoods and culture).

International mechanisms for emission reduction through forest and land management have been developed under the global initiative REDD, now REDD+. These mechanisms are designed to use market tools (e.g. payment for ecosystem services) to reduce emissions, while providing social co-benefits following the principles of effectiveness, efficiency and equity (Hoang *et al.*, 2013; Hall, 2012; Brown *et al.*, 2008b). However, there have been many criticisms that the rural poor are excluded from participation (Hall, 2012; van Noordwijk *et al.*, 2010; Sikor *et al.*, 2010; Campbell, 2009); and that community participation can undermine a general decentralization of forest management (Phelps *et al.*, 2010).

9.3.4. Valuation of Climate Impacts

This section assesses studies that have adopted various economic methods for valuation of impacts of climate change on rural areas. This is a difficult task and should reflect the significance of the ecological service categories for different stakeholders, including women (Kennet 2009) and minority groups, and ideally the valuations of unit changes in the levels of those services across management options. Valuations can be made at individual or communal levels (Farber *et al.*, 2006) and often involve complexities with regard to the use of social discount rates for comparing intergenerational effects over varying time horizons (Dasgupta, 2011). Different understandings of value, and different philosophical approaches to address it may exist (Spangenberg and Settele, 2010; Kosoy and Corbera, 2010; Weisbach and Sunstein, 2008), which makes it more difficult to agree on valuation methodologies. The impacts of climate change are expected to be unequally distributed across the globe, with developing countries at a disadvantage, given their geographical position, low adaptive capacities (Stern, 2007; World Bank, 2010a) and the significance of agriculture and natural resources to the economies and people (World Bank, 2010a; Collier *et al.*, 2008). Both direct and indirect impacts have been projected, such as lower agricultural productivity, increase in prices for major crops, and rise in poverty (Hertel *et al.*, 2010), which have implications for rural areas and rural communities. This section discusses the valuation of impacts with reference to agriculture, fisheries and livestock, water resources, mining, extreme weather events and sea level rise, recreation, tourism and forestry. There are various channels through which changes in economic values may occur in rural areas, such as through changes in profitability, crop and land values and loss of livelihoods of specific communities through changes in fisheries and tourism values. Losses and gains in health status and nutrition, and wider economy-wide impacts such as changes in job availability and urbanization also impact economic values that accrue to rural communities, the opportunities and the constraints that rural communities experience and changes that rural landscapes undergo. Since rural areas are included, but not exclusively dealt with in calculations of economy wide GDP losses due to climate change impacts, these are not dealt with separately in this chapter. Studies on the health impacts of climate change for the most part do not distinguish between rural and urban areas, although there are specific vulnerabilities that communities in rural areas face arising from a variety of factors such as remoteness, lack of access to services and dependence on certain occupations such as farming which are dealt with in chapter 11, section 11.3. The impact on availability of fresh water resources is another major area of concern for the developing regions in particular. Climate change can adversely impact poverty through multiple channels (Section 10.9 and Chapter 13).

Viewing impacts regionally, despite the ongoing debates around the uncertainty and limitations of valuation studies, scholars generally agree that some African countries could experience relatively high losses compared to countries in other regions (World Bank, 2010a; Watkiss *et al*., 2010; Collier *et al.*, 2008). These conclusions emerge across a range of climate scenarios and models used by researchers. For instance, Watkiss *et al.* (2010) use the FUND model for a business-as-usual scenario and a scenario of mitigation to 450ppm and 2℃ global mean temperature increase as generated by using the PAGE2002 model, while the World Bank uses a range of country specific models for calculating costs. Global costs including adaptation costs are calculated for an approximately 2℃ warmer world by 2050 for Mozambique, Ethiopia, Ghana, Bolivia, Vietnam, Samoa and Bangladesh. Overall negative consequences are seen for Africa and Asia, due to changes in rainfall patterns and increases in temperature (Müller *et al*., 2011). Though climate change and climate variability would impact a range of sectors, water and agriculture are expected to be the two most sensitive to climatic changes in Asia (Cruz *et al*., 2007; Chapter 3) and for droughts in particular for Australia (Nelson *et al.*, 2007; Meinke and Stone 2005). In Latin American and Caribbean countries, higher temperatures and changes in precipitation patterns associated with climate change affect the process of land degradation, compromising extensive agricultural areas. Research on climate change impacts in rural North America has largely focused on the effects on agricultural production and on indigenous populations, many of whom rely directly on natural resources. Developed countries in Europe will be less affected than the developing world (Tol *et al.*, 2004), with most of the climate sensitive sectors located in rural areas.

Valuation and costing of climate impacts draw upon both monetary and non-monetary metrics. Most studies use models that estimate aggregated costs or benefits from impacts to entire economies, or to a few sectors, expressed in relation to a country's gross domestic product (GDP) (Stage, 2010; Watkiss, 2011). Values which are aggregated across sectors generalize across multiple contexts and could mask particular circumstances that could be significant to specific locations, while expressing outcomes in aggregated GDP terms. This is a matter of concern for economies in Africa and Asia, where subsistence production continues to play a key role in rural livelihoods. Valuation of non marketed ecosystem services poses further methodological and empirical concerns (Dasgupta, 2008; Dasgupta, 2009; Watkiss, 2011; Stage, 2010). Würtenberger *et al.* (2006) developed a methodology to estimate environmental and socio-economic impacts of agricultural trade regarding virtual land use, and Adger *et al.* (2011) use qualitative methodologies to consider non-market metrics of risk, focusing on place and identity based principles of justice, which recognizes individual and community identity in decision-making.

Integrated assessment models and cost-benefit tools have been criticized: for being inadequate to assess intergenerational events, or processes with high levels of uncertainty and irreversibility; for not considering equity concerns and power structures; for assigning monetary values on the basis of incomplete information or assuming speculative judgements regarding the monetary value of, e.g. natural resources (Ackerman et al. 2009; Kuik *et al.*, 2008); and for not recognising incommensurability (Aldred 2012). In recent years, various perspectives for valuing the economic impacts of climate change have come into focus including the feminist (Nelson 2008; Power 2009), deliberative (Zografos and Howarth 2010) or behavioural economics-based (Brekke and Johansson-Stenman 2008; Gowdy 2008), and the integration of economics with moral and political philosophy (Dietz *et al.*, 2008). Some common characteristics of these new approaches include interdisciplinarity, acknowledging the diversity of views and maintaining complexity in models. Research in this area although relatively recent, shows promise. Illustrative regional and sub-regional estimates for the value of agricultural and non-agricultural impacts of climate change, as available in the literature, are presented here.

9.3.4.1. Agriculture

Changes in agricultural production will have corresponding impacts on incomes and wellbeing of rural peoples. The largest known economic impact of climate change is upon agriculture because of the size and sensitivity of the sector, particularly in the developing world and to a lesser extent in parts of the developed world. A large number of studies to evaluate the impacts on the agricultural sector and its ramifications for communities have been conducted at various scales, ranging from micro level farm models to large scale regional and country level climate cum socio-economic scenario modeling exercises. Some of these also report values for associated economic losses.

Since models are simplifications of complex real world phenomena, different models tend to highlight different aspects of impacts and their consequent economic values. For instance, in estimating economic losses the Ricardian method has been used widely to study climate change impacts (with adaptation inbuilt) in agriculture. However, often such analysis does not incorporate features like technological progress, relative price changes, agricultural policy and other dynamic characteristics. Similarly on the bio-physical impacts side, changes in the El Niño/Southern Oscillation (ENSO) statistics may also have serious economic implications for the agricultural sector in certain countries such as in Latin America and Australia (Kokic *et al.*, 2007). However, ENSO responses differ strongly across climate models, and at the current stage of understanding do not allow conclusions to be drawn on how global warming will affect the Tropical Pacific climate system (Latif and Keenlyside, 2009). A sample of the available studies is provided in Table 9-5.

[INSERT TABLE 9-6 HERE
Table 9-6: Illustrative sample of studies on economic value and changes in value from climate change for the agriculture sector.]

9.3.4.2. Other Rural Sectors: Water, Fisheries, Livestock, Mining

The changes in valuation of water resources due to climate change arise from expected impacts on populations dependent on these water resources and these will be felt in several parts of the world (Sections 3.4.9, 3.5 and 3.8, Chapter 3, AR5). Monetary estimates of losses due to impacts on water resources are not generalizable. Among alternative approaches to value water resources, use of the water footprint tool (Hoekstra and Mekonnen, 2012) which measures human utilization of water by a nation and the concept of virtual water has been suggested for informing policy-makers in water-scarce countries, such as Egypt.

Analysis of intergenerational valuation has provided some interesting results in valuation of marine fisheries (Ainsworth and Sumaila 2005). For fisheries in rural coastal areas, some of the challenges faced include the valuation of environmental externalities such as breeding habitats, or mangroves, that might be lost due to climate change or other forces (Hall 2011). It has also been argued that the true worth of livelihoods dependent on fisheries in developing countries, where these constitute part of a diversified livelihood or subsistence strategy, requires a different set of metrics from those used in the developed world (Mills *et al.*, 2011). Climate change can also have significant impacts on livestock production (Section 9.3.3.1).

A relatively less researched area which may impact the livelihoods of rural communities is mining (Section 26.11.1.2). Economic viability of mining enterprises as well as communities dependent on them is vulnerable to climate change. Pearce *et al.* (2011) highlight concerns for Canada, where mining is a rural activity with few other available economic activities while Damigos (2012) finds economic losses for mining in the Mediterranean region and Greece in particular. Current and past infrastructure for mines was built under a no-climate change presumption and economic and ecological vulnerabilities as a result are substantial, and industry actors are unprepared to deal with this. There is little research in impacts on mining sectors in the US and Mexico. Changes in the energy and water sector present a complex mix of risks and opportunities for primary extraction and processing industries. Site management, transport of supplies and resources to and from mines, exploration activities and their associated costs are would determine the extent of loss, along with the importance of the sector in the local economy (Backus et al 2012).

9.3.4.3. Extreme Weather Events, Sea-Level Rise

The climate change related extreme events that may cause changes in economic values in rural areas include heat waves and droughts, storms, inundation and flooding (Stern 2007; Handmer *et al.*, 2012; Section 3.4.9, Chapter 3, AR5). A detailed discussion on the costs of climate extremes and disasters is set out by Handmer *et al.*, 2012. Costs can be of two kinds: losses or damage costs and costs of adaptation. While some of the costs lend themselves to monetary valuation (such as infrastructure costs) others cannot be easily estimated such as the value of lives lost and the value of eco system services lost (for discussion on the methodologies for valuing costs refer to Handmer *et al.*, 2012: Section 4.5.3).

Damage costs of floods and droughts (Section 10.3.1, chapter 10, AR5) and from sea-level rise in Europe (Swiss Re, 2009) demonstrate the cost implications for rural communities in the developed regions of the world. Studies mapping the adverse impacts in UK and Europe show a range of sectors that are impacted in rural areas particularly due to drought in Europe and flooding in UK, the worst effect being on summer crops in Mediterranean regions (Giannakopoulos *et al.*, 2009). Longer term adaptation could reduce the severity of losses but could include displacement of agricultural and forestry production from Southern Europe to the North. The UK Government's Foresight Programme (2004) estimates that global warming of 3 to 4 ºC could increase flood damage costs from 0.1% up to 0.4% of GDP. Much of the investment in flood defences and coastal protection would be in rural coastal areas.

Several studies from the developing countries provide evidence on the substantial costs rural communities in particular face in these countries. Salinity and salt water intrusion have implications for rural livelihoods as they impact both fisheries and agriculture (Section 5.5.3; Chapter 5). Sea-level rise also leads to wetland loss and coastal erosion. A few illustrations of the range of impacts of relevance for the rural economy are provided here. Loss of agricultural land and changes in the saline-freshwater interface is estimated to impact the economies of Africa adversely (SEI, 2009, S. Dasgupta *et al.*, 2009). Ahmed *et al.* (2009) suggest that climate volatility from increase in extreme events, increases poverty in developing countries, particularly Bangladesh, Mexico, Indonesia and countries in Africa. They also find that on simulating the effect of climate extremes on poverty in Mexico using the A2 scenario as generated by a CMIP3 multi-model dataset, rural poverty increases by 43-52% following a single climate shock due to climate extremes. Studying extreme events, Boyd and Ibarrarán (2009) use a CGE model to simulate the effects of persistent droughts on the Mexican economy and find declines in production of 10-20% across a variety of agricultural sectors between 2005 and 2026. Scenario-based stakeholder engagement has been tested for coastal management planning under climate change threats (Tompkins *et al*., 2008) and to determine impacts and responses of extreme-events in coastal areas (Toth and Hizsnyik, 2008).

9.3.4.4. Recreation and Tourism; Forestry

Studies assessing the changes in economic value of recreation and tourism due to climate change are relatively fewer in number (coastal tourism is discussed in Section 5.4.4.2; Chapter 5). Both sensitivity to climate variability and climate change have been considered in the literature. While some studies locate an increase in values for certain regions others estimate shifts in tourism and losses (Bigano *et al.*, 2007; Hamilton *et al*., 2005; Beniston, 2010), methodological challenges and contrasting findings for the short and long run pose problems in generalizing findings (economic values for recreation and tourism are discussed in Section 10.6). Change in economic values will impact rural communities (Lal *et al.*, 2011), with the linkages between biodiversity, tourism and rural livelihoods and rural landscapes being an established one both for developing and developed countries (Nyaupane and Poulde 2011, Scott *et al*., 2007, Hein *et al*., 2009, Wolfsegger et al 2008, Collins 2008).

It has been argued that climate change would have adverse impacts on various ecosystems, including forests and biodiversity in many regions of the world (Stern, 2007; Eliasch, 2008; Ogawa-Onishi *et al.*, 2010; ADB, 2009; Tran *et al.*, 2010; Preston *et al*., 2006) and these will have implications for rural livelihoods and economies (Chopra and Dasgupta, 2008; Safranyik and Wilson, 2006; Kurz *et al*., 2008; Walton, 2010, Fleischer and Sternberg 2006). However, monetary valuation of changes in non-marketed ecosystem services due to climate change continues to pose a challenge to researchers. To overcome some of the limitations, multicriteria analysis has been used for forest management (Fürstenau *et al*., 2007).

9.3.5. Key Vulnerabilities and Risks

9.3.5.1. Drivers of Vulnerability and Risk

Discussions on climate vulnerability in rural areas must recognize competing conceptualizations and terminologies of vulnerability, particularly those of "starting point" and "end-point" vulnerability (O'Brien *et al.*, 2007). The focus here is on starting point vulnerability, or contextual vulnerability (see Glossary and Chapter 19) while we consider risk to be the probability of adverse impact resulting from exposure and vulnerability (see Chapter 19). These distinctions are important, because, they can result in contradictory findings regarding vulnerability in rural areas, and the policy prescriptions derived therein are also different.

There is *low agreement,* but *medium evidence* on the direction in which some key factors may affect vulnerability or resilience in rural areas, including rain-fed as opposed to irrigated agriculture, small-scale and family-managed farms, integration into world markets, and diversification. Brouwer *et al.* (2007), contrary to expectations, found that vulnerability to flooding in Bangladesh in terms of damage suffered was lower for households that fully depended on natural resources than those who did not. Osbahr *et al.* (2008) found that diversification in rural areas does not always reduce vulnerability and can increase inequity within communities if it is not accompanied by reciprocity. There is *high agreement, robust evidence* on the importance for resilience of drivers such as access to land and natural resources, flexible local institutions and knowledge and information, and the association of gender and vulnerability (see Box CC-GC, and Chapter 13).

The most commonly used approaches to analyzing causes of vulnerability use the concepts of entitlements or livelihoods in evaluating the multi-scale factors shaping people's assets, as well as their adaptive capacity to hazards and stressors. Although vulnerability is experienced locally, its causes and solutions occur at different social, geographic, and temporal scales, and are seen as context-dependent (Ribot, 2010). Non-climate factors affecting vulnerability in rural areas at both individual and community levels (Eakin and Wehbe, 2009) include the following:

- Physical geography, e.g. desert or semi-desert conditions (Lioubimtseva and Henebry, 2009), remoteness (Horton *et al.*, 2010), level of dependence on climate conditions (Brondizio and Moran 2008; Sietz *et al.*, 2012)
- Economic constraints and poverty (Ahmed *et al.*, 2011; Macdonald *et al.*, 2009; Mertz *et al.*, 2009a; Sietz *et al.*, 2011)
- Gender inequalities (Nelson *et al.*, 2002)
- Social, economic and institutional shocks and trends (e.g. urbanization, industrialization, prevalence of female-headed households, landlessness, short-time policy horizons, low literacy, high share of agriculture in GDP), as well as demographic changes, HIV/AIDS, access and availability of food, density of social networks, memories of past climate variations, knowledge and long-term residence in the region (Macdonald *et al.*, 2009; Mougou *et al.*, 2011; Ruel *et al.*, 2010; Sallu *et al.*, 2010; Simelton *et al.*, 2009; Mertz *et al.*, 2009a; Parks and Roberts, 2006; Gbetibouo *et al.*, 2010b; Ahmed *et al.*, 2011; Cooper *et al.*, 2008; Brondizio and Moran, 2008; Seto 2011).

This section focuses on the following drivers of vulnerability to climate change: water, market orientation and farm scale, institutions and access to resources, gender, migration and access to information and knowledge.

9.3.5.1.1. Access to water

Reducing vulnerability requires a reduction of the multiple non-climate-related pressures on freshwater resources (e.g. water pollution, high water withdrawals) together with improvement of water supply and sanitation in developing countries (Kundzewicz *et al*., 2008). Water supply will be adversely affected by climate change, but vulnerability of populations will also be determined by other elements, such as the role of institutions in facilitating the access to water, or people's demand, which in turn is influenced by local cultural norms (Wutich *et al.*, 2012) and perceptions of vulnerability which may differ between men and women (Larson *et al.*, 2011). Improvements in technologies can reduce the perception of water scarcity and increase water demand without reductions in underlying vulnerability (El-Sadek, 2010; Sowers *et al.*, 2011). Where appropriate water management institutions exist and are effective, their role in improving rural livelihoods has been demonstrated, for example in Tanzania's Great Ruaha basin (Kashaigili *et al.*, 2009).

Past research has tended to agree that rain-fed agriculture is more vulnerable to climate change (Bellon *et al.*, 2011) and that irrigation is needed to decrease that vulnerability (Gbetibouo *et al.*, 2010a). More recent findings suggest that this is context-dependent and irrigation has been found to increase vulnerability in certain cases (Lioubimtseva and Henebry, 2009; Eakin, 2005). Cooper *et al.* (2008) concluded that in rainfed Sub-Saharan Africa the focus should be on improving productivity of rain-fed agriculture instead of irrigation as irrigation schemes are also being threatened by drought, and Ahmed *et al.* (2011) emphasize the role of drought-tolerant crops.

9.3.5.1.2. Market orientation and farm scale

Some authors argue that opening markets to international trade increases vulnerability of small farmers and poor people. However, linkages among international, regional and local markets are not clear, including how global prices affect regional and local prices in the long term (Ulimwengu *et al.*, 2009). Market integration is seen as reducing the capacity of indigenous or smallholder systems for dealing with climate risk in Bolivia (Valdivia *et al.*, 2010), Honduras (McSweeney and Coomes, 2011), Mexico (Eakin, 2005), Mozambique (Eriksen and Silva, 2009; Silva *et al.*, 2010), and in the Sahel (Fraser *et al.*, 2011) by variously accelerating socio-economic stratification and reducing crop diversity. On the other hand distance from large markets is seen as increasing vulnerability of rainfed mixed crop/livestock areas in sub-Saharan Africa (Jones and Thornton 2009) and the Peruvian Altiplano (Sietz *et al.*, 2011). Each case needs to be analysed within its complexity, considering interactions among all the factors that can affect vulnerability (Rivera-Ferre *et al.*, 2013a).

Regarding the scale of farms, some authors suggest that small-scale farming increases the vulnerability of communities in rural areas (Bellon *et al.*, 2011; Gbetibouo *et al.*, 2010b) although their resilience capacity (stemming from factors such as indigenous knowledge, family labour, livelihood diversification) should not be underestimated. Brondizio and Moran (2008) indicate that small farmers are less vulnerable than large, monocrop farmers when climatic variations make an area inappropriate for a particular crop, because they tend to cultivate multiple crops and work with on-farm biodiversity. However, they recognize that small farmers tend to suffer from technological limitations, low access to extension services, and market disadvantages.

9.3.5.1.3. Institutions, access to resources, and governance

Institutions and networks can affect vulnerability to climate change: through distribution of climate risks between social groups; by determining the incentive structures for adaptation responses; and by mediating external interventions (e.g. finances, knowledge and information, skills training) into local contexts (Ribot, 2010; Agrawal and Perrin, 2008). Institutions can decrease vulnerability (Anderson *et al.* 2010) or increase it (Eakin, 2005) Governance structures and communication flows as shown in a Swiss mountain region vulnerable to climate change (Ingold *et al.*, 2010) and the knowledge and perceptions of decision-makers are also important. Romsdahl *et al.*(2013) show that local government decision-makers in the US Great Plains resist seeing climate change as within their responsibilities, which has contributed to low levels of planning for either adaptation or mitigation, and thus to greater vulnerability, but that a reframing of issues around current resource management priorities could allow proactive planning.

Lack of access to assets, of which land is an important one, is accepted to be an important factor increasing vulnerability in rural people (McSweeney and Coomes 2011). The breakdown of traditional land tenure systems increases vulnerability, particularly for those who experience poorer land access as a result (Fraser *et al.*, 2011;

Dougill *et al.*, 2010; Brouwer *et al.*, 2007). Those that benefit, for example wealthier farmers who increased their landholding after privatization in Botswana, remain less vulnerable (Dougill *et al.* 2010).

9.3.5.1.4. Migration

The relationship of vulnerability to migration is complex. Areas of out-migration can experience reduced vulnerability if migrants send remittances, or increased vulnerability if the burden of work, usually for women, also increases. The decline in transmission of traditional knowledge through social networks can also increase vulnerability (Valdivia *et al.*, 2010). Furthermore, those places receiving migrants can experience an excessive demographic growth, which increases pressure over scarce resources, as is being experienced in the semi-arid tropics (Cooper *et al.*, 2008; Obioha, 2008). Brondizio and Moran (2008) found that in-migration in the Amazon brought people with knowledge that is ill-adapted to the local environment (see chapter 12.4)

9.3.5.1.5. Gender

Box CC-GC sets out the general issues on climate change and gender-related inequalities. These are of special relevance to rural areas, particularly, but not solely in the developing world (Alston, 2011; Vincent *et al.*, 2010; Nelson and Stathers 2009) (*high agreement, robust evidence*). Access to land shows strong differences between men and women, as do labour markets (FAO, 2010), and access to non-farm entrepreneurship (Rijkers and Costa, 2012). Less than 20% of the world's landholders are women, but women still play a disproportionate role in agriculture. On average women make up around 43% of the agricultural labour force in developing countries; in South Asia almost 70% of employed women work in agriculture, and more than 60% in sub-Saharan Africa (FAO, 2011; FAO, 2010). Climate change also increases vulnerability through male out-migration that increases the work to women (Chindarkar, 2012); cropping and livestock changes that affect gender division of labour (Lambrou and Paina, 2006); increased difficulty in accessing resources (fuelwood and water) (Tandon, 2007) and increased conflicts over natural resources (Omolo, 2011). Women are generally, though not in every context, more vulnerable to the impacts of extreme events, such as floods and tropical cyclones (Neumayer and Plümper, 2007).

9.3.5.1.6. Knowledge and information

Lack of access to information and knowledge of rural people can also interact with all the above mentioned drivers to mediate vulnerability. Shared knowledge and lessons learned from previous climatic stresses provide vital entry points for social learning and enhanced adaptive capacity (Tschakert, 2007). But while some authors emphasize the need for local responses and indigenous knowledge to reduce vulnerability (Valdivia *et al.*, 2010), and call for an integration of local knowledge into climate policies (Nyong *et al.*, 2007; Brugger and Crimmins 2012), Bellon *et al.* (2011) state that local knowledge is too local, and in some contexts gathering information from further away is important.

Access to information alone is not a guarantee of success. Coles and Scott (2009) found that in Arizona, despite ample access to weather forecasting, ranchers did not rely on such information, implying that changes are required to make more attractive information to users, as well as to understand prevailing local cultures and norms.
It is also important how knowledge is produced, managed, and disseminated within the formal institutional structure to address vulnerability issues. A local case-study in Sweden shows that limited co-operation between local sector organizations, lack of local co-ordination, and an absence of methods and traditions to build institutional knowledge present barriers to manage vulnerability (Glaas *et al.*, 2010). In Benin, as elsewhere in Africa, there is a lack of co-ordination between climate policies and the policies and practices which govern agricultural research and extension, while good practice at project level has been insufficiently harnessed to foster collective learning of farmers and other agricultural stakeholders, and thus adaptation to climate change (Moumouni and Idrissou 2013a and 2013b). For institutional learning, knowledge transfer, and more reliable assessments of local vulnerabilities, local institutional structure must be flexible, establishing communication mechanisms between public authorities, other knowledge producers, and civil society (Glaas *et al.*, 2010).

9.3.5.2. Outcomes

The outcome of vulnerability is the result of, and interaction of, the driving forces that determine vulnerability in a given sector, social group, etc. This section analyses how different drivers may affect specific vulnerable groups in rural areas, particularly pastoralists, mountain farmers and artisanal fisherfolk. Box 9-2 takes a specific economic sector important in rural areas, and demonstrates the interplay of vulnerability and exposure.

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Box 9-2. Tourism and Rural Areas

The three major market segments of tourism most likely to be affected by climate change are rural-based, namely, coastal tourism, nature-based tourism and winter sports tourism (Scott *et al.*, 2012). Tourism is a significant rural land use in many parts of the world, yet compared to other economic sectors in rural areas, the impacts of climate change are typically under-researched. In the Caribbean, for example, tourism has overtaken agriculture in terms of economic importance, with several regional states (including the Bahamas, the Cayman Islands and St Lucia) receiving more than 60 percent of their GDP from this industry (Meyer, 2006). Coastal environments elsewhere in the world are also characterized by dependence on rural tourism, and are known to be vulnerable to cyclones and sea level rise (Klint *et al.*, 2012a; Payet, 2007).

Terrestrial natural resource-based tourism is also a significant foreign exchange earner in many countries. In sub-Saharan Africa, between 25 and 40% of mammal species in national parks are likely to become endangered by 2080, assuming no species migration (and 10-20% with the opportunity for migration) (Thuiller *et al.*, 2006). There are also many rural environments viewed as “iconic” or having cultural significance that are vulnerable to climate change. In South Africa, for example, the Cape Floral (fynbos) ecosystem has a high level of species endemism which will be vulnerable to the projected increase in dry conditions (Midgley *et al*., 2002; Boko *et al*., 2007). The projected increase in climate change-related hazards, such as glacial lake outbursts, landslides, debris flows and floods, may affect trekking in the Nepali Himalayas (Nyaupane and Chhetri, 2009).

The development of tourism has, in many cases, increased levels of exposure to climate change impacts. In the Caribbean, for example, tourism has led to considerable coastal development in the region (Potter, 2000), which may exacerbate vulnerability to sea-level rise. In many cases, the carbon emissions resulting from participating in rural tourism threaten the very survival of the areas being visited. This is often the case for very remote locations, for example polar bear tourism in Canada (Dawson *et al.*, 2010), dive tourism in Vanuatu (Klint *et al.*, 2012b). Although on aggregate resource consumption of tourists and locals has been shown to be similar in developed county contexts (e.g. in Italy – Patterson *et al*., 2007); in many developing countries resource use by tourists is much higher than that of locals (e.g. in Nepal - Nepal, 2008).

Despite the potential impacts of climate change on rural tourism, there is *low evidence* of significant concern, which impedes adaptive responses. Surveys in both the upper Norrland area of northern Sweden and New Zealand showed that climate change is not perceived to pose a major threat in the short term, relative to other business risks perceived by small business owners and tourism operators (Brouder and Landmark, 2011; Hall, 2006).

That said, there is evidence that, with planned adaptation, tourism can flourish in rural areas under climate change. In the Costa Brava region of Spain, for example, although the increasing temperatures and reduced water availability is projected to negatively impact tourism in the current high seasons, there is scope to shift to the current shoulder seasons, namely April, May, September and October (Ribas *et al.*, 2010). Recognition of the opportunities for adaptation has also necessitated reassessment of the extent of the potential impacts of climate change on the tourism industry in rural areas. With the availability of snowmaking as a (costly and uncertain) adaptation in the eastern North American ski industry, only four out of fourteen ski areas are at risk before 2029, but ten out of fourteen in the period 2070-2099 (Scott *et al.*, 2006).

_____ END BOX 9-2 HERE _____

9.3.5.2.1. Pastoralists

Pastoralists have developed successful strategies for responding to climate variability, especially "strategic mobility" in pursuit of high-quality grazing (Krätli *et al.* 2013), in combination with shorter-term coping strategies (Morton, 2006), for example in Sub-Saharan Africa (Davies and Bennett, 2007; Kristjanson et al. 2010) or Inner Mongolia (Wang and Zhang 2012). However, mobility, a key component for community resilience, is declining , increasing the vulnerability of people in arid and semiarid regions (Lioubimtseva and Henebry, 2009; Fraser *et al.*, 2011). The lack of other alternatives in certain marginal areas where animals are the only secure assets can lead to overstocking and overgrazing, and thus, to increased vulnerability of pastoralism (Cooper *et al.*, 2008).

This is "induced vulnerability" (Krätli *et al.*, 2013), arising from a range of social, economic, environmental and political pressures external to pastoralism that bring about encroachment on rangelands, inappropriate land policy, undermining of pastoral culture and values, and economic policies promoting uniformity and competition over diversity and complementarity. Other authors list as constituents of increased vulnerability: population growth; increased conflict over natural resources; changed market conditions and access to services under liberalization; concentration of political power in national centres; and perceptions that pastoralists are backward (Dougill *et al.*, 2010; Rivera-Ferre and López-i-Gelats, 2012; Smucker and Wisner, 2008; Dong *et al*,. 2011). These in turn can be seen as results of what Reynolds *et al.*, (2007) conceptualize as two key features of dryland populations: remoteness, and distance from the centres and priorities of decision-makers or "distant voice". However Dong *et al.* (2011) and Sietz *et al.* (2011) stress the geographic differentiation of pastoral systems (and more broadly of dryland systems).

9.3.5.2.2. Mountain farmers

Mountain ecosystems have been identified as extremely vulnerable to climate change (Fischlin et al. 2007), and thus populations have a high exposure to climate change. A detailed understanding of climate change impacts in mountain areas is difficult because of physical inaccessibility and scarcity of resources for research in mountain states and regions (Singh *et al.*, 2011), as well as more generic uncertainties relating to climate projection. Mountain dwellers, as pastoralists in drylands, are adapted to live in steep and harsh and variable conditions, and thus have a variety of strategies to adapt and foster resilience to changing climatic conditions. However, to develop their strategies they need to overcome other drivers that can affect their vulnerability in different contexts. For instance, in most developed countries, mountains are becoming depopulated (Gellrich *et al.*, 2007; López-i-Gelats, 2013; Gehrig-Fasel *et al.*, 2007) given the extreme climatic conditions, their remoteness and subsequent isolation, while in developing countries (e.g. tropical mountain areas) there is a trend towards increasing population (Lama and Devkota, 2009; Huber *et al.*, 2005). The impacts of the projected warming on mountain farming, as well as their adaptation strategies, differ spatially because the socioeconomic role of mountains varies significantly between industrialized and industrializing or non-industrialized countries (Nogués-Bravo *et al.*, 2007). Mountain grasslands in developed countries are usually managed via a sub-exploitation model that involves the intensive use of the most productive areas and the abandonment of those regions where production is economically less viable (López-i-Gelats *et al.*, 2011). In contrast, mountain grasslands in developing countries remain centres of fodder and livestock production. Thus, two general trends are identified in world mountain grasslands, while temperate grasslands tend to suffer from conversion to agriculture, and land abandonment where livestock raising is less feasible (Gellrich *et al.*, 2008); in tropical grasslands the main cause of degradation is overgrazing, linked to processes of demographic growth. Land privatization, loss of grazing rights, or changes in land use (e.g., development of infrastructure) also affect mountain farmers both in developed and developing countries (Tyler *et al.*, 2007; Xu *et al.*, 2008).

9.3.5.2.3. Artisanal fisherfolk

Small coastal and riparian rural communities face several drivers that increase their vulnerability, which remain largely ignored by mainstream fisheries policy analysts; for example, the potential impact of demographic, health and disease trends, or of wider development policy trends (Hall, 2011), pressure from other resources (e.g. water, agriculture, coastal defense), unbalanced property-rights; lack of adequate health systems, potable water, or sewage and drainage (Badjeck *et al.*, 2010). The most important drivers affecting small-scale fisheries can be grouped into: international trade and globalization of markets; technology; climate and environment; health and disease; demography; development patterns and aquaculture; for instance, freshwater fisheries are threatened by increasing irrigation, while vulnerability of coastal fisheries increases with mangrove loss to aquaculture facilities in response to growing markets for prawns (Hall, 2011). Another difficulty faced by fisheries-based livelihoods is the neglect of governments and researchers, which is more focussed on industrial fishing to the neglect of artisanal fishing (Mills *et al.*, 2011).

9.4. Adaptation and Managing Risks

9.4.1. Framing Adaptation

AR4 stated with very high confidence that adaptation to climate change was already taking place, but on a limited basis, and more so in developed than developing countries. Since then, the documentation of adaptation in developing countries has grown *(high confidence*). Adaptation is progressive, and is distinguished from coping as it reduces vulnerability in the cast of re-exposure to the same hazard (Vincent *et al*., 2013): it can therefore be identified even without high confidence that a local hazard or climate trend is attributable to global climate change – indeed many cases of adaptation are primarily driven by other stressors, but have the result of aiding adaptation to climate change (Berrang-Ford *et al.*, 2011).

Many adaptations do build on examples of responses to past variability in resource availability, and it has been suggested that the ability to cope with current climate variability is a prerequisite for adapting to future change (Cooper *et al*., 2008). At the same time, however, it cannot be assumed that past response strategies will be sufficient to deal with the range of projected climate change. In some cases, existing coping strategies may increase vulnerability to future climate change, by prioritising short–term resource availability (O’Brien *et al.*, 2007; Adepetu and Berthe, 2007). In Malawi, for example, forest resources are used for coping (gathering wild food and firewood to sell), but this process reduces the natural resource base and increases vulnerability to future flooding through reduced land cover and increased overland flow (Fisher *et al*., 2010). In developing countries, there is *high confidence* that adaptation could be linked to other development initiatives aiming for poverty reduction or improvement of rural areas (Nielsen *et al*., 2012; Hassan, 2010; Eriksen and O’Brien, 2007, section 13.4). For more information on the integration of adaptation and development in climate-resilient development pathways, see Chapter 20. In Ethiopia, for example, “low regrets” measures to respond to current variability are important to shift the trajectory from disaster-focused to longer-term vulnerability reduction (Conway and Schipper, 2011).

9.4.2. Decision-Making for Adaptation

Decision-making for adaptation takes place at a variety of levels, and can be public or private. International mechanisms variously support adaptation decision-making at all levels (see sections 14.4, 15.2). At the national and local levels, law and policies can enable planned adaptation (Stuart-Hill and Schulze, 2010). A longer history of evidence for public policies to support adaptation exists from developed countries, although increasingly developing countries are also introducing such policies (for more information see section 15.2; and Box 25-2 for information on Australia’s water policy and management, section 26.9.1 for information on federal adaptation policies in the USA and Canada). At local level, some progress towards adaptation planning has been observed, particularly in developed countries. In Australia, for example, Western Australia, South Australia and Victoria have mandatory State planning benchmarks for 2100 (see Box 25-1), and in the Great Plains of the US, some jurisdictions have developed plans on either climate adaptation or climate mitigation, although so far less than 20% have done so (Romsdahl *et al.*, 2013).

At the local level, many adaptations are examples of private decisions for adaptation, undertaken by NGOs (primarily in developing countries, often in the form of community-based adaptation), and companies and individuals. Public and private decision-making for adaptation is not always mutually exclusive: one example of where policy can support private adaptation is in the provision of index-based insurance schemes (Suarez and Linnerooth-Bayer, 2010; Linnerooth-Bayer and Mechler, 2007), which have variously been trialed in India, Africa and South America (Patt *et al*., 2010; Patt *et al*., 2009; for a case study on index-based weather insurance in Africa see Box 22-1). However, national policies and laws are not always mutually-supportive of private actions (Stringer *et al.*, 2009).

There is now *high confidence* that public decision-making for adaptation can be strengthened by understanding the decision-making of rural people in context, and in particular considering examples of autonomous adaptation and the interplay between informal and formal institutions (Eakin and Patt, 2011; Naess, 2012; Adhikari and Taylor, 2012; Bryan *et al.*, 2009). Adaptation can also build upon local and indigenous knowledge for responding to weather events and a changing climate as has been observed in Samoa (Lefale, 2010 – see chapter 29), the Solomon Islands (Rasmussen *et al*., 2009 – see chapter 29), Namibia (Newsham and Thomas, 2011), Canada (Nakashima *et al*., 2011-see chapter 24), the Indo-Gangetic Plains (Rivera-Ferre *et al*., 2013b), and Australia (Green *et al*., 2010)

9.4.3. Practical Experiences of Adaptation in Rural Areas

In AR4, examples of adaptation in rural areas exhibited a bias towards developed countries (chapter 17), but since then practical examples of adaptation in rural areas have increased substantially in developing countries (*very high confidence*). These practical experiences of adaptation are found in agriculture, water, forestry and biodiversity, and fisheries.

*9.4.3.1. Agricultur*e

Agricultural societies have a history of responding to the impacts of change in exogenous factors, including (but not limited to) weather and climate (Mertz *et al.*, 2009a). They undertake a range of adjustment measures relating to their farming practices – for example, planting, harvesting and watering/fertilizing existing crops; using different varieties, diversifying crops; implementing management practices such as shading and conservation agriculture. Table 9-7 gives some examples; Box 9-3 describes adaptation initiatives in the beverage crop sector: more information on agricultural adaptation is available in Sections 23.8.2 (Europe), 24.4.3.5 (Asia), 25.7.2 (Australasia), 26.5.4 (North America), 27.3.4.2 (Central and South America).

[INSERT TABLE 9-7 HERE
Table 9-7: Examples of adaptations in the agricultural sector in different regions.]

Conservation agriculture shows promising results and can be used as an adaptation (Speranza, 2013) and for sustainable intensification of production (Pretty *et al.*, 2011), with significant yield productions observed in South Asia and southern Africa (Erenstein *et al.*, 2012). See Box 22-2 for a case study on integrating trees into annual cropping systems. Water management for agriculture is also critical in rural areas under climate change, for example the use of rainwater harvesting (Kahinda *et al.*, 2010, Vohland and Barry, 2009; Rivera-Ferre *et al.*, 2013b), and more efficient irrigation, particularly in rural drylands (Thomas, 2008).

Adaptations are also evident among small-scale livestock farmers (Rivera-Ferre and López-i-Gelats, 2012; (Kabubo-Mariara, 2009, 2008), who use many different strategies, including changing herd size and composition, grazing and feeding patterns, or diversifying their livelihoods, also they may use new varieties of fodder crops suited to the changing conditions (Salema *et al.*, 2010).

Diversified farms are more resilient than specialized ones (Seo, 2010); but rural societies also diversify their income sources beyond agriculture, which in many contexts allows them to reduce their risk exposure. Examples include the exploitation of gums and resins in Kenya (Gachathi and Eriksen, 2011).There may be some rural areas, however, where limits to agricultural adaptation are reached, and thus the only option that remains is to migrate or diversify away from farming (Mertz *et al.*, 2011). According to chapter 7, adaptation leads to lower reductions in food production with more effective adaptation (of around 15-20% compared with no adaptation), and adaptations are more successful at higher latitudes (for maize, wheat and rice) than in tropical regions. Figure 7-8 shows the varying efficiency of different crop adaptation measures, with cultivar adjustment leading to the largest percentage difference from the baseline, compared with irrigation optimization and planting date adjustment (although this shows the largest variation).

9.4.3.2. Water

As well as being an important input to agriculture, adaptation in water resources through improved management is critical in rural areas, not only at basin level but also for human settlements (Mukheibir, 2008). The extent to which adaptation measures have been implemented to date varies: in a study from Europe, Africa and Asia, European basins were most advanced (Krysanova *et al.*, 2010). In the cases of transboundary basins additional barriers exist to adaptive management measures, particularly in Africa (Goulden *et al.*, 2009), although examination of potential institutional designs has been undertaken (Huntjens *et al.*, 2012). In the Middle East and North Africa, whilst supply-side measures are advanced, little attention has been paid to the demand-side measures that will be critical in a changing climate (Sowers *et al*., 2011).

Whilst the majority of focus on adaptation concerning water relates to its availability, many rural areas in both developed and developing countries are subject to riverine or coastal flooding. In the low-lying Netherlands protection measures have been employed, including increasing river runoff, increasing storage for water (Deltacommissie, 2008; Kabat *et al.*, 2009), and small scale containment of flood risks through increasing compartmentalization (Klijn *et al.*, 2009). In the Mekong Delta in Vietnam, the government's "living with floods" program has encouraged rice farmers to shift to aquaculture, while the planned relocation of 20,000 "landless and poor households" has altered social networks and livelihoods (De Sherbinin *et al.*, 2011). See Table 9-8 for further examples.

[INSERT TABLE 9-8 HERE
Table 9-8: Examples of adaptations in the water sector observed in different regions.]

More information on adaptation in the water sector is available in sections 24.4.1.5 and 24.4.2.5 (Asia), 26.3.3 (North America), 27.3.1.2 and 27.3.2.2 (Central and South America).

9.4.3.3. Forestry and Biodiversity

Effective management is also essential for adaptation of forests and biodiversity to climate change, particularly involving (where appropriate) communities (Porter-Bolland *et al*., 2012). Forest resources have been shown to play a role in enabling livelihood adaptation during extreme events in Zambia, Mali and Tanzania, although should take place within a managed context to ensure sustainability (Robledo *et al.*, 2011). As with water resources, forests can adapt through management of forest fires, silvicultural practices, and the conservation of forest genetic resources. Ecological restoration, where required, is another effective adaptation measure that enhances biodiversity and environmental services (Benayas *et al.*, 2009) and increases the potential for carbon sequestration and promotes economic livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon *et al.*, 2011; Rodrigues *et al.*, 2011). Direct species management is important (Mawdsley *et al.*, 2009). In terms of managing protected areas, to maintain appropriate habitats a network approach may be effective (Hole *et al.*, 2011).

As the climate changes, part of adaptive management may entail modification of existing biodiversity management practices. Manipulating vegetation composition and stand structure, for example, has been proposed as an adaptation option to wildfires in Canada (Terrier et a, 2013; Girardin *et al*., 2013); for more information on wildfires see Box 26-2. In Central and South America, protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas (Nelson and Chomitz, 2011).

Reflecting the growing evidence for community-based management and wise use, an emerging mechanism for ecosystem-based adaptation includes payment for ecosystem services (PES) (Montagnini and Finney, 2011). The PES literature is more developed for carbon payments, CDM and REDD+, but some research suggests potential for adaptation as well (see 13.3.1.2 for an assessment of the relationship between REDD+ and poverty alleviation). Particularly developed in Central and South America (see Table 27-7 for examples of PES schemes), communities can be paid for collecting scientific data to contribute to research and monitoring protocols (Luzar *et al.*, 2011), or for actively managing natural resources, which may improve adaptive capacity in the longer term, bearing in mind with reforestation there is a time delay before payments are received (Locatelli *et al*., 2008). More indirectly, there are opportunities for PES to contribute to adaptation indirectly through natural adaptation co-benefits (for example water regulation and soil protection for reduced climate impacts in watersheds)(Pramova *et al*., 2012) and through the creation of institutional structures that may support adaptive capacity (Wertz-Kanounnikof *et al*., 2012). For further case studies on ecosystem-based adaptation see Figure 22-8 (Africa), Box CC-EA (cross-chapter), Section 14.3.2; and for a diagrammatic representation see Figure CC-EA-1. More information on adaptation for forestry and biodiversity is available in Sections 23.8.2 and 23.8.4 (Europe), 24.5.1 (Asia) and 25.7.1.2 (Australasia).

9.4.3.4. Fisheries

Adaptation in marine ecosystems is also of relevance to rural areas. As with terrestrial natural resources, evidence from the marine resources sphere shows that a transformative approach to fisheries co-management, introducing ecosystem, rights and participation principles is essential for adaptation (Andrew and Evans 2011; Charles 2011). Such an approach, involving local fishermen and allowing limited extraction of resources, favours a balance between resource conservation and livelihoods, e.g. in Brazil (Francini-Filho and Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations (Hastings, 2011; Moura *et al*., 2009)(see also section 30.6.2.1). Selective use of fishing gear is a recommended management measure, based on 15 global sites, to ensure sustainable harvesting of remaining fish stocks (Cinner *et al.*, 2009). According to section 6.4.1.1, appropriate management will have a greater impact on biological and economic conditions than climate change. Table 30-2 outlines potential adaptation options and supporting policies for fisheries and aquaculture in the Pacific Islands considering a variety of timescales. Section 7.5 gives additional examples on adaptation for aquaculture.

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Box 9-3. Adaptation Initiatives in the Beverage Crop Sector

One of the leading initiatives to prepare small holder producers of beverage crops for adaptation to climate change is the AdapCC project which worked with coffee and tea producers in Latin America and East Africa (Schepp, 2010). This process used risk and opportunity analysis and participatory capacity building (CafeDirect/GTZ, 2010) to help farmers identify changes in management practices to both mitigate their contribution to climate change and adapt to the changes in climate they perceived to be occurring. In general the actions for adaptation were a reinforcement of principles of sustainable production, such as using tree shade. Facilitating processes of adaptation in the context of strong variability in vulnerability between different communities in the same region and even families within the same community (Baca 2011) will be a challenge, but supports the need for participatory community adaptation processes that would enable families to implement strategies appropriate to their own circumstances and capacity.

Policy recommendations to support adaptation in these sectors (Eakin *et al.*, 2011; Laderach *et al.*, 2010 Schepp, 2010; Schroth *et al.*, 2009) have prioritized the follows interventions to support adaptation:

- Community-based analysis of climate risks and opportunities as a basis for community adaptation strategies
- Improved recording and access to climate information including medium and long-term predictions
- Sustainable production techniques including soil and water conservation, shaded production systems, diversification of production systems
- Development of new varieties with broader adaptability to climate variation, higher temperatures and increased drought tolerance
- Financial support to invest in adaptation and reduce risks through climate insurance

- Organization of small producers to improve access to knowledge, financial support and coordinate implementation
- Environmental service payments and access to carbon markets to support sustainable practices
- Development of value chain strategies across all actors to support adaptation and increase resilience across the sectors.

There are possibilities for synergy between adaptation and mitigation. The sustainability standards Rainforest Alliance and Common Code for the Coffee Community are piloting climate-friendly standards for producers that aim to reduce the GHG emissions from agricultural practices, increase sequestration of carbon in soils and trees, but also prepare producers for adapting to climate change (SAN, 2011; Linne, 2011. The later consists of improved understanding of climate impacts and promoting sustainable production practices to increase resilience in the production systems.

_____ END BOX 9-3 HERE _____

9.4.4. Limits and Constraints to Rural Adaptation

The Fourth Assessment Report stated with *very high confidence* that there are substantial limits and barriers to adaptation (Adger *et al.*, 2007). Limits are typically defined (Dow *et al.*, 2013) as hard, i.e. they will not change over time, and are particularly applicable to biophysical systems (where, for example, there are critical thresholds to species and ecosystem tolerances of climate parameters and regimes). Constraints, on the other hand, are typically soft, and are more relevant to social systems, where changes in factors such as financial and physical resources, technology and infrastructure, knowledge and information and human resources may change over time. For further information, see Figure 16-1 and Sections 16.3.2 and 16.4.1. Here we focus on the soft constraints in social systems that act as barriers to implementation of practical adaptation options in rural areas.

As with risks and vulnerabilities, the literature emphasizes constraints to adaptation in rural areas in developing regions, although adaptation bottlenecks exist also in developed countries (where there has been an increase in awareness and planning for adaptation, but that has not necessarily translated into implementation – see chapter 14). Constraints to adaptation in developed regions have been observed in North America (Section 26.8.4.2) and Australasia (Section 25.4.2, Boxes 25-1, 25-2 and 25-9). Another key bottleneck comes from the fact that the need for adaptation to climate change is not the only pressing issue in rural areas in developed countries (Kiem and Austin, 2013).

There is *very high confidence* that lack of financial resources (in the form of credit) and physical resources (such as water and land) are major factors inhibiting adaptation for farmers in Africa and Asia (e.g. Ringler, 2010; Deressa *et al*., 2009; Bryan *et al*., 2009; Hassan and Nhemachena, 2008). A multinomial logit analysis of climate adaptation responses suggested that access to water, credit, extension services and off-farm income and employment opportunities, tenure security, farmers' asset base and farming experience are key to enhancing farmers' adaptive capacity (Gbetibouo *et al.*, 2010).

Rural households’ lack of access to technologies and infrastructure (e.g. markets) is also a major barrier to adaptation for certain production systems (*high agreement, medium evidence*). According to a study of adoption of improved, high yield maize in Zambia, production and price risks could render input use unprofitable and prevent rural households from benefiting from technological change crucial for adaptation (Langyintuo and Mungoma, 2008). The severe 1997 drought in the Central Plateau of Burkina Faso highlighted that household with a larger resources base took the advantage of distress sales and high prices of agricultural commodities (Roncoli *et al.*, 2001). A nationally representative rural household survey in Mozambique from 2005 shows that, overall, using an improved technology (improved maize seeds, improved granaries, tractor mechanization, and animal traction) did not have a statistically significant impact on household income. However when distinguishing between households using improved technologies, especially improved maize seeds and tractors, and those who do not, households who had better market access had significantly higher income (Cunguara and Darnhofer, 2011). A multinomial choice model fitted to data from a cross-sectional survey of over 8000 farms from 11 African countries showed that better access to markets, extension and credit services, technology and farm assets (labour, land and capital) are critical for helping African farmers adapt to climate change. Hence education, markets, credit and information about adaptation to climate change, including technological and institutional methods are important (Hassan and Nhemachena, 2008).

Although access to credit, water, technologies and markets are barriers, more fundamental is access to knowledge and information (*very high confidence)*. Since adaptation strategies involve dealing with uncertainty, whether stakeholders have access to information for decision making and how they perceive and utilize this information affects their adaptation choices (Ringer, 2010; Bryan *et al*., 2009; Deressa *et al*., 2009; Sheate *et al.*, 2008; Patt and Schröter, 2008; Dockerty *et al.*, 2006). Relevant information includes that on agricultural technologies that can be used in adaptation, but in developing countries agricultural research and extension systems are not integrated with climate planning to deliver this, as discussed by Moumouni and Idrissou (2013a) for Benin. There is now an important literature on dissemination of short-term or seasonal weather forecasts to farmers in developing countries, as detailed in Box 9-4.

Access to information is affected by human resources, or social characteristics (*high agreement, medium evidence*). These include culture, gender, age, governance and institutions (Jones and Boyd, 2011; Nielsen and Reenberg, 2010; Deressa *et al*., 2009; Goulden *et al*., 2009). A growing body of literature investigates the socio-cognitive, psychological and cultural barriers to adaptation. Section 2.2.1.2 explains how culture and psychology affect decision-making; Section 16.2 also discusses how the framing of adaptation depends on perception of risk and values. For planned adaptation to be successful, or autonomous adaptation to occur, actors need to be convinced of the magnitude of risks of climate change (Patt and Schröter, 2008).

_____ START BOX 9-4 HERE _____

Box 9-4. Factors Influencing Uptake and Utility of Climate Forecasts in Rural Africa

The IPCC SREX report identified the use of forecasts as a risk management measure (IPCC, 2012). So far the uptake of weather and climate information has been suboptimal (Vogel and O'Brien, 2006). In Africa annual climate information (e.g. seasonal forecasts) is more used than climate change scenarios for agricultural development (Ziervogel and Zermoglio, 2009), although attempts to use longer term climate projections for crop forecasting and livestock farming have been examined (Challinor, 2009; Boone *et al.*, 2004). The potential for improved prediction and effective timely dissemination of such information has been noted in different sectors, including water managers (Ziervogel *et al*., 2010a) and disaster planners (Tall *et al.*, 2012), as well as farmers (both arable and pastoral)(Archer *et al*., 2007; Klopper *et al*., 2006, Bryan *et al*., 2009).

Extensive research has taken place to assess factors influencing uptake and utility of climate forecasts, including mapping of dissemination through stakeholder networks (Ziervogel and Downing, 2004), and user needs (Ziervogel, 2004). Such studies have shown that various factors affect dissemination and use: including stakeholder involvement in the process (usually higher when participatory processes had taken place) (Peterson *et al.*, 2010; Roncoli et al, 2009); effects of user wealth, risk aversion, and presentational parameters, such as the position of forecast parameter categories, and the size of probability categories (Millner and Washington, 2011), and the legitimacy, salience, access, understanding and capacity to respond (Hansen *et al*., 2011). Gender differences have been observed in preferred dissemination channels (Archer, 2003; Naab and Korenteng, 2012).

There are promising signs for the integration of scientific-based seasonal forecasts with indigenous knowledge systems (Ziervogel *et al*., 2010b; Speranza *et al.*, 2010). Ensuring improved validity and utility of seasonal forecasts will require collaboration of researchers, data providers, policy developers and extension workers (Coe and Stern, 2011), as well as with end users. Additional opportunities to benefit rural communities come from expanding the use of seasonal forecast information for coordinating input and credit supply, food crisis management, trade and agricultural insurance (Hansen *et al*., 2011). For more information on climate information and services, and the history, politics and practice of this area, see section 2.4.1.

_____ END BOX 9-4 HERE _____

9.5. Key Conclusions and Research Gaps

9.5.1. Key Conclusions

This chapter has assessed impacts of climate change, vulnerability to climate change and prospects for adaptation to climate change in the rural areas of the world. Rural areas are distinctive and important in the context of climate change because:

- They account for nearly half of the world's population, even with rapid urbanization
- They account for well over half of the world's poor and extremely poor people
- Economic activity and livelihoods in rural areas are closely linked to natural resources and thus particularly sensitive to climate variability and climate change
- Conversely, it is in rural areas that long-established adaptations to climate variability exist and can form a basis under certain conditions for adaptations to climate change.

Rural areas are both hard to define – there is no internationally valid definition, and definitions that do exist depend on definitions of the urban (see Table 9-1). They are also extremely diverse, existing in nearly every country of the world, across low-, middle- and high income- countries, although 90% of the world's rural population lives in low- and middle-income countries, which receive particular attention in this chapter. Rural areas are undergoing important and rapid changes in terms of their demography, economic profile and governance (see Table 9-3); some specific to developing countries, some to high-income counties and some generic. Many of these changes are in the direction of economic and livelihood diversification away from agriculture and natural resources. Others are in the direction of increased rural-urban interdependencies and less well-defined boundaries between the rural and the urban.

Many of the non-climate factors characterizing rural areas and populations within them, especially in low- and middle-income countries, are cited as factors increasing vulnerability to climate change. There is *high agreement* on the importance for resilience of access to land and natural resources, flexible local institutions, and knowledge and information, and the association of gender inequalities with vulnerability. There are *low levels of agreement* on some of the key factors associated with vulnerability or resilience in rural areas, including rainfed as opposed to irrigated agriculture, small-scale and family-managed farms, and integration into world markets. Specific livelihood niches such as pastoralism and artisanal fisheries are vulnerable and at high risk of adverse impacts (*high confidence*), partly due to neglect, misunderstanding or inappropriate policy towards them on the part of governments (9.3.5).

Against this background, discussion of impacts of climate change will be complex. The impacts of climate change on patterns of settlement, livelihoods and incomes in rural areas will be the result of multi-step causal chains of impact, starting either with increased frequency of extreme events or with more gradual manifestations of climate change, and working through impacts on agriculture, ecosystems or infrastructure. This increases the uncertainty associated with any particular projected impact. Biophysical impacts on food production are discussed in Chapter 7: this is supplemented here by an assessment of impacts on the production of non-food crops on which many millions of rural people depend, illustrated in particular by coffee, tea and cocoa (Box 9-1). Literature on the downstream impacts on incomes and livelihoods of changes in agricultural production (including livestock and fisheries) is also assessed.

Despite methodological problems in attribution, around the difficulties of attributing extreme events to climate change, the status of local knowledge, and the action of non-climate shocks and trends, evidence for observed impacts, both of extreme events and other categories, is increasing. Impacts on income and livelihoods can be inferred from biophysical impacts, but with *low confidence*. There is *high confidence* in geographically-specific impacts such as glacier melt in the Andes (9.3.2).

Major impacts of climate change in rural areas will be felt through impacts on agricultural production and therefore through agricultural incomes. In some regions shifts in agricultural production, of food and non-food crops, are *likely* to take place, not only as a result of changes in temperature and rainfall, but also through changes in availability of irrigation water, which are not necessarily factored into crop yield projections based on crop models

(9.3.3.1). There are also *likely* to be impacts on rural infrastructure both in developing and developed countries (9.3.3.2).

The interconnections between rural and urban areas will be affected in complex ways. Climate change will impact international trade volumes in both volume and value terms (*medium agreement, limited evidence).* Options exist for adaptations within international agricultural trade (*medium confidence)* to reduce market volatility and manage food supply shortages caused by climate change. Migration patterns will be driven by multiple factors of which climate change is only one (*high confidence*) and establishment of a relation between climate change and intra-rural and rural-to-urban migration, observed or projected, remains a major challenge (9.3.3.3).

Climate policies, such as increasing energy supply from renewable resources, encouraging cultivation of biofuels, or payments under REDD, will have significant secondary impacts, both positive (increasing employment opportunities) and negative (landscape changes, increasing conflicts for scarce resources), in some rural areas (*medium confidence*). These secondary impacts, and trade-offs between mitigation and adaptation in rural areas, have implications for governance, including the need to promote participation of rural stakeholders (9.3.3.4).

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

There is a growing body of literature on successful adaptation in rural areas and constraints upon it, including both documentation of practical experience, and discussion of preconditions (9.3.4). In developing countries adaptation can be linked to other development initiatives aiming for poverty reduction or improvement of rural areas, and “low regrets” measures to respond to current variability can shift the trajectory from disaster-focused to longer-term vulnerability reduction. Prevailing constraints, such as low levels of educational attainment, environmental degradation, gender inequalities, and isolation from decision-making create additional vulnerabilities which undermine rural societies’ ability to cope with climate risks (*high confidence*). The supply of information and opportunities for learning will be a key issue.

9.5.2. Research Gaps

There is a major continuing need for research on climate change in rural areas, which takes in their nature as areas with shifting combinations of human activity, in which agriculture (food crops, non-food crops and livestock) is important but not necessarily predominant. Such research will need to be developed, and extended to rural areas and diverse categories of rural people throughout the world.

Integrated research is needed on changes in land-use and trade-offs between land-uses under climate change, including non-agricultural land-uses such as conservation, and tourism. It should examine the trade-offs and synergies between adaptation and mitigation in rural areas, the impact of climate policies on rural livelihoods, and the appropriate structures for governance of natural resources at a landscape level for both developed and developing countries.

Research is required on the valuation and costing of climate change impacts, which takes note of the complexity and specificity of rural areas, with special emphasis on non-marketed ecosystem services and specific populations that have not as yet been studied.

More research is needed on vulnerability, to identify the most vulnerable areas, populations and social categories, but it should include research on methodological questions such as conceptualizations of vulnerability, assessment tools, spatial scales for analysis, and the relations between short-term support for adaptation, policy contexts and development trajectories, and long-term resilience or vulnerability.

A relevant area will be that of improving understanding of rural-urban linkages, their evolution and their management under climate change, including the respective roles of climate and other factors in rural-urban migration.

Research is needed on practical adaptation options, not only for agriculture but for non-agricultural livelihoods. Adaptation research must also look at adaptations to institutions, to better enable them to address lack of access to credit, markets, information, risk-sharing tools and property rights. Research must be open to participatory and action-research approaches which build on both local and scientific knowledge, and foster learning for adaptation and resilience among rural people.

Frequently Asked Questions

FAQ 9.1: What is distinctive about rural areas in the context of climate change impacts, vulnerability and adaptation? *[to be placed in Section 9.1.2]*
Nearly half of the world's population, approximately 3.3 billion people, lives in rural areas, and 90% of those people live in developing countries. Rural areas in developing countries are characterized by a dependence on agriculture and natural resources, high prevalence of poverty, isolation and marginality, neglect by policy-makers, and lower human development. These features are also present to a lesser degree in rural areas of developed countries, where there are also a closer interdependencies between rural and urban areas (such as commuting), and where there are also newer forms of land-use such as tourism and recreational activities (although these also generally depend on natural resources.

The distinctive characteristics of rural areas make them uniquely vulnerable to the impacts of climate change because:

- Greater dependence on agriculture and natural resources makes them highly sensitive to climate variability, extreme climate events and climate change
- Existing vulnerabilities caused by poverty, lower levels of education, isolation and neglect by policy makers, can all aggravate climate change impacts in many ways.

Conversely, rural people in many parts of the world have, over long timescales, adapted to climate variability, or at least learned to cope with it. They have done so through farming practices and use of wild natural resources (often referred to as indigenous knowledge or similar terms), as well as through diversification of livelihoods and through informal institutions for risk-sharing and risk management. Similar adaptations and coping strategies can, given supportive policies and institutions, form the basis for adaptation to climate change, although the effectiveness of such approaches will depend on the severity and speed of climate change impacts.

FAQ 9.2: What will be the major climate change impacts in rural areas across the world?
[to be placed in Section 9.3.3.4]
The impacts of climate change on patterns of settlement, livelihoods and incomes in rural areas will be complex and will depend on many intervening factors, so they are hard to project. These chains of impact may originate with extreme events such as floods and storms, some categories of which, in some areas, are projected with high confidence to increase under climate change. Such extreme events will directly affect rural infrastructure and may cause loss of life. Other chains of impact will run through agriculture and the other ecosystems (rangelands, fisheries, wildlife areas) on which rural people depend. Impacts on agriculture and ecosystems may themselves stem from extreme events like heat waves or droughts, from other forms of climate variability, or from changes in mean climate conditions like generally higher temperatures. All climate-related impacts will be mediated by the vulnerability of rural people living in poverty, isolation, or with lower literacy etc., but also by factors that give rural communities resilience to climate change, such as indigenous knowledge, and networks of mutual support.

Given the strong dependence in rural areas on natural resources, the impacts of climate change on agriculture, forestry and fishing, and thus on rural livelihoods and incomes, are likely to be especially serious. Secondary (manufacturing) industries in these areas, and the livelihoods and incomes that are based on them will in turn be substantially affected. Infrastructure (e.g. roads, buildings, dams and irrigation systems) will be affected by extreme events associated with climate change. These climate impacts may contribute to migration away from rural areas, though rural migration already exists in many different forms for many non-climate-related reasons. Some rural areas will also experience secondary impacts of climate policies – the ways in which governments and others try to reduce net greenhouse gas emissions such as encouraging the cultivation of biofuels or discouraging deforestation. These secondary impacts may be either positive (increasing employment opportunities) or negative (landscape changes, increasing conflicts for scarce resources).

FAQ 9.3: What will be the major ways in which rural people adapt to climate change?
[to be placed in Section 9.4.4]
Rural people will in some cases adapt to climate change using their own knowledge, resources and networks. In other cases governments and other outside actors will have to assist rural people, or plan and execute adaptation on a scale that individual rural households and communities cannot. Examples of rural adaptations will include modifying farming and fishing practices, introducing new species, varieties and production techniques, managing water in different ways, diversification of livelihoods, modifying infrastructure, and using or establishing risk sharing mechanisms, both formal and informal. Adaptation will also include changes in institutional and governance structures for rural areas.

Cross-Chapter Boxes

Box CC-GC. Gender and Climate Change

[Jon Barnett (Australia), Marta G. Rivera Ferre (Spain), Petra Tschakert (U.S.A.), Katharine Vincent (South Africa), Alistair Woodward (New Zealand)]

Gender, along with socio-demographic factors of age, wealth and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger *et al.*, 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer *et al.*, 2007; Nightingale, 2009; Buechler, 2009; Nelson and Stathers, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resureccion, 2011; Omolo, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labour markets, making women in particular less able to cope with and adapt to climate change impacts (Rijkers and Costa, 2012; Djoudi and Brockhaus, 2011; Paavola, 2008). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whilst both men and women experience increases in productive roles, only women experience increased reproductive roles (Resureccion, 2011; 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income, and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity since food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota *et al.*, 2011).

AR4 assessed a body of literature that focused on women's relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger *et al.*, 2007). Additional literature published since that time adds nuances by showing how socially-constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*) [11.3.3, Table 12-3]. Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981-2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007) [Box 13-1]. Reasons for gendered differences in mortality include various socially- and culturally-determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house, even during floods and in risk-prone areas (Bradshaw, 2010). While the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality [Box 13-1]. In Hai Lang district, Vietnam, for example, more men died than women due to their involvement in search and rescue and protection of fields during flooding (Campbell *et al.*, 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the U.S. and Australia (Jenkins and Phillips, 2008; Anastario *et al.*, 2009; Alston, 2011; Whittenbury, 2013; Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and Sao Paulo (Bell *et al.*, 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Figueiredo and Perkins, 2012; Arora-Jonsson, 2011; Vincent *et al.*, 2010). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women since cash generation is seen as a male activity in rural areas (Gladwin *et al.*, 2001;13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor which women cannot necessarily afford to provide (Baiphethi *et al.*, 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Below *et al.*, 2012; Goulden *et al.*, 2009; Vincent *et al.*, 2010) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert, 2013; Bee *et al.*, 2013; Tschakert and Machado, 2012; see also 22.4.3 and Table 22-5).

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Box CC-UR. Urban-Rural Interactions –
Context for Climate Change Vulnerability, Impacts, and Adaptation

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Rural areas and urban areas have always been interconnected and interdependent, but recent decades have seen new forms of these interconnections: a tendency for rural-urban boundaries to become less well-defined, and new types of land-use and economic activity on those boundaries. These conditions have important implications for understanding climate change impacts, vulnerabilities, and opportunities for adaptation. This box examines three critical implications of these interactions:

1) Climate extremes in rural areas resulting in urban impacts – teleconnections of resources and migration streams mean that climate extremes in non-urban locations with associated shifts in water supply, rural agricultural potential, and the habitability of rural areas will have downstream impacts in cities;
2) Events specific to the rural-urban interface – given the highly integrated nature of rural-urban interface areas and overarching demand to accommodate both rural and urban demands in these settings, there is a set of impacts, vulnerabilities and opportunities for adaptation specific to these locations. These impacts include loss of local agricultural production, economic marginalization resulting from being neither rural or urban, and stress on human health; and,
3) Integrated infrastructure and service disruption – as urban demands often take preference, interdependent rural and urban resource systems place nearby rural areas at risk, because during conditions of climate stress, rural areas more often suffer resource shortages or other disruptions in order to sustain resources to cities. For example, under conditions of resource stress associated with climate risk (e.g., droughts) urban areas are at an advantage because of political, social, economic requirements to maintain service supply to cities to the detriment of relatively marginal rural sites and settlements.

Urban areas historically have been dependent on the lands just beyond their boundaries for most of their critical resources including water, food, and energy. While in many contexts, the connections between urban settlements and surrounding rural areas are still present, long distance, teleconnected, large-scale supply chains have been developed particularly with respect to energy resources and food supply (Güneralp et al., 2013). Extreme event disruptions in distant resource areas or to the supply chain and relevant infrastructure can negatively impact the urban areas dependent on these materials (Wilbanks et al., 2012). During the summer of 2012, for instance, an extended drought period in the central United States led to significantly reduced river levels on the Mississippi River which led to interruptions of barge traffic and delay of commodity flows to cities throughout the country. Urban water supply is also vulnerable to droughts in predominantly rural areas. In the case of Bulawayo, Zimbabwe, periodic urban water shortages over the last few decades have been triggered by rural droughts (Mkandla et al., 2005).

A further teleconnection between rural and urban-areas is rural-urban migration. There have been cases where migration and urbanization patterns have been to attributed to climate change or its proxies such as in parts of Africa (Morton 1989, Barrios et al., 2006). However, as recognized by Black *et al.* (2011), life in rural areas across the world typically involves complex patterns of rural-urban and rural-rural migration, subject to economic, political, social and demographic drivers, patterns which are modified or exacerbated by climate events and trends rather than solely caused by them.

Globally, an increased blending of urban and rural qualities has occurred. Simon *et al*. (2006:4) assert that the simple dichotomy between ‘rural’ and ‘urban’ has “long ceased to have much meaning in practice or for policy-making purposes in many parts of the global South”. One approach to reconciling this is through the increasing application of the concept of “peri-urban areas” (Simon *et al*., 2006; Simon, 2008). These areas can be seen as rural locations that have “become more urban in character” (Webster 2002: 5); as sites where households pursue a wider range of income-generating activities while still residing in what appear to be “largely rural landscapes” (Learner and Eakin 2010: 1); or as locations in which rural and urban land uses coexist, whether in contiguous or fragmented units (Bowyer-Bower, 2006). The inhabitants of “core” urban areas within cities have also increasingly turned to agriculture, with production of staple foods, higher-value crops and livestock (Bryld, 2003; Devendra et al., 2005; Lerner and Eakin, 2010; Lerner et al., 2013). Bryld (2003) sees this as driven by rural-urban migration and by structural adjustment (e.g. withdrawal of food price controls and food subsidies). Lerner and Eakin (2011, also

Lerner et al., 2013) explored reasons why people produce food in urban environments, despite high opportunity costs of land and labour: buffering of risk from insecure urban labour markets; response to consumer demand; and the meeting of cultural needs.

Livelihoods and areas on the rural-urban interface suffer highly specific forms of vulnerability to disasters, including climate-related disasters. These may be summarised as specifically combining: urban vulnerabilities of population concentration, dependence on infrastructure, and social diversity limiting social support with rural traits of distance, isolation and invisibility to policy-makers (Pelling and Mustafa, 2010). Increased connectivity can also encourage land expropriation to enable commercial land development (Pelling and Mustafa, 2010). Vulnerability may arise from the co-existence of rural and urban perspectives, which may give rise to conflicts between different social /interest groups and economic activities (Darly and Torre 2013, Masuda and Garvin 2008, Solona-Solona 2010).

Additional vulnerability of peri-urban areas is on account of the re-constituted institutional arrangements and their structural constraints (Iaquinta and Drescher 2000). Rapid declines in traditional informal institutions and forms of collective action, and their imperfect replacement with formal state and market institutions, may also increase vulnerability (Pelling and Mustafa, 2010).

Peri-urban areas and livelihoods have low visibility to policy-makers at both local and national levels, and may suffer from a lack of necessary services, and inappropriate and uncoordinated policies. In Tanzania and Malawi, national policies of agricultural extension to farmer groups for example, do not reach peri-urban farmers (Liwenda et al., 2012). In peri-urban areas around Mexico City (Eakin et al., 2013), management of the substantial risk of flooding is led *de facto* by agricultural and water agencies, in the absence of capacity within peri-urban municipalities and despite clear evidence that urban encroachment is a key driver of flood risk. In developed country contexts suburban areas, suburban-exurban fringe areas often are overlooked in the policy arena that traditionally focuses on rural development and agricultural production, or urban growth and services (Hanlon et al., 2011). The environmental function of urban agriculture, in particular, in protection against flooding, will increase in the context of climate change. (Aubry et al., 2012).

However, peri-urban areas and mixed livelihoods more generally on rural-urban interfaces, also exhibit specific factors that increase their resilience to climate shocks (Pelling and Mustafa, 2010). Increased transport connectivity in peri-urban areas can reduce disaster risk by providing a greater diversity of livelihood options and improving access to education. The expansion of local labour markets and wage labour in these areas can strengthen adaptive capacity through providing new livelihood opportunities (Pelling and Mustafa, 2010). Maintaining mixed portfolios of agricultural and non-agricultural livelihoods also spreads risk (Lerner et al., 2013).

In high-income countries, practices attempting to enhance the ecosystem services and localized agriculture more typically associated with lower density areas have been encouraged. In many situations these practices are focused increasingly on climate adaptation and mitigating the impacts of climate extremes such as those associated with heating and the urban heat island effect, or wetland restoration efforts to limit the impact of storm surge wave action (Verburg et al., 2012).

The dramatic growth of urban areas also implies that rural areas and communities are increasingly politically and economically marginalized within national contexts, resulting in potential infrastructure and service disruptions for such sites. Existing rural-urban conflicts for the management of natural resources (Castro and Nielsen, 2003) such as water (Celio et al., 2011) or land-use conversion in rural areas (e.g. wind farms in rural Catalonia (Zografos and Martínez-Alier, 2009); industrial coastal areas in Sweden (Stepanova and Bruckmeier, 2013); or conversion of rice land into industrial, residential and recreational uses in the Philippines (Kelly, 1998) or Spain have been documented, and it is expected that stress from climate change impacts on land and natural resources will exacerbate these tensions. For instance, climate induced reductions in water availability may be more of a concern than population growth or increased per-capita use for securing continued supplies of water to large cities (Darrel Jenerette and Larsen, 2006), both of which requires an innovative approach to address such conflicts (Pearson et al., 2010).

Box CC-UR References

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Table 9-1: Definitions of the "rural" and the "urban" in selected countries.

Indicative examples of urban and rural definitions	
Country	**Definitions**
Australia	**Major Urban Areas**: population of over 100,000 **Other Urban Areas**: population of 1,000-99,999 **Rural Areas**: includes small towns with a population of 200-999 (Australian Bureau of Statistics, 2013)
China	**Major Urban Areas**: population of over 10,000 **Medium Urban Areas**: population of 3,000-9,999 **Small Urban Areas**: population of less than 3,000 **Major Villages**: population of 1,000-3,000 **Medium Villages**: population of 300-1,000 **Small Villages**: population of less than 300 (Ministry of Construction, 1993)
India	**Urban Areas**: population of 5,000 or more; or where at least 75% of the male working population is non-agricultural; or having a density of population of at least 400 people / km^2 (Government of India, 2012). It is implied that all non-urban areas are rural.
Jamaica	A **place** is considered to be **urban** if: it has a population of more than 2,000 people and provides a certain set of amenities and facilities that are deemed to indicate "modern living" (Statistical Institute of Jamaica, 2012). It is implied that all non-urban areas are rural.
United States of America	**Rural Areas**: all territory outside of defined urbanized areas and urban clusters, that is open country and settlements with fewer than 2,500 residents; with population densities as high as 386 people / km^2 (Womach, 2005)

Table 9-2: Relevant findings on rural areas from the IPCC Fourth Assessment Report and the International Assessment of Agricultural Science and Technology for Development.

Importance of non-climate trends	Source
The significance of climate change needs to be considered in the multi-causal context of its interactions with other non-climate sources of change and stress (e.g. water scarcity, governance structures, institutional and jurisdictional fragmentation, limited revenue streams for public sector roles, resource constraints, or inflexible land use patterns)	W 7.4.2 I 6.7.5
Different development paths may increase or decrease vulnerabilities to climate-change impacts	W 7.7
Neglect by policy-makers and under-investment in infrastructure and services has negatively affected rural areas	I 1.3.4.
Policy neglect specifically disfavours rural women	I 1.3.4.
Assessment of climate change impacts on agriculture has to be undertaken against a background of demographic and economic trends in rural areas	E 5.3.2
Global numbers of people at risk from hunger will be affected by climate change, but more by socioeconomic trends as captured in the difference between the SRES scenarios	E 5.6.5
Specific characteristics of smallholder agriculture	
Subsistence and smallholder livelihood systems suffer from a number of non-climate stressors, but are also characterized for having certain resilience factors (efficiencies associated with the use of family labour, livelihood diversity to spread risks)	E 5.3.2
Traditional knowledge on agriculture and natural resources is an important resilience factor	I 2.1.2, 3.2.2, 3.2.3 E 5.3.2 CC4
The combination of stressors and resilience factors gives rise to complex and locally specific impacts, resistant to modelling	E 5.4.7 W 7.2, 7.4, 7.5
Impacts on agriculture and agricultural trade	
In low-latitude regions, temperature increases of 1-2°C are likely to have negative impacts on yields of major cereals. Further warming has increasingly negative impacts in all regions	E 5.4.2
Increases in global mean temperatures (GMTs) of 2-3°C might lead to a small rise or decline (10-15%) in food (cereals) prices, while GMT increases in the range of 5.5°C or more might result in an increase in food prices of, on average, 30%	E 5.6.1
Forestry	
Loss of forest resources through climate change may affect 1.2 billion poor and forest-dependent people, including through impacts on Non-Timber Forest Products.	E 5.4.5
Valuation	
Robust valuation of climate change impact on human settlements is difficult, and social and environmental costs are poorly captured by monetary metrics: non-monetary valuation methods should be explored	W 7.4.3, 7.5, I 8.2.5
Adaptation	
The need and the capacity to adapt vary considerably from region to region, and from farmer to farmer	I 1.3.3
Adaptation actions can be effective in achieving their specific goals, but they may have other (positive or negative) effects, including resource competition	I 6.7.5
Diversification of agricultural and non-agricultural livelihood strategies is an important adaptation trend, but requires institutional support and access to resources	E 5.5.1, 5.5.2
The effectiveness of adaptation efforts is likely to vary significantly between and within regions, depending on geographic location, vulnerability to current climate extremes, level of economic diversification and wealth, and institutional capacity	I 6.8
Multi-stakeholder processes are increasingly important with respect to climate change adaptation	I 7.5.3
Links between adaptation and mitigation	
Mitigation and adaptation policies are in many cases, and certainly for agriculture, closely linked	K 18.4.3, 18.7.1 E 5.4.1, 5.4.2, 5.6.5 W 7.1, 7.7

Sources: W = Wilbanks *et al.* 2007; E = Easterling *et al.* 2007; I = McIntyre *et al.* 2009; K = Klein *et al.* 2007, CC4 = Cross-Chapter Case Study C4 “Indigenous knowledge for adaptation to climate change” in AR4 (Parry *et al*. 2007).

Table 9-3: Major demographic, poverty-related, economic, governance, and environmental trends in rural areas of developed and developing countries.

	Developed countries	**Developing countries**
Demographic Trends	Rural population accounts for 22.3% of the total population (or about 276 million people) (UN-DESA Population Division, 2012). Rural areas account for 75% of land area in OECD countries (OECD 2006). Rural population has peaked (absolute numbers) in Europe and North America. Rural depopulation in some places, but also counter-urbanization with people moving from urban to rural areas elsewhere.	Rural population accounts for 50.3% of the total population (or about 2.5 billion people) in less developed countries (excluding LDCs), 71.5% (or about 608 million people) in the LDCs (UN-DESA Population Division, 2012) Rural population has already peaked in Latin America and Caribbean, East and South East Asia; expected to peak around 2025 in Middle East, North Africa, South and Central Asia; around 2045 in sub-Saharan Africa.
Dependence on agriculture	Agriculture accounts for only 13% of rural employment in the EU (2006), and less than 10% on average across developed countries; however, has a strong indirect influence on rural economies. Increased competition as a result of economic globalization has resulted in agriculture no longer being the main pillar of the rural economy in Europe. Economic policies are primary drivers with social re-composition and economic restructuring taking place.(Marsden, 1999, Lopez-i-Gelats, *et al.*, 2009)	Proportion of rural population engaged in agriculture declining in all regions (Figure 9-2). Agriculture still provides jobs for 1.3 billion smallholders and landless workers (World Bank, 2008). Non-agricultural including labour-based and migration-based livelihoods increasingly existing alongside (and complementing) farm-based livelihoods. Agricultural initiatives and growth still important for adaptation and for small holders in Africa and Asia; (Osbahr *et al.*, 2008; Collier *et al.*, 2008; Kotir, 2011)
Poverty and Inequality	Per capita GDP in rural areas of OECD countries is only 83% of national average (but significant variation within and between countries): driven by out-migration, aging, lower educational attainment, lower productivity of labour, low levels of public services.(OECD, 2006)	Rates of poverty (percentage of population living on less than US $ 2/day) and extreme poverty (percentage of population living on less than US $ 1.25/day) falling in rural areas in most parts of the world; but rural poverty and rural extreme poverty rising in sub-Saharan Africa. Recent price hikes and volatility exacerbated hunger and malnutrition among rural households many of which are net-food buyers (FAOSTATS, 2013). Hunger and malnutrition prevalent among rural children in South Asia and Sub-Saharan Africa (UN, 2010; IFAD, 2010; World Bank, 2007).Figure 9-2 and Table 9-3

Table 9-3 (continued)

Economic, Policy, Governance Trends	Shift from agricultural (production) to leisure (consumption) activities; focus on broader amenity values of rural landscapes for recreation, tourism, and forests, ecosystem services. (Bunce, 2008; OECD, 2006; Rounsevell *et. al.*, 2006) Agricultural subsidies under pressure from international trade negotiations and domestic budgetary constraints. As a result of recent price hikes, domestic price support has been lowered in OECD countries. New policy approach in OECD countries that focuses on investments and targets a range of rural economic sectors and environmental services.	Interconnectedness and economic openness in rural areas have encouraged shifts to commercial agriculture, livelihoods diversification and aid knowledge transfers (section 9.3.3). Interlinkages between land tenure, food security and biofuel policies impact rural poverty (see Chapter 7, section 7.1 and 7.3.2 for further details) Decentralization of governance and emergence of rural civil society. Movements towards land reform in some parts of Asia (Kumar, 2010). Emergence of economies in transition, characterised in places by co-existence of leading and lagging regions; political and democratic decentralization expanding leading to increasing complexity of policy (World Bank, 2007).
Environmental Degradation	Different socio-economic scenarios have varying impacts on land use and agricultural biodiversity (Reidsma *et al.*, 2006).	Resource degradation, environmentally fragile lands subject to overuse and population pressures, exacerbate social and environmental challenges. Multiple stressors increase risk, reduce resilience and exacerbate vulnerability among rural communities from extreme events and climate change impacts (Chapter 13, Section 13.2.6).
Rural-Urban Linkages and Transformations	Changes in land-use and land-cover patterns at urban-rural fringe affected by new residential development, local government planning decisions, and environmental regulations (Brown *et al.*, 2008).	Stronger rural-urban linkages through migration, commuting, transfer of public and private remittances, regional and international trade, inflow of investment and diffusion of knowledge (through new information and communication technologies) (IFAD, 2010). Continued out-migration to urban areas by the semi-skilled and low-skilled, reducing the size of rural workforce (IFAD, 2010). Trend for migration to small and medium-sized towns (Sall *et al.*, 2010). Increased volumes of agricultural trade, growing by 5% on average (annually) between 2000-2008 (WTO, 2009). New initiatives of foreign direct investment (FDI) in agriculture in the form of large-scale land acquisitions in developing countries (Anseeuw *et al.*, 2012; World Bank, 2010).

Table 9-4: Poverty indicators for rural areas of developing countries.

	Incidence of poverty (%)		**Incidence of rural poverty (%)**		**Incidence of extreme poverty (%)**		**Incidence of extreme rural poverty (%)**		**Rural people as % of those in extreme poverty**	
	1988	2008	1988	2008	1988	2008	1988	2008	1988	2008
Developing World	69.1	51.2	83.2	80.9	45.1	27.0	54.0	34.2	80.5	71.6

* The incidence of extreme poverty and poverty is defined as percentage of people living on less than US$1.25 per day and less than US$2 per day, respectively.
Source: adapted from IFAD, 2010.

Table 9-5: Projected changes in areas suitable for production of tropical beverage crops by 2050.

Crop	**Countries**	**Change in climate to 2050**	**Change in total area by 2050**	**Change in distribution by 2050**
Coffee	Guatemala, Costa Rica, Nicaragua, El Salvador, Honduras, Mexico[5]	2.0-2.5ºC increase in temperature 5-10% decline in total rainfall	Between 38 and 89% decline in area suitable for production	Minimum altitude suitable for production rises from 600 to 1000 m.a.s.l.
	Kenya[1]	2.3ºC increase in temperature Rainfall increase from 1405mm to 1575 mm	Substantial decline in suitability of western highlands, some decline in area optimal for production in eastern highlands	Minimum altitude for production rise from 1000 to 1400 m.a.sl.
Tea	Kenya[2]	2.3ºC increase in temperature Rainfall increase from 1655mm to 1732 mm	Majority of western highlands loose suitability, while looses are compensated by gains at higher altitude in eastern highlands	Optimum altitude for production change from 1500-2100 m.a.s.l. to 2000-2300 m.a.s.l.
	Uganda[4]	2.3ºC increase in temperature Rainfall increase from 1334mm to 1394 mm	Considerable reduction in suitability for production across all areas	Optimal altitude change from 1450-1650 m.a.s.l. to 1550-1650 m.a.s.l.
Cocoa	Ghana, Ivory Coast[4]	2.1ºC increase in temperature No change in total rainfall	Considerable reduction in area suitable for production; almost total elimination in Ivory Coast	Optimal altitude changes from 100-250 m.a.s.l. to 450-500 m.a.s.l.

Sources: [1]CIAT, 2010; [2]CIAT 2011a [3]CIAT, 2011b; [4]Laderach *et al*. 2013; [5]Glenn *et al*. 2013. Projections use the A2 scenario, the projection methodology is described in Box 9-1.

Table 9-6: Illustrative sample of studies on economic value and changes in value from climate change impacts in the agriculture sector.

Findings and Estimates	**Study : Author /s**	**Country / Region and Model/ Scenario**
Annual economic loss in rice production: $ 54.17 million	Vaghefi *et al.*, 2011	Malaysia (2 degrees C rise in temperature)
GDP reduction from loss of agricultural productivity by 2080: 1.4%; welfare loss 1.7%	Zhai and Zhuang, 2009	South East Asian countries : Thailand, Vietnam, Philippines, Singapore, Malaysia, Indonesia(dynamic CGE)
Decline in foodgrain production between 2030-2050 by up to 18%	Dasgupta *et al*., 2013	India (AIB Scenario)
Annually spending for coping with adverse agricultural impacts between 2010-2050: $4.2 - $ 5 billion	ADB and IFPRI, 2009	Asia(various scenario based estimates)
Decline in farmland values for each degree Celsius of warming: 4-6000 pesos	Mendelsohn *et al.*, 2010	Mexico (Ricardian Analysis)
Fall in crop land values for rural communities: 13%	Mendelsohn *et al.*, 2007	U.S. A. (10% average increase in temperature)
Mixed effects with some improved profits Adverse impacts on farming	Mendelsohn and Reinsborough, 2007	Canada (increasing precipitation) U.S.A. (increasing temperature)
Crop losses under drought: CAN$ 7-171 per hectare	Wittrock *et al.*, 2011	Canada (Canadian Global Model 2)
Annual Agricultural losses upto $3billion Flooding increases losses	Franco *et al.*, 2011	California (B1 – low emissions and A2 – medium emissions scenarios)
Damages to agriculture, hydropower and infrastructure (including coastal areas) by 2050: $7.6 billion	World Bank, 2010a	Mozambique (Dynamic CGE model)
Decline in GDP from agriculture and linked sectors: 10% from benchmark levels	Mideksa, 2010	Ethiopia (Cline, CGCM2 and PCM)
By 2100: Total losses of $48.2 billion to gains of $ 90 billion In 2020 for 1.6% warmer and 3.7% dryer climate: net farm revenues decline by upto 25%	Dinar *et al.*, 2008	11 African countries (Ricardian analysis; various climate scenarios)
Decline in daily per capita calorie availability by upto 10% in 2050	Nelson *et al.*, 2009	Developing countries (A2 scenario; CSIRO and NCAR models)
Losses in gross value of production upto 25% (Guatemala, followed by other countries)	ECLAC, 2010a, b	Guatemala, Belize, Costa Rica, Honduras (SRES A2 and B2; Regional climate models)
Loss in incomes of farmers by: 2020: 14% 2060: 20%	Seo and Mendelsohn, 2008	South America (SRES A1; Canadian Climate Centre)
Annual damages between: 1 – 39%	Sanghi and Mendelsohn, 2008	Brazil (Climate predictions from 14 GCMs)
Varying impacts across regions; Declining agricultural crop productivity in some	Falloon and Betts, 2010	Southern Europe (IPCC AR4 climate projections; qualitative assessment)
Large variation in impacts on crops in Europe by 2050, mostly negative	Olesen *et al.*, 2011	Most affected : Hungary, Serbia, Bulgaria, Romania (Expert evaluation; climate predictions from RCMs)

Table 9-7: Examples of adaptations in the agricultural sector in different regions.

Agricultural adaptations	**Where it has been observed and source**
Modifying planting, harvesting and fertilizing practices for crops	Anchioreta in Brazil (Bonatti *et al*., 2012), semi-arid mountain regions of Bolivia (PNCC, 2007), Chile (Meza and Silva, 2009), maize and wheat crops in Argentina (Magrin et al., 2009)South Africa and Ethiopia (Bryan *et al.,* 2009), composting and coralling of livestock to collect waste in northern Burkina Faso (Barbier *et al*., 2009), Sahelian region of Mali (Adepetu and Berthe, 2007), in North West Province, Limpopo Province and KwaZulu Natal, South Africa (Thomas *et al.*, 2007)
Changing amount or area of land under cultivation	Moving winter wheat northwards and expanding rice crops (Lin *et al.*, 2005), South Africa (Bryan *et al*., 2009), expansion of fields in northern Burkina Faso (Barbier *et al.*, 2009), increase in the size of plots in the Sahelian region of Mali (Adepetu and Berthe, 2007)
Using different varieties (e.g. early maturing, drought-resistant)	Early maturing cultivars in South Brazil (Walter et al, 2010), North America (Coles and Scott, 2009), drought-tolerant in Asia (Thomas, 2008; Zhao *et al.*, 2010), South Africa and Ethiopia (Bryan *et al.*, 2009), Ghana (Gyampoh *et al*., 2008), northern Burkina Faso (Barbier *et al*., 2009), Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), in North West Province, Limpopo Province and KwaZulu Natal, South Africa (Thomas *et al*, 2007)
Diversifying crops and/or animal species	Crops in Peruvian Andes (Lin, 2011), South America (Montenegro and Ragrab, 2010), northeastern Mexico (Eakin and Appendini, 2008; Eakin and Bojorquez-Tapia, 2008), Tasmania, Australia (Smart, 2010), in KwaZulu Natal, South Africa (Thomas *et al*., 2007); cows by goats and camels in Kenya (Rivera-Ferre and López-i-Gelats , 2012)
Commercialisation of agriculture	Income generation from natural resources (e.g. fuelwood) in the Limpopo River Basin, Botswana (Dube and Sekhela, 2007), Ghana (Gyampoh *et a.l*, 2008), Limpopo Province, South Africa (Thomas *et al.*, 2007)
Water control mechanisms (including irrigation and water allocation rights)	Improved rice harvests in monsoonal Asia (Hatcho et al., 2010); adaptation for quinoa (Bolivian Altiplano), tomatoes (central Brazil) and cotton (northern Argentina (Geerts and Raes, 2009); for rice in northeast China (Lin et al, 2005); small water harvesting pits (known as zai) in improved yields and incomes due to improved soil moisture in Ethiopia (Amede*et al*., 2011;Bryan *et al*, 2009) and Burkina Faso (Hertsgaard, 2011, Barbier*et al*, 2009), in South Africa (Bryan et al, 2009), amongst rural women farmers in the Eastern Cape, South Africa (Bryan *et al*, 2009), Ghana (Gyampoh et al, 2008), dry season vegetable production through irrigation in northern Burkina Faso to enable two crop cycles (Barbier et al, 2009), Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), in Limpopo Province, South Africa (Thomas et al, 2007)
Shading and wind breaks	For coffee in Brazil, Costa Rica and Colombia (Camargo, 2010), Ethiopia (Bryan *et al,* 2009)
Conservation agriculture (e.g. soil protection, agroforestry)	Honduras, Nicaragua and Guatemala (Holt-Gimenez, 2002), Burkina Faso (Hertsgaard, 2011, Barbier *et al.*, 2009),Ethiopia (Bryan *et al*, 2009), Sahelian region of Mali (Adepetu and Berthe, 2007)
Modifying grazing patterns for herds	Arctic (Bartsch *et al.*, 2010), East Africa (Eriksen and Lind, 2009) and southern Africa (O'Farrell *et al*., 2009), moving livestock to less densely populated pastures in northern Burkina Faso (Barbier *et al*., 2009) and the Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), in North West Province, Limpopo Province and KwaZulu Natal, South Africa (Thomas *et al.*, 2007)
Providing supplemental feeding for herds/ storage of animal feed	Arctic (Forbes and Kumpula, 2009), South Africa (Bryan *et al.*, 2009), use of sorghum and hay residue for feeding livestock in northern Burkina Faso (Barbier *et al*., 2009), Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007), cutting fodder for livestock in Limpopo Province, South Africa (Thomas *et al.*, 2007)
Ensuring optimal herd size	Changing size of European reindeer herds to match pasture availability (Rees *et al.*, 2008), (, culling of livestock in Northern Nigeria (Adepetu and Berthe, 2007), selling of livestock northern Burkina Faso (Barbier *et al*., 2009) and the Sahelian region of Mali and Nigeria (Adepetu and Berthe, 2007)
Developing new crop and livestock varieties (e.g. biotechnology and breeding)	Brazil and Argentina (Marshall, 2012; Urcola *et al*., 2010), Northern Nigeria (Adepetu and Berthe, 2007)

Table 9-8: Examples of adaptations in the water sector observed in different regions.

Type	Example	Where it has been observed and source
Supply-side mechanisms	Dams	Proposed in the Volta River in Ghana (van de Giesen *et al.*, 2010).
	Reservoirs	Asia (Tyler and Fajber, 2009), particularly in areas where water stress is an issue of distribution rather than absolute shortage (Biemans *et al*., 2011; Rivera-Ferre *et al*. 2013)
	Groundwater pumping	Arid and semi-arid South America (Burte *et al.*, 2011; Döll, 2009; Kundzewicz and Döll, 2009; Zagonari, 2010)
	Groundwater recharge	Potential identified in India (Sukhija, 2008)
	Irrigation (often using water-saving technology)	Asia (Ngoundo *et al.*, 2007; Tischbein *et al.*, 2011)
	Fog interception practices	South America (Holder, 2006; Klemm *et al.*, 2012)
	Water capture	Bolivia (PNCC, 2007)
Demand-side mechanisms	Improved management, e.g. through efficiency	Asia (Kranz et al, 2010), South America (Bell *et al.*, 2011; Geerts *et al.*, 2010; Montenegro and Ragab, 2010; Van Oel *et al.*, 2010); Pampas Argentina (Quiroga and Gaggioli, 2011)
	Policies	Murray-Darling Basin Authority (MDBA) established to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011) See also box 26-3 on Australia's water policies;
	Reviewing allocation rights	Indogangetic Plains (Rivera-Ferre *et al.*, 2013b); Australia's MDBA reviewed the "exceptional circumstances" concept in drought policy (Productivity Commission, 2009);

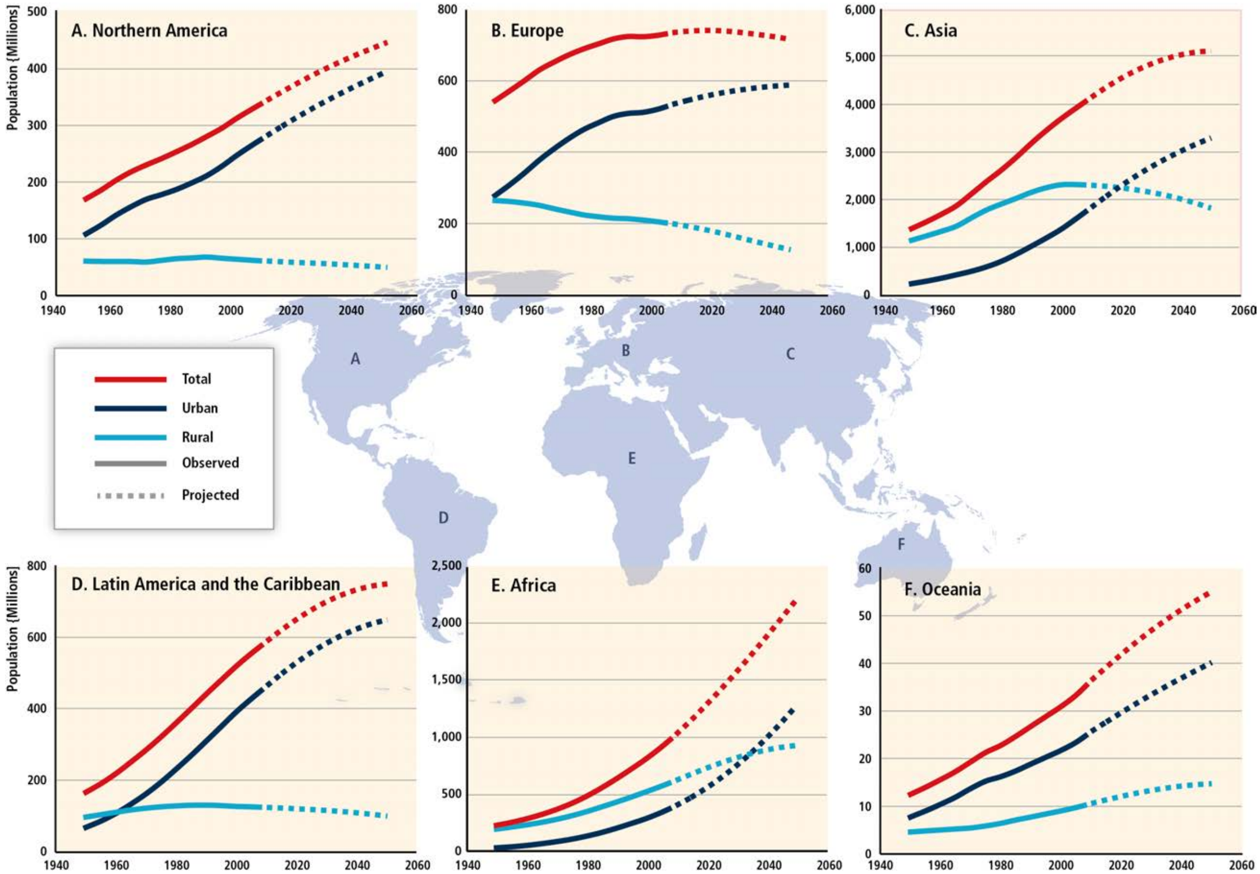

Figure 9-1: Trends in rural (blue), urban (black), and total (red) populations by region. Solid lines represent observed values and dotted lines represent projections. Source: United Nations, Department of Economic and Social Affairs/Population Division (2012).

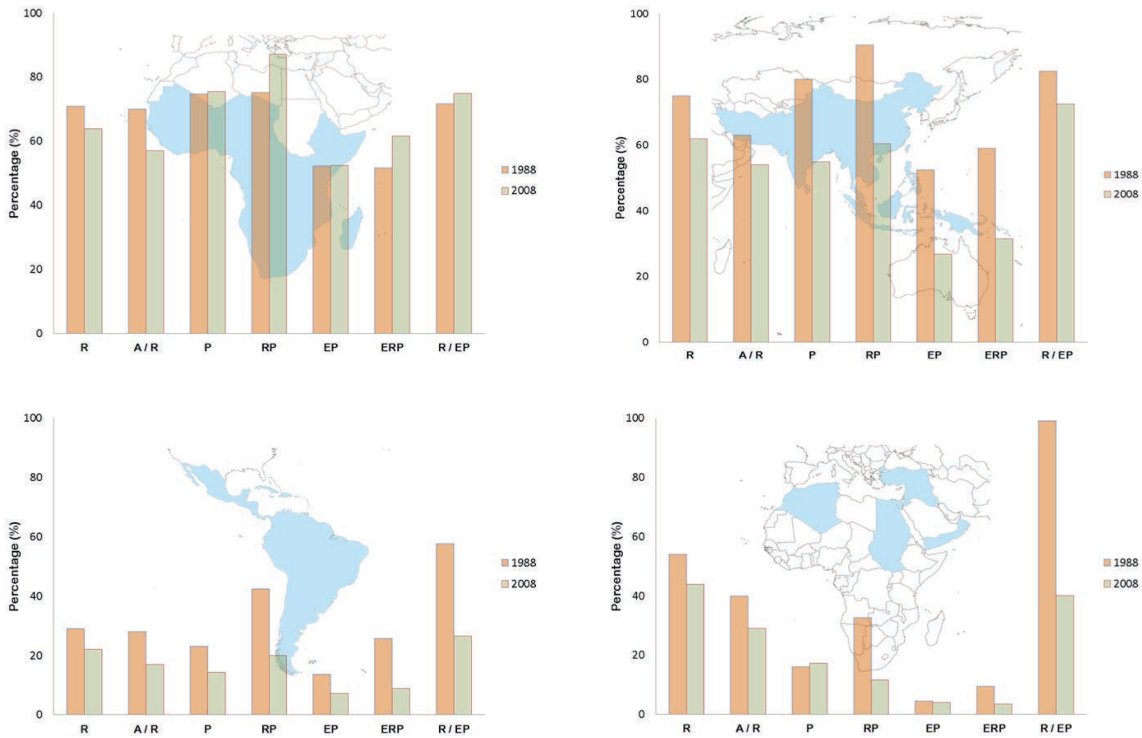

Figure 9-2: Demographic and poverty indicators for rural areas of developing countries, by region. R: rural people as percentage of population; A/R: agricultural population as percentage of rural; P: incidence of poverty; RP: incidence of poverty in rural areas; EP: incidence of extreme poverty; ERP: incidence of extreme poverty in rural areas; R/EP : rural people as percentage of those in extreme poverty. Source: Adapted from IFAD (2010).
[Illustration to be redrawn to conform to IPCC publication specifications.]

10. Key Economic Sectors and Services

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Appendices

Executive Summary

This chapter assesses the implications of climate change on economic activity in key economic sectors and services, on economic welfare, and on economic development.

For most economic sectors, the impact of climate change will be small relative to the impacts of other drivers (*high agreement, medium evidence*). Changes in population, age, income, technology, relative prices, lifestyle, regulation, governance and many other aspects of socio-economic development will have an impact on the supply and demand of economic goods and services that is large relative to the impact of climate change [10.10].

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

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

Climate change may influence the integrity and reliability of pipelines and electricity grids (*medium agreement, medium evidence*). Pipelines and electric transmission lines have been designed and operated for over a century in diverse and often extreme climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. Due to the private nature and high economic value to the energy sector, they have been designed to higher tolerance levels than most transportation infrastructure. Climate change may require changes in design standards for the construction and operation of pipelines and power transmission and distribution lines. Adopting existing technology from other geographical and climatic conditions may reduce the cost of adapting new infrastructure as well as the cost of retrofitting existing pipelines and grids to the changing climate, sea-level and weather conditions which is likely to become more intense over time. [10.2]

Climate change will have impacts, positive and negative and varying in scale and intensity, on water supply infrastructure and water demand (*high agreement, robust evidence*), but the economic implications are not well understood. Economic impacts include flooding, scarcity and cross sectoral competition. Flooding can have major economic costs, both in term of impacts (capital destruction, disruption) and adaptation (construction, defensive investment). Water scarcity and competition for water, driven by institutional, economic or social factors, may mean that water is not available in sufficient quantity or quality for some uses or locations. [10.3]

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

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

Climate change will affect insurance systems (*high agreement, robust evidence*). More frequent and/or intensive weather disasters as projected for some regions/hazards will increase losses and loss variability in various regions and challenge insurance systems to offer affordable coverage while raising more risk-based capital, particularly in low- and middle-income countries. Economic-vulnerability reduction through insurance has proven effective. Large-scale public-private risk prevention initiatives and government insurance of the non-diversifiable portion of risk offer example mechanisms for adaptation. Commercial reinsurance and risk-linked securitization markets also have a role in ensuring financially resilient insurance and risk transfer systems. [10.7]

Climate change will affect the health sector (*high agreement, medium evidence*) through increases in the frequency, intensity, and extent of extreme weather events as well as increasing demands for health care services and facilities, including public health programs, disease prevention activities, health care personnel, infrastructure, and supplies related to treatment of infectious deceases and temperature related events. [10.8]

Well-functioning markets provide an additional mechanism for adaptation and thus tend to reduce negative impacts and increase positive ones for any specific sector or country (*high agreement, medium evidence*). The impacts of climate on one sector of the economy of one country in turn affect other sectors and other countries though product and input markets. Markets increase overall welfare, but not necessarily welfare in every sector and country. [10.9]

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

Globally aggregated economic impacts of global warming are a small fraction of income up until 3°C [10.9.2, *medium evidence, high agreement*]. A global mean average temperature rise of 2.5C may lead to global aggregated economic losses between 0.2 and 2.0% of income (*medium evidence, medium agreement*) and losses increase with greater warming. Little is known about aggregate economics impacts above 3°C. Impact estimates are incomplete and depend on a large number of assumptions, many of which are disputable. Aggregate impacts hide large differences between and within countries. **The incremental impact of emitting a tonne of carbon dioxide lies between a few dollars and several hundreds of dollars per tonne of carbon [10.9.3, *robust evidence, medium agreement*]. Estimates vary strongly with the assumed discount rate.** The uncertainty about the marginal impacts is large, and more so for lower discount rates. [10.9]

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

10.1. Introduction and Context

This chapter discusses the implications of climate change on key economic sectors and services; e.g., economic activity. Other chapters discuss impacts from a physical, chemical, biological, or social perspective. Economic impacts cannot be isolated; and therefore, there are a large number of cross-references to other chapters in this chapter. In some cases, particularly agriculture, the discussion of the economic impacts is integrated with the other impacts.

Focusing on the potential impact of climate change on economic activity, this chapter addresses questions such as: how does climate change affect the demand for a particular good or service? What is the impact on its supply? How do supply and demand interact in the market? What are the effects on producers and consumers? What is the effect on the overall economy, and on welfare?

An inclusive approach was taken, discussing all sectors of the economy. Appendix A shows the list of sectors according to the International Standard Industrial Classification. This assessment reflects the breadth and depth of the state of knowledge across these sectors; many of which have not been evaluated in the literature. We extensively discuss five sectors: Energy (10.2), water (10.3), transport (10.4), tourism (10.6), and insurance (10.7). Other primary and secondary sectors are discussed in 10.5, and 10.8 is devoted to other service sectors. Food and agriculture is addressed in Chapter 7. Sections 10.2 through 10.8 discuss individual sectors in isolation. Markets are connected, however. Section 10.9 therefore assesses the implications of changes in any one sector on the rest of the economy. It also discusses the effect of the impacts of climate change on economic growth and development. Chapter 19 assesses the impact of climate change on economic welfare – that is, the sum of changes in consumer and producer surplus, including for goods and services not traded within the formal economy. This is not attempted here. The focus is on economic activity. Section 10.10 discusses whether there may be vulnerable sectors that have yet to be studied.

Previous assessment reports by the IPCC did not have a chapter on “key economic sectors and services”. Instead, the material assembled here was spread over a number of chapters. AR4 is referred to in the context of the sections below. In some cases, however, the literature is so new that previous IPCC reports did not discuss these impacts at any length.

10.2. Energy

Studies conducted since AR4 and assessed here confirm the main insights about the impacts of climate change on energy demand as reported in the SAR (Acosta *et al.*, 1995) and reinforced by the TAR (Scott *et al.*, 2001) and AR4 (Wilbanks *et al.*, 2007): ceteris paribus, in a warming world, energy demand for heating will decline and energy demand for cooling will increase; the balance of the two depends on the geographic, socioeconomic and technological conditions. The relative importance of temperature changes among the drivers of energy demand varies across regions and will change over time. Earlier IPCC assessments did not write much about energy supply, but an increasing number of studies now explore its vulnerability, impacts and the adaptation options (Ebinger and Vergara, 2011; Troccoli, 2010; USGCRP, 2009). The energy sector will be transformed by climate policy (IPCC WG3 AR5 Chapter 7) but impacts of climate changes too will be important for secure and reliable energy supply.

10.2.1. Energy Demand

Most studies conducted since AR4 explore the impacts of climate change on residential energy demand, particularly electricity (Mideksa and Kallbekken, 2010). Some studies encompass the commercial sector as well but very few deal with industry and agriculture. In addition to a few global studies based on global energy or integrated assessment models, the new studies tend to focus on specific countries or regions (Olonscheck *et al.*, 2011; Zachariadis, 2010), rely on improved methods (more advanced statistical techniques) (de Cian *et al.*, 2013) and data (both historical and regional climate projections), and many of them explicitly include non-climatic drivers of energy demand (e.g., sources). A few studies consider changes in demand together with changes in climate-dependent energy sources, like hydropower (Hamlet *et al.*, 2010).

Sorting the assessed studies according to the present climate (represented by mean annual temperature based on 1971-2000 climatology) and current income (represented by GDP per capita in 2009), the general patterns are as follows. In countries and regions with already high incomes, climate related changes in energy demand will be primarily driven by increasing temperatures. In countries/regions with high incomes and warm climates, increasing temperatures will be associated with heavier use of air conditioning. In countries/regions with high incomes and temperate and cold climates, increasing temperatures will result in lower demands for various energy forms (electricity, gas, coal, oil). Increasing incomes will play a marginal role in these countries and regions. In contrast, changes in income will be the main driver of increasing demand for energy (mainly electricity for air conditioning and transportation fuels) in present-day low-income countries in warm climates. Neither indicator is ideal because country-level mean annual temperatures for large countries can hide large regional differences and average incomes may conceal large disparities, but they help cluster the national and regional studies in the search for general finding.

At the global scale, energy demand for residential air conditioning in summer is projected to increase rapidly in the 21st century under the reference climate change scenario (medium population and economic growth globally, but faster economic growth in developing countries; no mitigation policies in addition to those in place in 2008) by the TIMER/IMAGE model (Isaac and Van Vuuren, 2009). The increase is from nearly 300 TWh in 2000, to about 4,000 TWh in 2050 and more than 10,000 TWh in 2100, about 75% of which is due to increasing income in emerging market countries and 25% is due to climate change. Energy demand for heating in winter increases too, but much less rapidly, since in most regions with the highest need for heating, incomes are already high enough for people to heat their homes to the desired comfort level (except in some poor households). In these regions, energy demand for heating will decrease.

These general patterns and especially the quantitative results of the projected shifts in energy and electricity demand can be modified by many other factors. In addition to changes in temperatures and incomes, the actual energy demand will be influenced by changes in demographics (upwards by increasing population and decreasing average household size, mixed effects from urbanization), lifestyles (upwards by larger floor area of dwellings), building codes and regulations for the design and insulation of the housing stock, the energy efficiency of heating/cooling devices, the abundance and energy efficiency of other electric household appliances, the price of energy, etc.

10.2.2. Energy Supply

Changes in various climate attributes (temperature, precipitation, windiness, cloudiness, etc.) will affect different energy sources and technologies differently. Gradual climate change (CC) will progressively affect the operation of energy installations and infrastructure over time. Possible changes in the frequency and intensity of extreme weather events (EWEs) as a result of CC represent a different kind of hazard forthem.. (EWEs are weather events that are rare at a particular place and time of the year; usually defined as rare or rarer than the 10^{th} and 90^{th} percentile of a probability density function estimated from observations – see the Glossary in this report). (Rummukainen, 2013) and (Mika, 2013) summarize recent trends and prospects relevant for the energy sector. This section assesses the most important impacts and adaptation options in both categories. Table 10-1 provides an overview.

[INSERT TABLE 10-1 HERE
Table 10-1: Main projected impacts of climate change and extreme weather events on energy supply and the related adaptation options.]

Currently, thermal power plants provide about 80% of global electricity and their share is projected to remain high in most mitigation scenarios (IEA, 2010a). Thermal power plants can be designed to operate under diverse climatic conditions from the cold Arctic to the hot tropical regions and are normally well adapted to the prevailing conditions. However, they might face new challenges and will need to respond by hard (design or structural methods) or soft (operating procedures) measures as a result of climate change.

A general impact of CC on thermal power generation (including combined heat and power) is the decreasing efficiency of thermal conversion as a result of rising temperature that cannot be offset per se. Yet there is much room to improve the efficiency of currently operating subcritical steam power plants (IEA, 2010b). As new materials allow higher operating temperatures in coal-fired power plants (Gibbons, 2012), supercritical and ultra-supercritical steam-cycle plants (operating at much higher pressure and temperature conditions than conventional power plants) will reach even higher efficiency that can more than compensate the efficiency losses due to higher temperatures. Yet in the absence of CC, these efficiency gains from improved technology would reduce the costs of energy, so there is still a net economic loss due to CC. Another problem facing thermal power generation in many regions is the decreasing volume and increasing temperature of water for cooling, leading to reduced power generation, operation at reduced capacity and even temporary shutdown of power plants (Hoffmann *et al.*, 2010; IEA, 2012; Ott and Richter, 2008; Sieber, 2013). Both problems will be exacerbated if CO_2 capture and handling equipment is added to fossil-fired power plants: energy efficiency declines by 8-14 % and water requirement per MWh electricity generated can double (IPCC, 2005). Using partial equilibrium river basin models, (Hurd *et al.*, 2004; Strzepek *et al.*, 2013) estimate USA welfare loses due to thermal cooling water changes at $622 million per year up to 2100, a 6.5 % welfare loss in the energy sector. (Van Vliet *et al.*, 2012) find that the southeastern United States, Europe, eastern China, southern Africa and southern Australia could potentially be affected by reduced water available for thermoelectric power and drinking water, inducing changes to dry or hybrid cooling (with concomitant loss in electric output), or plant shut downs, with associated impacts on local and regional economic activity.

Adaptation possibilities range from relatively simple and low-cost options like exploiting non-traditional water sources and re-using process water to measures like installing dry cooling towers, heat pipe exchangers and regenerative cooling (De Bruin *et al.*, 2009; Ott and Richter, 2008), all which increase costs. Water use regulation, heat discharge restrictions and occasional exemptions might be an institutional adaptation (Eisenack and Stecker, 2012). While it is easier to plan for changing climatic conditions and select the site and the conforming cost-efficient cooling technology for new builds, response options are more limited for existing power plants, especially for those towards the end of their economic lifetime.

CC impacts on thermal efficiency and cooling water availability affect nuclear power plants as well but the safety regulations are stricter than for fossil-fired plants (Williams and Toth, 2013). A range of alternative cooling options are available to deal with water deficiency, ranging from re-using wastewater and recovering evaporated water (Feeley III *et al.*, 2008) to installing dry cooling (EPA, 2001).

The implications of EWEs for nuclear plants can be severe if not properly addressed. Reliable interconnection (onsite power and instrumentation connections) of intact key components (reactor vessel, cooling equipment, control instruments, back-up generators) is indispensable for the safe operation and/or shutdown of a nuclear reactor. For most of the existing global nuclear fleet, a reliable connection to the grid for power to run cooling systems and control instruments in emergency situations is another crucial item (IAEA, 2011). Several EWEs can damage the components or disrupt their interconnections. Preventive and protective measures include technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown) (Williams and Toth, 2013).

Hydropower is by far the largest of renewable energy sources in the current electricity mix. It is projected to remain important in the future, irrespective of the climate change mitigation targets in many countries (IEA, 2010a; IEA, 2010b). The resource base of hydropower is the hydrologic cycle driven by prevailing climate and topology. The former makes the resource base and hence hydropower generation highly dependent on future changes in climate and related changes in extreme weather events (Ebinger and Vergara, 2011; Mukheibir, 2013).

Assessing the impacts of climate change on hydropower generation is a highly complex. A series of non-linear and region-specific changes in mean annual and seasonal precipitation and temperatures, the resulting evapotranspiration losses, shifts in the share of precipitation falling as snow and the timing of its release from high elevation, and the climate response of glaciers make resource estimates difficult (see Chapters 2 and 3) while regional changes in water demand due to changes in population, economic activities (especially irrigation demand for agriculture) present competition for water resources that are hard to project (see Section 10.3). Further complications stem from the possibly increasing need to combine hydropower generation with changing flood control and ecological (minimum dependable flow) objectives induced by changing climate regimes. For hydropower locations, adaption to climate change to maintain output has been reported; in Ethiopia, (Block and Strzepek, 2012) report that capital expenditures through 2050 may either decrease by ~3% under extreme wet scenarios, or increase by up to 4% under a severe dry scenario. In the Zambezi river basin, hydropower may fall by 10% by 2030, and by 35% by 2050 under the driest scenario (Strzepek *et al.*, 2012). Lower generation is *likely* in the upstream powerstations of the Zambezi basin and increases are *likely* downstream (Fant *et al.*, 2012).

Focusing on the possible impacts of CC on hydroelectricity and the adaptation options in the sector in response to the changes in the amount, the seasonal and inter-annual variations of available water, and in other demands, the conclusion from the literature is that the overall impacts of CC and EWEs on hydropower generation by 2050 is expected to be slightly positive in most regions (e.g., in Asia, by 0.27%) and negative in some (e.g., in Europe, by -0.16%), with diverging patterns across regions, watersheds within regions and even river basins within watersheds (IPCC, 2011). Adaptation responses and planning tools for long-term hydrogeneration may need to be enhanced to cope with slow but persistent shifts in water availability. Short-term management models may need to be enhanced to deal with the impacts of EWEs. A series of hard (raising dam walls, adding bypass channels) and soft (adjusting water release) measures are available to protect the related infrastructure (dams, channels, turbines, etc.) and optimize incomes by timing generation when electricity prices are high (Mukheibir, 2013).

Solar energy is expected to increase from its currently small share in the global energy balance across a wide range of mitigation scenarios (IEA, 2008; IEA, 2009; IEA, 2010a; IEA, 2010b). The three main types of technologies for harnessing energy from insolation include thermal heating (TH) (by flat plate, evacuated tube and unglazed collectors), photovoltaic (PV) cells (crystalline silicon and thin film technologies) and concentrating solar power (CSP) (power tower and power trough producing heat to drive a steam turbine for generating electricity). The increasing body of literature exploring the vulnerability and adaptation options of solar technologies to CC and EWEs is reviewed by (Patt *et al.*, 2013).

All types of solar energy are sensitive to changes in climatic attributes that directly or indirectly influence the amount of insolation reaching them. If cloudiness increases under climate change (see Chapters 11 and 12 of the WGI report), the intensity of solar radiation and hence the output of heat or electricity would be reduced. Efficiency losses in cloudy conditions are less for technologies that can operate with diffuse light (evacuated tube collectors for TH, PV collectors with rough surface). Since diffuse light cannot be concentrated, CSP output would cease under cloudy conditions but the easy and relatively inexpensive possibility to store heat reduces this vulnerability if sufficient volume of heat storage is installed (Khosla, 2008; Richter *et al.*, 2009).

The exposure of sensitive material to harsh weather conditions is another source of vulnerability for all types of solar technologies. Windstorms can damage the mounting structures directly and the conversion units by flying debris, whereby technologies with smaller surface areas are less vulnerable. Hail can also cause material damage and thus reduced output and increased need for repair. Depending on regional conditions, strong wind can deposit sand and dust on the collectors' surface, reducing efficiency and increasing the need for cleaning.

CC and EWE hazards per se do not pose any particular constraints for the future deployment of solar technologies. Technological development continues in all three solar technologies towards new designs, models and materials. An objective of these development efforts is to make the next generation of solar technologies less vulnerable to existing physical challenges, changing climatic conditions and the impacts of EWEs. Technological development also results in a diverse portfolio of models to choose from according to the climatic and weather characteristics of the deployment site. These development efforts can be integrated in addressing the key challenge for solar technologies today: reducing the costs.

Harnessing wind energy for power generation is an important part of the climate change mitigation portfolio in many countries. Assessing the possible impacts of CC and EWEs and identifying possible adaptation responses for wind energy is complicated by the complex dynamics characterizing this generation source. Relevant attributes of climate are expected to change; the technology is evolving (blade design, other components); see (Barlas and Van Kuik, 2010; Kong *et al.*, 2005); there is an increasing deployment offshore and a transition to larger turbines (Garvey, 2010) and to larger sites (multi megawatt arrays) (Barthelmie *et al.*, 2008).

The key question concerning the impacts of a changing climate regime on wind power is related to the resource base: how climate change will rearrange the temporal (inter- and intra-annual variability) and spatial (geographical distribution) characteristics of the wind resource. In the next few decades, wind resources (measured in terms of multi-annual wind power densities) are estimated to remain within the ±50% of the mean values over the past 20 years in Europe and North America (Pryor and Barthelmie, 2010). The wide range of the estimates results from the circulation and flow regimes in different General Circulation Models (GCMs) and regional climate models (RCMs) (Bengtsson *et al.*, 2006; Pryor and Barthelmie, 2010). A set of four GCM-RCM combinations for the period 2041-2062 indicates that average annual mean energy density will be within ±25% of the 1979-2000 values in all 50 km grid cells over the contiguous USA (Pryor and Barthelmie, 2013; Pryor *et al.*, 2011). Yet, little is known about changes in the inter-annual, seasonal or diurnal variability of wind resources.

Wind turbines already operate in diverse climatic and weather conditions. As shown in Table 10-1, siting, design and engineering solutions are available to cope with various impacts of gradual changes in relevant climate attributes over the coming decades. The requirements to withstand extreme loading conditions resulting from climate change are within the safety margins prescribed in the design standards, although load from combinations of extreme events may exceed the design thresholds (Pryor and Barthelmie, 2013). In summary, the wind energy sector does not face insurmountable challenges resulting from climate change.

In the coal fuel cycle, vulnerability in mining depends on the mining method. Surface mining might be particularly affected by high precipitation extremes and related floods and erosion, and temperature extremes, especially extreme cold that might encumber extraction for some time, whereas impacts on coal cleaning and operation of underground mines will probably be less severe (Ekman, 2013). Changes in drainage and run-off regulation for on-site coal storage as well as in coal handling might be required due to the increased moisture content of coal and more energy might be required for coal drying before transportation (CCSP, 2007). At the back end of the fuel cycle, the management of fly-ash, bottom ash and boiler slag may need to be modified in response to changes in some EWE patterns like wind, precipitation and floods. Impacts on biomass-based energy sources are discussed in Chapter 7 of this report.

Climate and weather related hazards in the oil and gas sector include tropical cyclones with potentially severe effects on off-shore platforms and on-shore infrastructure as well, leading to more frequent production interruptions and evacuation (Cruz and Krausmann, 2013). Gradual changes in air temperature and precipitation are projected to generate risk and opportunities for the oil and gas industry. For example, new areas for oil and gas exploration could open in the Arctic, potentially increasing the technically recoverable resource base (Cruz and Krausmann, 2013). Reduced sea ice thickness and coverage might open new shipping routes, thus reducing shipping costs, while ice scour and ice pack loading on marine structures would increase. However, most changes involve increased risks, such as thawing permafrost would increase construction costs on unstable ground relative to ice-based construction, while thaw subsidence would trigger increased maintenance costs. Sea level rise and coastal erosion would degrade coastal barriers, damage facilities and trigger relocation (Dell and Pasteris, 2010).

10.2.3. Transport and Transmission of Energy

Primary energy sources (coal, oil, gas, uranium), secondary energy forms (electricity, hydrogen, warm water) and waste products (CO_2, coal ash, radioactive waste) are transported in diverse ways to distances ranging from a few to thousands of kilometres. The transport of energy-related materials by ships (ocean and inland waters), rail and road are exposed to the same impacts of climate change as the rest of the transport sector (see Section 10.4). This subsection deals only with transport modes that are unique to the energy sector (power grid) or predominantly used by it (pipelines). Table 10-2 provides an overview of the impacts of CC and EWEs on energy transmission, together with the options to reduce vulnerability.

[INSERT TABLE 10-2 HERE
Table 10-2: Main impacts of climate change and extreme weather events on pipelines and the electricity grid.]

Pipelines play a central role in the energy sector by transporting oil and gas from the wells to processing and distributing centres to distances from a few hundred to thousands of kilometres. With the potential spread of CO_2 capture and storage (CCS) technology, another important function will be to deliver CO_2 from the capture site (typically fossil power plants) to the storage site onshore or offshore. Pipelines have been operated for over a century in diverse climatic conditions on land from hot deserts to permafrost areas and increasingly at sea. This implies that technological solutions are available for the construction and operation of pipelines under diverse geographical and climatic conditions. Yet adjustments may be needed in existing pipelines and improvements in the design and deployment of new ones in response to the changing climate and weather conditions.

In addition to reduced line-heating and dilution needs due to reduced viscosity of liquid fuels under warmer temperatures, pipelines will be mainly affected by secondary impacts of climate change: sea-level rise in coastal regions, melting permafrost in cold regions, floods washing away infrastructure, landslides triggered by heavy rainfall and bushfires caused by heat waves or extreme temperatures in hot regions. A proposed way to reduce vulnerability to these events is to amend land zoning codes, risk based design and construction standards for new pipelines, and structural upgrades to existing infrastructure (Antonioni *et al.*, 2009; Cruz and Krausmann, 2013).

Due to the very function of the electricity grid to transmit power from generation units to consumers, the bulk of its components (overhead lines, substations, transformers) are located outdoors and exposed to EWE. The power industry has developed numerous technical solutions and related standards to protect assets and provide reliable electricity supply under existing climate and weather conditions worldwide. However, these assets and the reliability of supply may be vulnerable to changes in the frequency and intensity of EWEs under changing climate conditions (DOE, 2013).

Higher average temperatures increase transmission efficiency and reduce current carrying capacity, but this effect is relatively small compared to the physical and monetary damages that can be caused by EWEs (Ward, 2013). Historically, high wind conditions, including storms, hurricanes and tornados, have been the most frequent cause of grid disruptions (mainly due to damages to the distribution networks); and, more than half of the damage was caused by trees (Reed, 2008). Other impacts include freezing precipitation, ice and winter storms, wildfires caused by higher temperatures, less precipitation and increased tree death caused by pests. If the frequency and power of high wind conditions, as well as extreme precipitation events, will increase in the future, vegetation management along existing power lines, rerouting new transmission lines along roads or across open fields or moving them underground might help reduce related risks. An important institutional option is to redefine technical standards to provide incentives for grid operators to implement appropriate adaptation measures. Such measures are cheaper to implement as part of the maintenance-renewal cycle than as independent retrofit measures.

The economic importance of a reliable transmission and distribution network is highlighted by the fact that the damage to customers tends to be much higher than the price of electricity not delivered (lost production, electricity enabled commerce, service delivery, food spoilage, lost or restricted water availability). Losses can be minimized through efficient rationing of electricity (de Nooij *et al.*, 2009) if generation is the limiting factor. Designing and building climate-resilient infrastructure will depend on technical standards, market governance, and the type and degree of liberalization and deregulation of grid services.

10.2.4. Macroeconomic Impacts

Most economic research related to climate change impacts on the energy sector has focused on mitigation rather than the economic implications of climate change itself. Table 10-3 summarizes the recent studies on the economic implications of climate change and extreme weather impacts in the energy sector.

[INSERT TABLE 10-3 HERE
Table 10-3: Economy-wide implications of impacts of climate change and extreme weather on the energy sector.]

Assessing across a broad array of studies that focus on different regions and regional divisions, examine different climate change impacts, include a different mix of sectors, model different timeframes, make different assumptions about adaptation, and employ different types of models with different output metrics leads to the overall conclusion that the macroeconomic impact of climate change on energy demand is *likely* to be minimal in developed countries (Aaheim *et al.*, 2009; Bosello *et al.*, 2007a; Bosello *et al.*, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010a; Jochem *et al.*, 2009; Jochem *et al.*, 2009).

The current literature sheds less light on the implications for developing countries and on other climate impacts in the energy sector beyond those related to changes in energy demand. Europe is the focus of most of the literature so far. Only two studies focus on developing countries: Mexico and Brazil (Boyd and Ibarraran, 2009; de Lucena *et al.*, 2010). Asia and Africa are not well represented, appearing as aggregated regions in only three global studies (Bosello *et al.*, 2007a; Bosello *et al.*, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010b). The limited results indicate that developing countries *likely* face a greater negative GDP impact with respect to climate change implications for the energy sector than developed countries, largely because of higher expected temperature changes (Aaheim *et al.*, 2009; Boyd and Ibarraran, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010b).

Despite the considerable number of potential climate change and extreme weather phenomena – higher mean temperatures, changes in rainfall patterns, changes in wind patterns, changes in cloud cover and average insolation, lightning, high winds, hail, sand storms and dust, extreme cold, extreme heat, floods, drought, fire, and sea-level rise – and their potential impacts on electricity generation and transmission systems, fuel infrastructure and transport systems, and energy demand (Williams, 2013) – the range of impacts modeled in the literature (Table 10-3) is quite limited. Most studies consider changing energy demand (specifically, changes in electricity and fuel consumption for space heating/cooling) resulting from rising temperatures as the only or primary climate change impact. These studies draw upon recent literature refining the relationship between climate change and energy demand: the demand for natural gas and oil in residential and commercial sectors tends to decline with climate change because of less need for space heating, and demand for electricity tends to increase because of greater need for space cooling (Eskeland and Mideksa, 2010; Gabrielsen *et al.*, 2005; Kirkinen *et al.*, 2005; Mansur *et al.*, 2005; Mideksa and Kallbekken, 2010; Rübbelke and Vögele, 2010).

Studies using a computable general equilibrium (CGE) model that consider only climate impacts in the energy sector find that the effect on GDP in 2050 is in the range of -0.3% to 0.03% (Bosello *et al.*, 2007a) and -1.3% to -0.6% (Jochem *et al.*, 2009). These findings are largely consistent despite the fact that (Bosello *et al.*, 2007a; Bosello *et al.*, 2009) are global studies that model only the change in demand due to rising temperatures, whereas (Jochem *et al.*, 2009) focus on the EU and model the change in demand plus six other climate impacts.

Studies using CGE models that examine the aggregate changes in GDP brought on by climate impacts in energy and several other sectors have also primarily found similar shifts in GDP. (Aaheim *et al.*, 2009) conclude that in 2100 in cooler regions in the EU, GDP changes by -1% to -0.25% and in warmer regions changes by -3% to -0.5%. (Boyd and Ibarraran, 2009) project a -3% change in GDP in 2026 for Mexico, consistent with the warmer regions modeled by (Aaheim *et al.*, 2009). Roughly consistent with each other, (Aaheim *et al.*, 2009; Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) find GDP impacts for the predominantly cooler regions of Japan, the EU, EEFSU, and Rest of Annex I as having a "significant positive impact", while the predominantly warmer regions of the USA, EEx (China/India, Middle East/Most of Africa/Mexico/parts of Latin America), and the Rest of the World have a "significantly negative impact." (Jorgenson *et al.*, 2004) find that overall GDP impacts are -0.6% to 0.7% in 2050 for the United States, which stands in contrast to (Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) with a "significantly negative impact" in the United States.

Several CGE studies attempt to evaluate how adaptation changes in the energy sector impact GDP but do not examine specific adaptation options since CGE models lack the necessary technological detail. They make general assumptions about the effectiveness of adaptation policy in reducing climate impacts. (Jorgenson *et al.*, 2004) find that pessimistic assumptions about adaptation imply a 0.6% reduction in GDP in 2050 but optimistic assumptions lead to a 0.7% gain in GDP. (Aaheim *et al.*, 2009) conclude that adaptation can mitigate the costs of climate change by 80% to 85%, and (Boyd and Ibarraran, 2009) find that adaptation can shift a 3% GDP loss in 2026 in Mexico to a gain in GDP of 0.33%.

Partial equilibrium models, by their nature, do not have a full macroeconomic representation and therefore rarely report changes in GDP. Instead, these models focus on details in the energy sector, such as price and quantity effects for fuels and electricity (and the mix of generation). For example, (Rübbelke and Vögele, 2013) conclude that the short-term effects of climate-related problems affecting water cooling and hydropower production can have negative distributional effects. (de Lucena *et al.*, 2010) find that rising temperature and changing precipitation lead to the need for an additional 153 – 162 TWh per year by 2035 with a capital investment of $48 to $51 billion.

(Golombek *et al.*, 2011) report a 1% increase in the price of electricity for Western Europe in 2030 stemming from rising temperatures that affect demand and thermal efficiency of supply, as well as water inflow. (UNDP, 2011) finds between a 0.06% and 1.74% increase in electricity system costs for Macedonia resulting from temperature changes. (Gabrielsen *et al.*, 2005) conclude that for Nordic countries in 2040, as a result of rising temperatures that affect demand, changes in water inflow, and changes in wind speeds, the price of electricity will decline by 1%. (Koch *et al.*, 2012) conclude that thermal plant outages in Berlin resulting from heat wave-driven water temperatures that exceed regulatory limits can amount to a cumulative cost of $80 million over the period 2010 through 2050 for 2850 MW of capacity. Assuming an 80% capacity factor, the premium for high water temperatures in Berlin is $0.1 per MWh. The magnitude of change in electricity price is small in each of the previously mentioned studies that evaluate gradual temperature increases.

In contrast, studies that consider shorter-term heat waves and water shortages find considerably higher price impacts. (Bye *et al.*, 2008) consider a hypothetical water shortage scenario – 25% lower inflow over 2 years – in Nordic countries and conclude that the price of electricity can double over a 2 year period and then return to normal as water flow returns. (McDermott and Nilsen, 2013) find more generally that electricity prices in Germany increase by 1% for every degree that water temperatures rise above 25°C and by 1% for every 1% that river levels fall. (DOE, 2009) also finds that a drought scenario can lead to average monthly electricity prices that are 8.1% (November) to 24.1% (July) higher. (Pechan and Eisenack, 2013) find that an equivalent of the 2006 German heat wave can result in an increase in electricity prices of 11% or even 24% (affected plants running at minimum output) and 50% (affected plants at zero output).

10.2.5. Summary

The balance of evidence emerging from the literature assessed in this section suggests that climate change per se will *likely* increase the demand for energy in most regions of the world. At the same time, increasing temperature will decrease the thermal efficiency of fossil, nuclear, biomass, and solar power generation technologies (Mideksa and Kallbekken, 2010). However, gradual temperature-induced impacts on energy supply will probably make a relatively small contribution to the cost of energy and electricity. Acute heat waves and droughts can have a much greater, albeit short-term, impact on electricity prices. Additionally, many other potential climate impacts on energy supply are possible but have not been fully studied, leading to cost estimates to date, based only on temperature change, that underestimate the full cost of climate change on energy supply. Pre-existing subsidies may distort signals for adaptation. CC impacts on energy supply will be part of an evolving picture dominated by technological development in the pursuit for safer, cheaper and more reliable energy sources and technologies as well as mitigation and adaptation response pathways.

Given the limitations in the literature, sweeping conclusions about results may be premature on macroeconomic implications. However, some narrow conclusions are possible. The change in GDP due to temperature-induced changes in energy demand – even if combined with other climate impacts – range from -3% to 1.2%. (Jochem *et al.*, 2009) is the most detailed and comprehensive study, and report only a 1.3% drop in GDP in 2050 in Europe due to at least seven climate impacts in the energy sector. The GDP impact in warmer regions tends to be greater than in cooler regions, which benefit from less need for space cooling. Energy related economic impact for developing countries is anticipated to be negative, and positive in developed countries. Adaptation within the energy sector can lower the cost of climate change, but these results may be driven largely by assumption since specific policies have not been modeled in these macroeconomic impact studies. Results from some of the partial equilibrium models suggests that CGE modeling studies, which largely focus on changes in energy demand, may be neglecting some potentially costly impacts from extreme weather events like drought (see, e.g., Box CC-WE), which, if modeled, may lead to greater GDP losses than reported thus far in the literature.

Much research is still needed to understand the implications of climate change and extreme weather on the energy sector and to identify cost-effective adaptation options. The best understood area is the implications of climate on energy demand. A comprehensive evaluation of a full range of supply-side climate change impacts and adaptation options for all aspects of energy infrastructure is needed. This information will lead improved assessment of climate impacts due to the use of better, empirically-based assumptions about the relationship of climate impacts and the economy, as well as about the effectiveness of adaptation options.

10.3. Water Services

This section focuses on economic aspects of climate change in water-intensive sectors and infrastructure to provide water services. The climate change impacts on biophysical water system, including the engineering aspects of water infrastructure, are assessed in Chapter 3. There is limited set of studies published in this area and conclusions are limited by the scope of information to date.

10.3.1. Water Infrastructure and Economy-wide Impacts

Between the 1950s and the 1990s, the annual economic losses from large extreme events, including floods and droughts, increased tenfold, with developing countries being hardest hit (Kabat *et al.*, 2003). Over the past few decades, flood damage constitutes about a third of the economic losses inflicted by natural hazards worldwide (Munich Re, 2005). The economic losses associated with floods worldwide have increased by a factor of five between the periods 1950-1980 and 1996-2005 (Kron and Berz, 2007). In 1990-1996 alone, there were six major floods throughout the world in which the number of fatalities exceeded 1,000, and 22 floods with losses exceeding US$1 billion each (Kabat *et al.*, 2003). Although these increases are primarily due to several non-climatic drivers, climatic factors are also partly responsible (Kundzewicz *et al.*, 2007). SREX Chapter 4 provides a comprehensive look at the impacts of extreme events on water supply (IPCC, 2012) and flooding at wide range of spatial scales.

Most of the studies examining the economic impacts of climate change on the water sector have been carried out at the local, national, or river-basin scale; and, the global distribution of such studies is skewed towards developed countries (Chen *et al.*, 2001; Choi and Fisher, 2003; Hall *et al.*, 2005; Hurd and Rouhi-Rad, 2013; Middelkoop *et al.*, 2001; Schreider *et al.*, 2000). In other studies, the economic impacts of climate variability on floods and droughts in developing countries were reported as substantial. These studies address climate variability; climate change may impact both mean and variability of the hydro-climatic system. The floods associated with the 1997-1998 El Niño and the drought associated with the 1998-2000 La Niña, show a cost to Kenya of 11% and 16% of GDP, respectively (Mogaka *et al.*, 2006). Floods and droughts are estimated to cost Kenya about 2.4% of GDP annually at mid-century, and water resources degradation a further 0.5% (Mogaka *et al.*, 2006). For Ethiopia, economy-wide models incorporating hydrological variability show a drop in projected GDP growth by up to 38% compared to when hydrological variability is not included (World Bank, 2006). Syria is projected to experience reduction in economy-wide growth and incomes of urban households (Breisinger *et al.*, 2013). However, it is not hydrological variability per se that causes the problem, but rather a lack of the necessary capacity, infrastructure, and institutions to mitigate the impacts (Grey and Sadoff, 2007). Similarly, future flood damages will depend not only on changes in the climate regime, but also on settlement patterns, land use decisions, flood forecasting quality, warning and response systems, and other adaptive measures (Changnon, 2005; Pielke and Downton, 2000; Ward *et al.*, 2008). In many developing countries, water related impacts are *likely* to be more pronounced with climate change (Chapter 3) and associated economic costs can be expected to be more substantial in the future, holding all other factors constant.

Climate change could increase the annual cost of flooding in the UK almost 15-fold by the 2080s under high emission scenarios. If climate change increased European flood losses by a similar magnitude, annual costs could increase by up to $120-150 billion, for the same high emission scenarios (ABI, 2005). (Feyen *et al.*, 2012) project average annual damage in the EU to increase to $18-28 billion by 2100 depending on the scenario, compared to $8.5 billion today. Continental US mean annual flood damages may increase by $5 billion and $12 billion in 2050 and 2100, respectively (Wobus *et al.*, 2013). (Ntelekos *et al.*, 2010) estimate a range of $7-19 billion, depending on the economic growth rate and the emissions scenarios. (Dasgupta *et al.*, 2010) report that by 2050 Bangladesh will face incremental cost to flood protection (against both sea and river floods) of $2.6 billion initial costs and $54 million annual recurring costs. (Ward *et al.*, 2008) found that the average annual costs to adapt to a 1in 50 year river flood to range from $3.5 to $6.0 billion per year for low- to upper-middle-income countries over the period 2010–50 for the A2 scenario.

10.3.2. Municipal and Industrial Water Supply

Municipal and industrial water supply economic systems are also impacted through changes in precipitation patterns and quantities. These impacts are evaluated as current costs of building in resiliency to the system to adapt to anticipated future changes. For example, the costs of adaptation to maintain supply and quality of water for municipal and industrial uses have been reported for the Assabet River near Boston (Kirshen *et al.*, 2006), Toronto (Dore and Burton, 2001) and Quito (Vergara *et al.*, 2007). Initial analysis indicates that adapatation measures may be beneficial for water infrastructure with an economic and engineering life of more than 25 years. (Nassopoulos *et al.*, 2012) suggest that neglecting to account for future climate change while designing water supply reservoirs can cost 0.2 to 2.8% of the net present value, based on analysis for Greece. For sub-Saharan Africa, adapting urban water infrastructure (storage facilities, wastewater, and additional supply infrastructure) to a 30% reduction in runoff could be $2-5 billion per year (Muller, 2007). Climate change impacts on the Berg River in South Africa are estimated to account for 15% revenue loss for the water supply provider (Callaway *et al.*, 2012). For the OECD, the cost of adaption in the water supply sector is 1-2% of base costs and would save $6-12 billion per year (Hughes *et al.*, 2010). U.S. impacts are estimated to be less than 1% of municipal and industrial welfare (Hurd *et al.*, 2004; Strzepek *et al.*, 2013). In Colorado, a 30% decrease in annual runoff will result in a 12% treatment cost increase and a 22% rise in residential costs (Towler *et al.*, 2011).

(Ward *et al.*, 2010) estimate the costs of adaptation to climate change to ensure enough raw water to meet future industrial and municipal water demand for each country to 2050. Increased demand is assumed to be met through a combination of increased reservoir yield and alternative backstop measures. The global adaptation costs are estimated to be US$12B/yr (0.04-0.06% of GDP), on top of US$73B/yr to meet the needs of development, with 83-90% in developing countries. The highest costs are in Sub Saharan Africa, and may be as high as 16% of the global total. Adding adaptive measures to water infrastructure adds 10-20% to the total costs of developing countries meeting the water related millennium goals (Ward *et al.*, 2010).

10.3.3. Wastewater and Urban Stormwater

More frequent heavy rainfall events may overload the capacity of sewer systems and water and wastewater treatment plants more often, and increased occurrences of low flows will lead to higher pollutant concentrations. It is projected for USA in 2100 that national wastewater treatment costs will increase by $0.6-8 billion per year (Henderson *et al.*, 2013). The annual costs of urban stormwater system adaptation , averaged costs over17 climate models simulating the A2 emissions scenario, is $3.0 billion per year in low- to upper-middle-income nations over the period 2010–50 (Hughes *et al.*, 2010). Adaptation costs estimates (for a 10-year, 24-hour storm in 2100) for various locations in the USA are relatively low; e.g., $135 million for Los Angeles, $7 million for Boston and $40 million for Chicago (Neumann *et al.*, 2013). Adapting bridges to altered urban floods could cost $140-250 billion in the USA through the 21st century (Wright *et al.*, 2012).

10.3.4. Inland Navigation

See 10.4.4.

10.3.5. Irrigation

Climate change impacts on the economics of irrigation reflect the anticipated change in temperature, precipitation, and agricultural demand and practices. Assessments of surface, ground and grey water irrigation supplies are addressed in Chapter 3; implications for food production are covered in Chapter 7. By 2080, the global annual costs of additional irrigation water withdrawals for currently existing irrigated land are estimated at $24-27 billion (Fischer *et al.*, 2007). The global cost of improved irrigation efficiency to maintain yields is $1.5-2.0 billion dollar per year for the A2 scenario in developing countries in 2050 (Nelson *et al.*, 2009). Adaptation to maintain agricultural production in Ethiopia would be best achieved by better soil water management with the application of integrated irrigation and drainage systems, improved irrigation efficiency and research related to on-farm practices; adaptation costs range from $68 million per year for the dry scenario dominated by irrigation, to $71 million per year under the wet scenario dominated by drainage (Strzepek *et al.*, 2010).

10.3.6. Nature Conservation

Climate change is expected to worsen many forms of water pollution, including the load of sediments, nutrients, dissolved organic carbon, pathogens, pesticides, and salt, as well as thermal pollution, increased precipitation intensity, and low flow periods (Kundzewicz *et al.*, 2007). Future water demands for nature conservation will be different than today’s (see Chapter 4). There is no published assessment of the economic implications.

10.3.7. Recreation and Tourism

Tourism and recreation use substantial amounts of water but the implications of climate-change-induced changes in tourism and recreation on water demand have yet to be quantified. See Section 10.6.

10.3.8. Water Management and Allocation

Water scarcity and competition for water, driven by institutional, economic or social factors, may mean that water assumed to be available for a sector is not and thus economic analyses at the sectoral level are crucial, inter-sectoral and economy-wide assessments are needed for comprehensive economic impacts of water services. Changes in water availability, demand and quality due to climate change would impact water management and allocation decisions. Traditionally, water managers and users have relied on historical experience when planning water supplies and distribution (Adger *et al.*, 2007; UNFCCC, 2007). Under a changing climate, existing allocations may no longer be appropriate. (Arndt *et al.*, 2012) examine the implications of alternative development paths and water allocations to suggest climate-smart development strategies in Africa; under stress situations, allocations of water to energy-generation and irrigation may have economy-wide welfare implications. Water resource related climate change impacts on the USA economy measured as cumulative undiscounted welfare changes over the 21st century range from plus (2000US$) $3 trillion for wet scenarios to minus $13 trillion under dry scenarios (Henderson *et al.*, 2013).

10.3.9. Summary

Globally, greenhouse gas induced increases in flooding and droughts may have substantial economic impacts (capital destruction, sectoral disruption) while estimates of adaptation costs (construction, defensive investment) range from relatively modest to relative high levels (see Box CC-WE).

10.4. Transport

The impact of climate change and sea level rise (SLR) on transport has received qualitative, but limited quantitative, focus in the published literature. The impact depends greatly on the climatic zone the infrastructure is in and how climate change will be manifest. There are three major zones:

Geographic Zone	Changes in Climate Expected to Impact Vulnerability
Freezing/Frost Zone	Permafrost, freeze-thaw cycles, precipitation, flooding, SLR and storms (coastal)
Temperate Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR and storms (coastal)
Tropical Zone	Precipitation intensity, flooding, maximum daily precipitation, SLR and storms (coastal)

As detailed below, several studies have explored the potential impacts of climate change on the transport sector, focusing for example on safety or disruptions of service. Quantitative, economic analyses of the impact on physical infrastructure include (Chinowsky *et al.*, 2010; Chinowsky *et al.*, 2011; Hunt and Watkiss, 2010; Larsen *et al.*, 2008) and on wider economic implications (Arndt *et al.*, 2012).

Adaptation options for each sub-sector of transport infrastructure have been studied. Existing literature includes (Chinowsky *et al.*, 2011; Savonis *et al.*, 2008) with proposed strategies ranging from technical to political, including focus on upgraded design specifications during new construction, retrofitting structures, and modified land-use planning in coastal area. Adaptation and resiliency to extreme events is of particular interest as they may have a cascading impact, in that the loss of critical infrastructure assets will negatively affect the recovery and resiliency of a community (Kirshen *et al.*, 2008a; Kirshen *et al.*, 2008b).

10.4.1. Roads

Studies on the direct effects of climate change on road networks are primarily focused on qualitative predictions and surveys concerning impacts on road durability (Eisenack *et al.*, 2012; Koetse and Rietveld, 2009; Ryley and Chapman, 2012; TRB, 2008); with some studies of the quantitative effects (Chinowsky *et al.*, 2013; Nemry and Demirel, 2012). Noted impacts from changes in precipitation and temperature include changes in required road maintenance. These quantitative studies focus on specific impacts such as maintenance in an effort to quantify the long-term costs that need to be assumed by national and regional road agencies. Examples of the metrics used include kilometers of roads lost over time, redistribution requirements of transport funds and benefits from adaptation on long-term maintenance. Chapter 8 addresses the indirect effects of climate change on roads in the areas of congestion and safety. As an example, increases in heavy precipitation events will negatively affect driving safety through decreased driver visibility and changing surface conditions (Qiu and Nixon, 2008).

Paved road degradation is directly related to heat stress that can lead to softening of the pavement as temperatures exceed design thresholds (Lavin, 2003) and an increase in the number of freeze-thaw cycles impacts both the base and pavement surface (FHWA, 2006). The melting of permafrost in northern climates, as well as increased precipitation and flooding, threaten the integrity of road base and sub-bases (Qin *et al.*, 2005). Drainage presents a specific problem for urban areas that experience rainfall above their built capacity and will influence new design standards and costs for urban transport (CCTF, 2008; Hunt and Watkiss, 2010; Lemmen and Warren, 2010). Increased fire danger from droughts could also pose a threat to roads.

Unpaved roads are vulnerable to a number of climate-based factors especially to increasingly intense precipitation, leading to wash out and disruption of service (Chinowsky and Arndt, 2012). Increased precipitation may agricultural areas may have negative economic impacts in addition to the direct impact on infrastructure. In cold climates, temporary winter roads are susceptible to warming and associated lower connectivity of rural areas and reduced economic activity in Northern climates (Mills and Andrey, 2002). Warming could imply that ice roads can no longer be maintained.

Bridges form a core component of any nation's infrastructure. However, highway bridges that cross water, ubiquitous to most highway networks, are exposed to climate changes via flood events and associated changes in long-term flow regimes. The potential disruptions that could occur due to the loss of or damage to these bridges are numerous. Estimates in the United States range from $140 to $250 billion to address adaptation requirements for bridge infrastructure over the next 50 years (Wright *et al.*, 2012). Similarly, European estimates range from $350-500 million per year to adapt bridge infrastructure (Nemry and Demirel, 2012). Once again, the potential cascading effects of these failures will affect the economic conditions of multiple sectors.

10.4.2. Rail

Rail beds are susceptible to increases in precipitation, flooding and subsidence, sea level rise, extreme events and incidence of freeze-thaw cycles (Nemry and Demirel, 2012). In Northern climates, the melting of permafrost (URS, 2010) may lead to ground settlement, undermining stability (Larsen *et al.*, 2008). Increased temperatures pose a threat to rail through thermal expansion. In urban areas, increased temperatures pose a threat to underground transport systems that will see a burden on increased need for cooling systems (Hunt and Watkiss, 2010). For example, $290 million has been allocated to finding a workable solution for increasing the capacity of London's underground cooling system (Arkell and Darch, 2006). The complexity of addressing rail infrastructure is increased through differences in design specifications, multiple types of rail and materials used, and uncertainty about the changes in future temperatures.

10.4.3. Pipeline

Increases in precipitation and temperature affect pipelines through scouring of base areas and unearthing of buried pipelines (URS, 2010), compromised stability of bases built on permafrost, and increases in necessary maintenance (TRB, 2008; URS, 2010). Temperature increase can result in thermal expansion of the pipelines, causing cracking at material connection points. In tropical areas, increased precipitation may lead to landslides that can compromise pipeline infrastructure (Sweeney *et al.*, 2005). There has been no economic assessment of the impacts.

10.4.4. Shipping

Impacts of inland navigation vary widely due to projected rise or fall in water levels. Overall, the effects on inland navigation are projected to be negative, and are region-specific.

Increased frequency of flood periods will stop ship traffic on the Rhine more often; longer periods of low flow will also increase the average annual number of days during which inland navigation is hampered or stagnates due to limited load carrying capacity of the river; channel improvements can only partly alleviate these problems (Middelkoop *et al.*, 2001). Economic impact could be substantial given the value of navigation on the Rhine (Krekt *et al.*, 2011). See Chapter 23 for more detail.

Virtually all scenarios of future climate change project reduced Great Lakes water levels and connecting channel flows, mainly because of increased evaporation resulting from higher temperatures. The potential economic impact may result in reductions in vessel cargo capacities and increases in shipping costs. The lower water levels predicted as a result of a doubling of the atmospheric carbon dioxide could increase annual transportation costs by 29%, while more moderate climate change could result in a 13 percent increase in annual shipping costs. The impacts vary across commodities and routes (Millerd, 2010).

Warming leads to increased ice-free navigation and longer shipping season, but also to lower water levels from reduced runoff (Lemmen and Warren, 2010). In cold regions, increased days of ice-free navigation and a longer shipping season could impact shipping and reduce transportation costs (Koetse and Rietveld, 2009; TRB, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010), although movement in ice waters as the Canada Arctic sea more become more difficult (Stewart *et al.*, 2007; Wilson *et al.*, 2004).

Ports will be affected by climate changes including higher temperatures, sea level rise, increasingly severe storms, and increased precipitation (Becker *et al.*, 2011; Nursey-Bray and Miller, 2012). However, (the need to prioritize) adaptation of ports has been overshadowed by a focus on potential impacts. Training of port personnel is needed to begin the adaptation process. Over $3 trillion in port infrastructure assets in 136 of the world's largest port cities are vulnerable to weather events (Potter *et al.*, 2008; UNCTAD, 2009; UNECE and UNCTAD, 2010).

Increased storminess in certain routes may raise cost of shipping through additional safety measures or longer routes that are less storm-prone (UNCTAD, 2009; UNECE and UNCTAD, 2010). Transport costs would increase or new routes sought if storms disrupt supply chains by destroying port infrastructure connecting road or rail (Becker *et al.*, 2011). Increased storminess may also affect passage through lock systems (Potter *et al.*, 2008; UNCTAD, 2009). Increased storminess may increase maintenance costs for ships and ports and result in more frequent weather-related delays.

10.4.5. Air

Hotter air is less dense. In summer months, especially at airports located at high altitudes, this may result in limitations for freight capacity, safety, and weather-related delays, unless runways are lengthened (Pejovic *et al.*, 2009; TRB, 2008). (Chapman, 2007) suggests that technological innovations will negate the challenges posed by extreme temperatures.

Increased storminess at airports, particularly those located in coastal regions, may increase the number of weather-related delays and cancellations (Lemmen and Warren, 2010; Pejovic *et al.*, 2009) and increase maintenance and repair costs (Gusmao, 2010). Clear-air turbulence will increase in the Atlantic corridor leading to longer and bumpier trips (Williams and Joshi, 2013). The impact of climate change on airport pavement is very similar to paved roads (DOT, 2002; Fortier *et al.*, 2007). The effect of temperature and increase precipitation intensity on airports imposes a risk to the entire facility if pavements are not adapted to these increases (Pejovic *et al.*, 2009).

10.5. Other Primary and Secondary Economic Activities

This section assesses the impact of climate change on primary (agriculture, mining) and secondary economic activities (manufacturing, construction), unless they are discussed elsewhere in the chapter or the report.

10.5.1. Primary Economic Activities

Primary economic activities (e.g. agriculture, forestry, fishing, mining) are particularly sensitive to the consequences of climate change because of their immediate dependence on the natural environment. In some regions, these activities dominate the economy.

10.5.1.1. Crop and Animal Production

Chapters 7 and 9 assess the impact of climate change on agriculture, including the effects on (international) markets for crops.

10.5.1.2. Forestry and Logging

Chapter 4 assesses the biophysical impact of climate change on forestry. Including adaptation in forest management, climate change will accelerate tree growth. This will reduce prices to the benefit of consumers everywhere. Low to mid latitude producers will benefit too as they switch to short-rotation forest plantations. Mid to high latitude producers will be hurt by lower prices while their productivity increases only modestly (*Adaptation of Forests and*

*People to Climate Change -- A Global Assessment Report.*2009; Lee and Lyon, 2004; Perez-Garcia *et al.*, 2002; Sohngen and Mendelsohn, 1997; Sohngen and Mendelsohn, 1998; Sohngen *et al.*, 2001). The value of the forest land in Europe would fall between 14 and 50 percent by 2100 (Hanewinkel *et al.*, 2013). Different trees will be affected differently (Aaheim *et al.*, 2011a; Aaheim *et al.*, 2011b). Higher biomass prices differentially impact different forest-based industries (Moiseyev *et al.*, 2011).

10.5.1.3. Fisheries and Aquaculture

Chapter 4 assesses the impact of climate change on freshwater ecosystems, and Chapter 5, 6 and 30 on marine ecosystems. These assessments include the effects on commercially valuable fish stocks, but exclude the effects on markets. Adaptation and markets will substantially change the effect of climate change on fisheries (Link and Tol, 2009; Yazdi and Fashandi, 2010).

(Allison *et al.*, 2009), using an indicator based approach, analyzed the vulnerability of capture fishery of 132 economies. They find, incongruously, that the sign and size of climate-driven change for particular fish stocks and fisheries are uncertain but are expected to lead to either increased economic hardship or missed opportunities for development in countries that depend upon fisheries but lack the capacity to adapt. A major part of the gross turnover of nine key fish and cephalopod species in the Bay of Biscay remains potentially unaffected by climate change (Floc'h *et al.*, 2008). In contrast, Iberian-Atlantic sardine biomass and profitability declines due to climate change (Garza-Gil *et al.*, 2011). The economic impact of climate change on fisheries is dominated by the impact of management regime and market (Eide and Heen, 2002; Eide, 2008; McGoodwin, 2007; McIlgorm, 2010; Merino *et al.*, 2010).

Ocean acidification has a range of impacts on the biological systems (Doney *et al.*, 2009), but the studies on the economic impacts of ocean acidification are rare (Cooley and Doney, 2009; Hilmi *et al.*, 2013). Using a partial equilibrium model, (Narita *et al.*, 2012) estimate the economic impact of ocean acidification on shellfish. By the turn of this century the aggregate cost could be over $100 billion.

10.5.1.4. Mining and Quarrying

Climate change will affect exploration, extraction, production, and shipping in the mining and quarrying industry (Pearce *et al.*, 2011). An increase in climate-related hazards (such as forest fires, flooding, windstorm) affects the viability of mining operations and potentially increases operating, transportation, and decommissioning costs. Most infrastructure was built based on presumption of a stable climate, and is thus not adapted to climate change (Ford *et al.*, 2010; Ford *et al.*, 2011; Pearce *et al.*, 2011). (Damigos, 2012) estimates the damages due to climate change under IPCC A1B scenarios for the period 2021-2050 of the extent of 0.8 billion US dollars for the Mediterranean Region. Note that other factors such as research and development might influence the viability of mining operations by lowering the cost of adaptation.

10.5.2. Secondary Economic Activities

10.5.2.1. Manufacturing

Climate change will impact manufacturing through three channels. First, climate change affects primary economic activities (see above), and this means that prices and qualities of inputs are different. Second, the supply chain is affected, or the quality of the product. The impact of climate change on energy demand is well understood (see 10.2). Using a biophysical model of the human body, (Kjellstrom *et al.*, 2009) project labour productivity to fall, particularly of manual labour in humid climates. Labour productivity losses will be accentuated by increased incidences of malaria and vector borne diseases. Note that the loss in labour productivity can be offset by the technological progress. (Hübler *et al.*, 2008) uphold the finding with a German case study, and (Hsiang, 2010) corroborate it with a statistical analysis of weather data and labour productivity in the Caribbean for 1970-2006.

Some manufacturing activity is location specific, perhaps because it is tied to an input or product market, and will thus have to cope with the current and future climate; other manufacturing has discretion over its location (and hence its climate). Third, climate change affects the demand for products. This is pronounced for manufactures that supply primary sectors (Kingwell and Farré, 2009) and construction material (see below). Unfortunately, there are only a few studies that quantify these effects (see Appendix A).

10.5.2.2. Construction and Housing

Climate and climate change affect construction in three ways. First, weather conditions are one of the key factors in construction delays and thus costs. Climate change will change the length of the building season. Additionally, precipitation affects the cost of construction through temporary flood protection (coffer) structures, slope stabilization management and dewatering of foundations. There are adaptation measures that may reduce some of the costs. (Apipattanavis *et al.*, 2010) show a reduction in the expected value of road construction delays and associated costs. Second, buildings and building materials are designed and selected to withstand a particular range of weather conditions. As climate changes, design standards will change too. Exterior building components including windows, roofing, and siding are all specified according to narrow environmental constraints. Climate change will introduce conditions that are outside the prescribed operating environment for many materials, resulting in increased failures of window seals, increased leaks in roofing materials, and reduced lifespan of timber or glass-based cladding materials. Similarly, the interior building systems that allow for proper airflow in a facility face significant issues with climate change. For example, the increases in temperature and precipitation will lead to increased humidity as well as indoor temperatures. This requires increased airflow in facilities such as hospitals, schools, and office buildings; that is, upgrades to air conditioning and fan units and perhaps further renovations that may be significant in scope and cost. Third, a change in the pattern of natural disasters will imply a change in the demand for rebuilding and repair. Unfortunately, these impacts have yet to be quantified (Hertin *et al.*, 2003). Note that the direction and magnitude of the effect on construction and housing costs will possibly vary geographically. Cost impacts due to changing precipitation and storms patterns (magnitude, frequency, and/or variation) will vary as these changes are expected to vary by region as well. Air to air heat exchangers, heat recovery ventilators, and dehumidifiers and other technologies may be useful in adapting indoor air quality.

10.6. Recreation and Tourism

Recreation and tourism is one of the largest sectors of the world economy. In 2011, it accounted for 9% of global expenditure, and employed 260 million people (WTTC, 2011). Supply of tourism services is the dominant activity in many regional economies.

Recreation and tourism encompass many activities, some of which are more sensitive to weather and climate than others: compare sunbathing to angling, gambling, business seminars, family visits, and pilgrimage. Climate change would affect the place, time and nature of these activities.

There is a large literature on the impact of climate change on tourism (Gössling *et al.*, 2012; Pang *et al.*, 2013; Scott *et al.*, 2012a). Some studies focus on the changes in the behavior of tourists, that is, the demand for recreation and tourism services (see 10.6.1). Other studies look at the implications for tourist operators and destinations, that is, the supply of recreation and tourism services (see 10.6.2). A few studies consider the interactions between changes in supply and demand (see 10.6.3).

10.6.1. Recreation and Tourism Demand

Conventionally, recreation does not involve an overnight stay whereas tourism does. That implies that recreation, unlike tourism, is done close to home. Whereas tourists, to a degree, chose the climate of their holidays, recreationists do not (although climate is a consideration in the choice where to live). Tourists would adapt to climate change by changing the region, timing and activities of their holidays; recreationists would adapt only timing and activities (Becken and Hay, 2007).

10.6.1.1. Recreation

There has been no research on systematic differences of recreational behaviour due to differences in climate at large spatial scales. The impact of climate change on recreation is therefore largely unknown. The economic impact is probably limited, as people will tend to change the composition rather than the level of their time and money spent on recreation. For instance, (Shaw and Loomis, 2008) argue that climate change would increase boating, golfing and beach recreation at the expense of skiing.

There are case studies that indicate the impact of climate change on recreation. (Buckley and Foushee, 2012) find that a trend toward earlier visits to US national parks between 1979 and 2008. They argue this is due to climate change, but do not rigorously test this hypothesis nor control for other explanations. (Whitehead *et al.*, 2009) find a substantial decrease in the recreational value of sea shore fishing in North Carolina due to sea level rise. (Daugherty *et al.*, 2011) conclude that climate change will make it more difficult to guarantee adequate water levels for boating and angling in artificial reservoirs. (Pouta *et al.*, 2009) project a reduction in cross-country skiing in Finland, particularly among women, the lower classes, and urban dwellers. (Shih *et al.*, 2009) find that weather affects the demand for ski lift trips. (Hamilton *et al.*, 2007) highlight the importance of “backyard snow” to induce potential skiers to visit ski slopes. One could expect people to adopt other ways of enjoying themselves but such alternatives were excluded from these studies. There are positive effects too (Richardson and Loomis, 2005). (Scott and Jones, 2006; Scott and Jones, 2007) foresee an increase in golf in Canada due to climate change, (Kulshreshtha, 2011) sees positive impacts on recreation on the Canadian Prairies, and (Coombes *et al.*, 2009) predict an increase in beach tourism in East Anglia. (Graff Zivin and Neidell, 2010) find that people recreate indoors when the weather is inclement. (Scott *et al.*, 2007) estimate the relationship between visitors to Waterton Lakes National Park and *weather* variables for eight years of monthly observations; and use this to project an increase in visitor numbers due to *climate change*. A survey among current visitors indicates that a deterioration of the quality of nature would reduce visitor numbers. (Jones *et al.*, 2006) study the impact of climate change on three festivals in Ottawa. They argue for heat wave preparedness for Canada Day, find that skating on natural ice may become impossible for Winterlude, and that the dates of the Tulip Festival may need to be shifted to reflect changing phenology.

10.6.1.2. Tourism

Climate (Becken and Hay, 2007; WTO and UNEP, 2008) and weather (Day *et al.*, 2013; Falk, 2013; Førland *et al.*, 2012; Rossello, 2011; Rosselló-Nadal *et al.*, 2010; Álvarez-Díaz and Rosselló-Nadal, 2010) are important factors in tourist destination choice, and the tourist sector is susceptible to extreme weather (Forster *et al.*, 2012; Forster *et al.*, 2012; Hamzah *et al.*, 2012; Tsai *et al.*, 2012). (Eijgelaar *et al.*, 2010), for instance, argues that so-called “last chance tourism” is a strong pull for tourists to visit Antarctica to admire the glaciers while they still can. (Farbotko, 2010; Prideaux and Mcnamara, 2012) use a similar mechanism to explain the rise in popularity of Tuvalu as a destination choice. (Huebner, 2012) find no impact of future climate change on current travel choices. (Taylor and Ortiz, 2009) show that domestic tourists in the UK often respond to past weather; the hot summer of 2003 had a positive impact on revenues of the tourist sector. (Denstadli *et al.*, 2011) find that tourists in the Arctic do not object to the weather in the Arctic; (Gössling *et al.*, 2006) reaches the same conclusion for tourists on Zanzibar; and (Moreno, 2010) for tourists in the Mediterranean.

There are a number of biometeorological studies of the impact of climate change on tourism. (Yu *et al.*, 2009a) find that Alaska has become more attractive over the last 50 years, and Florida less attractive to tourists. (Yu *et al.*, 2009b) conclude that the climate for sightseeing has improved in Alaska, while the climate for skiing has deteriorated. (Matzarakis *et al.*, 2010) construct a composite index of temperature, humidity, wind speed and cloud cover, and use this to map tourism potential. (Lin and Matzarakis, 2008; Lin and Matzarakis, 2011) apply the index to Taiwan POC and Eastern China. (Endler and Matzarakis, 2010a; Endler and Matzarakis, 2010b; Endler and Matzarakis, 2011) use an index to study the Black Forest in Germany in detail, highlighting the differences between summer and winter tourism, and between high and low altitudes (Endler *et al.*, 2010). (Matzarakis and Endler, 2010; Zaninović and Matzarakis, 2009) use this method to study Freiburg and Hvar. (Matzarakis *et al.*, 2007) project this potential into the future, finding that the Mediterranean will probably become less attractive to tourists. (Amelung and Moreno, 2012; Amengual *et al.*, 2012; Giannakopoulos *et al.*, 2011; Hein *et al.*, 2009; Perch-Nielsen *et al.*, 2009) reach the same conclusion, but also point out that Mediterranean tourism may shift from summer to the other seasons. (Giannakopoulos *et al.*, 2011) notes that coastal areas in Greece may be affected more than inland areas because, although temperature would be lower, humidity would be higher. (Moreno and Amelung, 2009), on the other hand, conclude that climate change will not have a major impact (before 2050) on beach tourism in the Mediterranean because sunbathers like it hot (Moreno, 2010; Rutty and Scott, 2010). (Amelung *et al.*, 2007) use a weather index for a global study of the impact of climate change on tourism, finding shifts from equator to pole, summer to spring and autumn, and low to high altitudes. (Perch-Nielsen, 2010) combines a meteorological indicator of exposure with indicators of sensitivity and adaptive capacity, and uses this to rank the vulnerability of beach tourism in 51 countries. India stands out as the most vulnerable, and Cyprus as the least vulnerable.

The main criticism of most biometeorological studies is that the predicted gradients and changes in tourism attractiveness have rarely been tested to observations of tourist behaviour. (De Freitas *et al.*, 2008) validate their proposed meteorological index to survey data. (Moreno *et al.*, 2008) and (Ibarra, 2011) use beach occupancy to test meteorological indices for beach tourism. (Gómez-Martín, 2006) tests meteorological indices against visitor numbers and occupancy rates. All four studies find that weather and climate affects tourists, but in a different way than typically assumed by biometeorologists.

(Maddison, 2001) estimates a statistical model of the holiday destinations of British tourists, (Lise and Tol, 2002) for Dutch tourists, (Bujosa and Rosselló, 2012) for Spanish tourists in Spain, and (Bigano *et al.*, 2006) for international tourists from 45 countries. These models control for as many other variables as possible; their focus on the average tourist may be misleading, and their representation of climate may be oversimplified (Gössling and Hall, 2006). Tourists have a clear preference for the climate that is currently found in Southern France, Northern Italy and Northern Spain. People from hot climates care more about the climate in which they spend their holidays than people from cool climates. Whereas (Bigano *et al.*, 2006) find regularity in *revealed* preferences, (Scott *et al.*, 2008b) find pronounced differences in *stated* preferences between types of people.

(Bigano *et al.*, 2007; Hamilton *et al.*, 2005a; Hamilton *et al.*, 2005b) construct a simulation model of domestic and international tourism and climate change (but not sea level rise), considering the simultaneous change in the attractiveness of all potential holiday destinations (Dawson and Scott, 2013); (Hamilton and Tol, 2007) downscale these national results to the regions of selected countries. Two main findings emerge. First, climate change would drive tourists to higher latitudes and altitudes. International tourist arrivals would fall, relative to the scenario without warming, in hotter countries, and rise in colder countries. Tourists from Northwestern Europe, the main origin worldwide of international travelers at present, would be more inclined to spend the holiday in their home country, so that the total number of international tourists falls. Second, the impact of climate change is dominated by the impact of population growth and, particularly, economic growth. In the worst affected countries, climate change slows down, but nowhere reverses, growth in the tourism sector.

10.6.2. Recreation and Tourism Supply

Studies on the supply side often focus on ski tourism. Warming is expected to raise the altitude of snow-reliable ski resorts, and fewer resorts will be snow-reliable (Hendrikx *et al.*, 2012; Hendrikx *et al.*, 2013; Steger *et al.*, 2012)(Dawson *et al.*, 2009). Snowmobiling will be negatively affected too (Scott *et al.*, 2008a)(Mcboyle *et al.*, 2007). Artificial snow-making cannot fully offset the loss in natural snowfall (Elsasser and Bürki, 2002; Scott *et al.*, 2006)(Hoffmann *et al.*, 2009), particularly in lower areas (Schmidt *et al.*, 2012)(Morrison and Pickering, 2012; Wolfsegger *et al.*, 2008), and water scarcity and the costs of snowmaking will be increasingly large problems (Matzarakis *et al.*, 2012)(Scott *et al.*, 2003)(Scott *et al.*, 2007)(Hendrikx and Hreinsson, 2012)(Steiger and Mayer, 2008)(Pons-Pons *et al.*, 2012); skiers prefer natural over artificial snow (Pickering *et al.*, 2010). Tourism alternatives to skiing or non-tourism alternatives need to be considered as a source of economic development (Hill *et al.*, 2010)(Scott and McBoyle, 2007)(Bicknell and Mcmanus, 2006)(Pickering and Buckley, 2010)(Moen and Fredman, 2007)(Tervo, 2008)(Serquet and Rebetez, 2011)(Landauer *et al.*, 2012)(Matzarakis *et al.*, 2012)(Bourdeau, 2009)(Steiger, 2010)(Potocka and Zajadacz, 2009). Other socio-economic trends dominate the impact of climate change (Steiger, 2012)(Hopkins *et al.*, 2012).

Other studies consider beach tourism. (Scott *et al.*, 2012b) highlight the vulnerability of coastal tourism facilities to sea level rise. (Hamilton, 2007) finds that tourists are averse to artificial coastlines, so that hard protection measures against sea level rise would reduce the attractiveness of an area. (Raymond and Brown, 2011) survey tourists on the Southern Fleurieu Peninsula. They conclude that tourists who are there for relaxation worry about climate change, particularly sea level rise, while tourists who are there to enjoy nature (inland) do not share that concern. (Becken, 2005) finds that tourist operators have adapted to weather events, and argues that this helps them to adapt to climate change. (Belle and Bramwell, 2005) find that tourist operators on Barbados are averse to public adaptation policies. (Uyarra *et al.*, 2005) find that tourists on Barbados would consider holidaying elsewhere if there is severe beach erosion. (Buzinde *et al.*, 2010a; Buzinde *et al.*, 2010b) find that there is a discrepancy between the marketing of destinations as pristine and the observations of tourists, at least for Mexican beach resorts subject to erosion. They conclude that tourists have a mixed response to environmental change, contrary to the officials' view that tourists respond negatively. (Jopp *et al.*, 2013) find that an increase in tourism in the shoulder season may offset losses in the peak season in Victoria.

Some studies focus on nature tourism. (Cavan *et al.*, 2006) find that climate change may have a negative effect on the visitor economy of the Scottish uplands as natural beauty deteriorates through increased wild fires. (Saarinen and Tervo, 2006) interviewed nature-based tourism operators in Finland, and found that about half of them do not believe that climate change is real, and that few have considered adaptation options. (Nyaupane and Chhetri, 2009) argue that climate change would increase weather hazards in the Himalayas and that this would endanger tourists. (Uyarra *et al.*, 2005) find that tourists on Bonaire would not return if coral were bleached. (Hall, 2006) finds that small tourist operators in New Zealand do not give high priority to climate change, unless they were personally affected by extreme weather in recent times. The interviewed operators generally think that adaptation is a sufficient response to climate change for the tourism sector. (Klint *et al.*, 2012) find that tourist operators in Vanuatu give low priority to adaptation to climate change and (Jiang *et al.*, 2012) find Fiji poorly prepared. (Saarinen *et al.*, 2012) find that tourist operators in Botswana think that climate change would not affect them. (Wang *et al.*, 2010) note that glacier tourism is particularly vulnerable to climate change, highlighting the Baishiu Glacier in China. (Brander *et al.*, 2012) estimate the economic impacts of ocean acidification on coral reefs under four IPCC marker scenarios using value transfer function approach and find that the annual economic impacts increase rapidly overtime, though it remains a small fraction of total income.

While the case studies reviewed above provide rich detail, it is hard to draw overarching conclusions. A few studies consider all aspects of the impact of climate change for particular countries or regions (Ren Guoyu, 1996)(Harrison *et al.*, 1999). In France, the Riviera may benefit because it is slightly cooler than the competing coastal resorts in Italy and Spain; the Atlantic Coast, although warming, would not become more attractive because of increased rainfall; it is not probable that the increase in summer tourism in the mountains would offset the decrease in winter tourism (Ceron and Dubois, 2005). In the Great Lakes regions, there is a reduced tourism potential in winter but increased opportunities in summer (Dawson and Scott, 2010). Tourist operators in Australia find the uncertainty about climate change too large for early investment in adaptation (Turton *et al.*, 2010).

10.6.3. Market Impacts

There are only two papers that consider the economic impacts of rather stylized climate-change-induced changes in tourism supply and demand. Both studies use a global computable general equilibrium model, assessing the effects on the tourism sector as well as all other markets. (Berrittella *et al.*, 2006) consider the consumption pattern of tourists and their destination choice. They find that the economic impact is qualitatively the same as the impact on tourist flows (discussed above): Colder countries benefit from an expanded tourism sector, and warmer countries lose. They also find a drop in global welfare, because of the redistribution of tourism supply from warmer (and poorer) to colder (and richer) countries. (Bigano *et al.*, 2008) extend the analysis with the implications of sea level rise. The impact on tourism is limited because coastal facilities used by tourists typically are sufficiently valuable to be protected against sea level rise. The economic impacts on the tourism sector are reinforced by the economic impacts on the coastal zone; the welfare losses due to the impact of climate change on tourism are larger than the welfare losses due to sea level rise.

10.7. Insurance and Financial Services

10.7.1. Main Results on insurance of AR4 and SREX

More intense or frequent weather-related disaster would affect property insurance, of which coverage is expanding with economic growth (WG II, 7.4.2.2.4). Insurability can be preserved through risk-reducing measures. Adaptation to climate change can be incentivized through risk-commensurate insurance premiums. Improved risk management would further financial resilience (WG II, 7.4.2.2.4, 7.6.3). Insurance is linked to disaster risk reduction and climate change adaptation, because it enables recovery, reduces vulnerability and provides knowledge and incentives for reducing risk (IPCC, 2012).

10.7.2. Fundamentals of Insurance Covering Weather Hazards

Insurance is organized either through private markets, publicly or public-private partnerships. It internalizes catastrophe risk costs prior to catastrophic events, reducing the economic impact of weather-related and other disasters to individuals, enterprises,and governments, thus stabilizing income and consumption, and decreasing societal vulnerability (Melecky and Raddatz, 2011) (17.5.1). Insurance is based on the law of large numbers: the larger the portfolio of uncorrelated and relatively small risks, the more accurately the average loss per policy can be predicted and charged accordingly, allowing for a lower premium than with a smaller ensemble. Besides spreading risk over a diversified insured population, insurance spreads risk over time. However, weather-related disasters such as floods simultaneously affect many, and thus violate the principle of uncorrelated risks. Consequently, large losses are much more probable, the loss variance is greater, and the tail risk is higher (Kousky and Cooke, 2012). If insurance coverage is to be maintained, insurers would need more risk-based capital to indemnify catastrophic losses and remain financially solvent. This coverage is purchased in the reinsurance and capital markets. The capital costs account for a substantial portion of premiums and the affordability and viability of weather insurance are subjects of ongoing research given future climate change (Charpentier, 2008); (Maynard and Ranger, 2012); (Clarke and Grenham, 2012).

Increasing volatility and burden of losses in many regions are expected to fundamentally impact the industry, leading insurers to adapt their business to the changing risk (Herweijer *et al.*, 2009); (Phelan *et al.*, 2011); (Mills, 2012); (Paudel, 2012), including the use of short-term contracts to adapt to changing cirumstances (Botzen *et al.*, 2010a).

10.7.3. Observed and Projected Insured Losses from Weather Hazards

Direct and insured losses from weather-related disasters have increased substantially in recent decades both globally and regionally (IPCC, 2012); (Bouwer *et al.*, 2007); (Swiss Re, 2013c); (Munich Re, 2013); (Crompton and McAneney, 2008); (Smith and Katz, 2013). Global insured weather-related losses in the period 1980-2008 increased by US$^{2008}1.4bn per year on average (Barthel and Neumayer, 2012). As a rule, insured loss figures are more accurate than direct economic loss estimates, because insurance payouts are closely monitored. Often they are the basis for estimates of direct overall losses (Kron *et al.*, 2012); (Smith and Katz, 2013). Economic growth, including greater concentrations of people and wealth in periled areas and rising insurance penetration, is the most important driver of increasing losses.

Growth induced changes in past losses are removed by normalizing to current levels of destructible wealth. So far, only one study analyzes normalized global weather-related insured losses (Barthel and Neumayer, 2012), but the period is too short (1990-2008) to support a meaningful analysis oftrends. A few studies focus on specific perils and regions, in particular Australia, USA and Europe. Trends were detected for the USA and Germany, but not for Australia and Spain (Table 10-4). Such trends can be influenced by changing damage sensitivities, adaptive measures, different normalization, and changes in insurance – besides changing hazards (Barthel and Neumayer, 2012); (Crompton and McAneney, 2008); (Bouwer, 2011); (IPCC, 2012). Prevention measures such as flood control structures, or improved building standards, would offset an increase in hazard (Kunreuther *et al.*, 2009); (Kunreuther *et al.*, 2012). Given such confounding factors, it can be challenging to estimate to what degree developments in losses convey a climate signal (Kron, 2012); (IPCC, 2012). Nonetheless, normalized direct natural disaster losses have already been demonstrated to properly reflect climate variability on various time scales (Pielke and Landsea, 1999); (Welker and Faust, 2013).

Studies analyzing changes in climate variables and insured losses in parallel are still rare. Variability and mean level of thunderstorm-related insured losses in the USA in the period 1970-2009 have substantially increased, while meteorological thunderstorm forcing has risen in parallel (Sander *et al.*, 2013). The number of days that a regional insurer in southwest Germany sustains hail losses displays an upward trend since 1986, while meteorological severe storm indicators also show upward trends (Kunz *et al.*, 2009). Although more studies find increases of large hail in Europe, general data and monitoring issues hindered assessing more than low confidence in observed meteorological trends (WG1-2.6.2.4). (Corti *et al.*, 2009) found an increase in modeled and partly observed insured subsidence losses in France over the period 1961-2002, consistent with a *likely* increase in dryness in Mediterranean regions (WG1-2.6.2.3). The observed rise in US normalized insured flood losses (Barthel and Neumayer, 2012) may partly correspond to *very likely* increased heavy precipitation events in central North America (WG1-2.6.2.1), while the evidence for climate driven changes in river floods is not compelling (WG1-2.6.2.2). Declining anthropogenic aerosol emissions may partly explain the recent upswing in hurricane hazard and losses (WG1-14.6; WG1-2.6.3; Table 10-4). Apart from detection, loss trends have not been conclusively attributed to anthropogenic climate change; most such claims are not based on scientific attribution methods.

[INSERT TABLE 10-4 HERE
Table 10-4: Observed normalized insured losses from weather hazards (trends significant at the 10% level are indicated as a trend).]

Many GCM-based projection studies agree that extreme winter storm wind speeds fall in the Mediterranean and increase in west, central, and northern Europe (WG1-14.6.2.2). Loss ratios, i.e. insured loss divided by insured value, follow the same pattern (Schwierz *et al.*, 2010); (Donat *et al.*, 2011); (Pinto *et al.*, 2012) (Table 10-5). Return periods per loss level are projected to shorten in large parts of Europe, indicating more frequent high losses (Pinto *et al.*, 2012) (Table 10-5). Projected overall losses and fatalities develop accordingly (IPCC, 2012); (Narita *et al.*, 2010). Across three modeling approaches calibrated to German insurance data, the 25-year loss is projected (A1B) to change by –10% to +18% (2011-2040), +5% to +41% (2041-2070), and +45% to +58% (2071-2100) against 1971-2000, keeping exposures and damage sensitivities constant (Held *et al.*, 2013). Although it is *unlikely* that the North Atlantic response to climate change is just a simple poleward shift of the stormtrack, overall confidence in the magnitude of regional storm track changes is low (WG1-14.6.3).

[INSERT TABLE 10-5 HERE
Table 10-5: Climate change projections of insured losses and/or insurance prices.]

Direct losses and fatalities from flooding will increase with climate change in various locations in the absence of adequate adaptation, given *very likely* wide-spread increases in heavy precipitation (WG1-12.4.5.4; 11.3.2.5.2) (IPCC, 2012). This is selectively reflected in studies projecting mean annual insured heavy rainfall and flood losses will rise with climate change in the UK, the Netherlands, Germany, southern Norway and the Canadian province of Ontario (Table 10-5).

Direct losses and fatalities from tropical cyclones will increase with exposure and may increase with the frequency of very intense cyclones in some basins (WG1-14.6); (IPCC, 2012); (Nordhaus, 2010); (Peduzzi *et al.*, 2012). (Ranger and Niehoerster, 2012), (Kunreuther *et al.*, 2012), and (Raible *et al.*, 2012) found insured hurricane losses change in opposite directions across a range of dynamical and statistical model projections, whereas a high-resolution approach tends to support a long-term increase (Emanuel, 2011). Here, increased probabilities of upward shifted accumulated loss might be detectable by 2025 at earliest, whereas a significant loss trend might emerge much later (Emanuel, 2011); (Crompton *et al.*, 2011). Insured typhoon-related property losses in China are projected to increase (Dailey *et al.*, 2009). Averaged across four GCMs, (Mendelsohn *et al.*, 2012) project rising direct losses for Central America, the Caribbean, North America, and East Asia. (Narita *et al.*, 2009) report an increase in damages and fatalities in all parts of the world.

Hailstorm insurance losses in the Netherlands (Botzen *et al.*, 2010b) and Germany (Gerstengarbe *et al.*, 2013) are projected to increase, consistent with more severe thunderstorms (WG1-12.4.5.5). Paddy rice insurance payouts in Japan are projected to decrease (Iizumi *et al.*, 2008) (Table 10-5).

Rising insured wealth will increase both losses and premium income, not necessarily altering the ratio of both. Such automatic compensation is not effective for changing hazards. Hence, projected ratios of losses to premiums or sums insured (while assuming constant insured property) are an approximation of the climate change impact (Donat *et al.*, 2011). Additional impact factors such as future economic growth (Aerts and Botzen, 2011) or changing vulnerability are rarely projected.

10.7.4. Fundamental Supply-Side Challenges and Sensitivities

10.7.4.1. High-Income Countries

The provision of weather hazard insurance is contingent on an insurer’s ability to find a balance between affordability of the premiums and costs that have to be covered by the revenue. Costs include, the expected level of losses, expenses for risk assessment, product development, marketing, operating, and claims processing. Moreover, the revenue must provide a return on shareholders’ equity and allow for the purchase of external capital to cover large losses (Charpentier, 2008); (Kunreuther *et al.*, 2009).

The balance between affordability and profitability is sensitive to climate change. Increases in large weather-related losses may corrode an insurer’s solvency if it fails to adjust its risk management, or is hampered in doing so by price regulation (Grace and Klein, 2009). Additionally, misguided incentives for development in hazard-prone areas, as with the US National Flood Insurance Program (Kousky and Cooke, 2012)); (Michel-Kerjan, 2010); (GAO, 2011), can aggravate the situation (Table 10-6).

[INSERT TABLE 10-6 HERE
Table 10-6: Fundamental supply-side challenges and sensitivities.]

The additional uncertainty induced by climate change translates into a need for more risk capital (Charpentier, 2008); (Kunreuther *et al.*, 2009); (Grace and Klein, 2009). This raises insurance premiums and affects the economy (Table 10-6). Health and life insurance may also be affected through the health impacts of climate change (Hecht, 2008). Liability insurance, too, may be susceptible to climate change. So far, no damages have been awarded for greenhouse gas emissions as such, but litigation where damages are sought is pending (Mills, 2009); (Heintz *et al.*, 2009); (Patton, 2011). Defense cost coverage under liability insurance in such cases depends on the specific contractual wording (Supreme Court of Virginia, U.S.A., 2012)) (Table 10-6).

10.7.4.2. Middle- and Low-Income Countries

Middle- and low-income countries account for a small share of worldwide non-life insurance: approximately 14% of premiums in 2012 (Swiss Re, 2013b). In high-income countries, some 35% of direct natural disaster losses have been covered by insurance in the period 1980-2011, about 5% in middle-income countries, and less than 1% in low-income countries (Wirtz *et al.*, 2013). For instance, only about 1% of direct overall losses in the 2010 floods in Pakistan were insured (Munich Re., 2011).

The small share of insurance in risk financing in middle and low income countries may be insufficient because other options, such as external credit or donor assistance, can be unreliable and late. This leaves a financial gap in the months immediately following an EWE, often exacerbated by overstretched public finances. Pre-disaster financing instruments such as insurance or trigger-based risk-transfer products have proven to be effective means of providing prompt liquidity for households, businesses, and governments (Ghesquiere and Mahul, 2007); (Linnerooth-Bayer *et al.*, 2011); (Melecky and Raddatz, 2011; von Peter *et al.*, 2012); (IPCC, 2012); Table 10-6). These may become more important if disaster incidence increases with climate change (IPCC, 2012); (Collier *et al.*, 2009); (Hochrainer *et al.*, 2010).

It is challenging to increase catastrophe insurance coverage because of low business volumes, high transaction costs, and high reinsurance premiums following large disasters. Small-scale insurance schemes in middle- and low-income countries may find it difficult to obtain sufficient risk capital (Cummins and Mahul, 2009); (Mahul and Stutley, 2010).

Microinsurance schemes, keeping transaction costs at the lowest operable level, mainly provide health and life insuracne to households and small enterprises in low-income markets. Supply of property insurance suffers from correlated weather risks, although weather-related agricultural damages are covered. Such weather coverage is growing, typically with government and NGO assistance or cross-subsidies from local insurers (Linnerooth-Bayer *et al.*, 2011; Qureshi and Reinhard, 2011). These schemes may be particularly sensitive to a rise in disaster risk due to climate change (Collier *et al.*, 2009); (Leblois and Quirion, 2011); (Clarke and Grenham, 2012).

Adverse selection is another challenge: clients do not always disclose their true risk, e.g. a floodplain site, to the insurer so as to benefit from lower rates. Lower-risk participants may be charged too high premiums and leave the scheme, thus increasing overall risk; and in low-income countries, where data to establish homogenous risk groups are not available, this can cause disaster insurance markets to fail. Moral hazard is another issue, where the insured adopt more risky behavior than anticipated by the insurer, particularly in the absence of proper monitoring (Barnett *et al.*, 2008); (Mahul and Stutley, 2010).

10.7.5. Products and Systems Responding to Changes in Weather Risks

10.7.5.1. High-Income Countries

A rise in weather-related disaster risk may drive the need for more risk-based capital to cover the losses. There are several options that sustain insurability. Reducing vulnerability often makes sense even if expected climate change impacts will not materialize. Theoretically, risk-based premiums incentivize policyholders to reduce their vulnerability (IPCC, 2012); (Hecht, 2008); (Kunreuther *et al.*, 2009) (Table 10-7). Premium discounts for loss-prevention can further promote this (Ward *et al.*, 2008); (Kunreuther *et al.*, 2009) (Table 10-7). Moral hazard can be reduced by involving the policyholder in the payment of losses, e.g. via deductibles or upper limits of insurance coverage (Botzen and van den Bergh, 2009); (Botzen *et al.*, 2009). Coordinated efforts of insurers and governments on damage prevention decrease risk (Ward *et al.*, 2008); (Reinhold *et al.*, 2012). For example, new building standards in Florida reduced mean damage per house by 42% in the period 1996-2004 relative to pre-1996; risks can be further reduced, and premium discounts contingent on building standard are offered (Kunreuther *et al.*, 2009); (Kunreuther *et al.*, 2012). However, risk-based premiums required to incentivize vulnerability reduction are often hampered (see also 15.4.4, 17.5.1). Price regulation, subsidies, competitive pressures, and bundling of perils in one product (implying cross-subsidies) have fostered underpricing. Also, availability of sufficient on-site risk information limits price adequacy, e.g. for flood insurance (Maynard and Ranger, 2012).

[INSERT TABLE 10-7 HERE
Table 10-7: Products and systems responding to changes in weather risks.]

Most commercial risk-assessment models only incipiently factor in changes in weather hazards, mainly to reflect higher hurricane frequencies (Seo and Mahul, 2009), assuming unchanging conditions for other weather hazards. Ignoring changing hazard conditions results in biased estimates of expected loss, loss variability and risk capital requirements (Charpentier, 2008); (Herweijer *et al.*, 2009) (10.7.3). Other confounding factors, e.g. systemic economic impact, in recent large losses have been addressed (Muir-Wood and Grossi, 2008) (Table 10-7). For example, geospatial risk-assessment tools, e.g. flood-recurrence zoning with premium differentiation, counteract adverse selection (Kunreuther *et al.*, 2009); (Mahul and Stutley, 2010). Some insurers have offered weather alert systems to clients (Niesing, 2004). Further, credit rating agencies and Solvency II insurance regulations in Europe contribute to enhanced disaster resilience (Michel-Kerjan and Morlaye, 2008); (Kunreuther *et al.*, 2009); (Grace and Klein, 2009). Finally, insurers and researchers have projected climate change driven losses to allow for adaptation of the industry (10.7.3).

Reinsurers are key to the supply of disaster risk capital. They operate globally to diversify the regional risks of hurricanes and other disasters. Access to reinsurance enhances risk diversification of insurers. Periodic shortages in reinsurance capacity following major disasters have moderated over the last two decades because of easier new capital inflow (Cummins and Mahul, 2009).

Global diversification potential of large losses has fallen over recent decades because of increasing dependence between major insurance markets. For instance, the floods in Thailand in 2011 disrupted industrial hubs and global supply chains (Courbage *et al.*, 2012). This process may continue with climate change (Sherement and Lucas, 2009); (Kousky and Cooke, 2012). However, global diversification potential can be increased by developing insurance markets in middle- and low-income countries (Cummins and Mahul, 2009).

Very large loss events, say in excess of US$ 100bn, may make additional capacity desirable. These disasters can be diversified in the financial securitization market (IPCC, 2012). Natural catastrophe risks are not correlated with capital market risks and hence are attractive to institutional investors. For instance, a catastrophe bond assures the investor above-market returns as long as a parametric index (e.g., wind-based) does not exceed a threshold, but pays the insurer’s loss otherwise. The catastrophe bond market reached critical mass after the hurricanes of 2004 and 2005, with some US$ 11bn of risk capital in effect by June 2011 (Cummins, 2012); (Cummins and Weiss, 2009); (Michel-Kerjan and Morlaye, 2008); (Kunreuther and Michel-Kerjan, 2009) (Table 10-7).

10.7.5.2. Middle- and Low-Income Countries

Index-based weather insurance is often considered well-suited to the agricultural sector in developing countries (Collier *et al.*, 2009); (IPCC, 2012). Payouts depend on a physical trigger, e.g. cumulative rainfall at a nearby weather station, instead of the policyholder’s condition. Thus, they can be timely; costly loss assessments and moral hazard are avoided, and adverse selection reduced (Barnett *et al.*, 2008). Risk-based premiums can encourage adaptive responses (Mahul and Stutley, 2010) (Table 10-7). However, basis risk, where losses occur but no payout is triggered, provokes distrust. Misunderstanding and scaling up of pilots pose further difficulties (Patt *et al.*, 2010); (Leblois and Quirion, 2011); (Clarke and Grenham, 2012). Suggested improvements include area-yield indices and coverage at aggregate levels to reduce basis risk, and a cooperative design (Clarke and Grenham, 2012); (Biener and Eling, 2012) (Table 10-7). Application of indemnity-based insurance and index-based concepts depend on the insured’s characteristics and the market setting ((Herbold, 2013a); (Swiss Re, 2013a)). Insurance-linked services can strengthen farmers’ resilience by seasonal-forecast-based agricultural guidance (*AgroClima. Informática Avanzada SA de CV.*2013).

Improved building standards at high-risk sites in the Caribbean ubstantially reduce damages from tropical cyclones and increase benefits twofold over costs over a twenty year period, assuming scenarios of changing hazard inferred from past decades (Ou-Yang *et al.*, 2013); (Michel-Kerjan *et al.*, 2013). Insurance coverage linked to credit for retrofitting could improve adaptation (Mechler *et al.*, 2006).

Sovereign insurance is deemed appropriate in developing countries suffering from post-disaster financing gaps (see 10.7.4). Current schemes include government disaster reserve funds (FONDEN, Mexico) and pools of developing states’ sovereign risks (e.g., CCRIF, Caribbean) (IPCC, 2012). In both cases, peak risk is transferred to reinsurance and catastrophe bonds (Table 10-7).

10.7.6. Governance, Public-Private Partnerships, and Insurance Market Regulation

10.7.6.1. High-Income Countries

Theory favors an arrangement where individual risk is insured, but the non-diversifiable component of risk (that may rise with climate change) is public (Borch, 1962); (Kunreuther *et al.*, 2009). Accordingly, many high-income states have public-private arrangements involving government intervention on peak risk (Aakre *et al.*, 2010); (Bruggeman *et al.*, 2010); (Schwarze *et al.*, 2011); (Paudel, 2012), or even public statutory insurance systems (Quinto, 2011) (Table 10-8). Expected post-disaster relief has been shown to counteract insurance uptake (Raschky *et al.*, 2013). The pro-adaptive, risk-reducing features of insurance are more effective if the price reflects the risk and the pool of insureds is larger, e.g. through bundled perils (Bruggeman *et al.*, 2010); (Paudel, 2012). People who cannot afford premiums can be covered by vouchers, leaving the price signal undistorted, or by subsidies (Kunreuther *et al.*, 2009); (Aakre *et al.*, 2010) (Table 10-8). Insurance regulation ensures availability, affordability, and solvency, but often adopts only short- to medium-term views. Because of climate change, the role of regulators has changed to include risk-adequate pricing, risk education, and risk-reduction in the long term (Hecht, 2008); (Grace and Klein, 2009); (Mills, 2009).

[INSERT TABLE 10-8 HERE
Table 10-8: Governance, public-private partnerships, and insurance market regulation.]

10.7.6.2. Middle- and Low-Income Countries

A key element of risk financing is the transfer of private risks to an insurance system. This reduces the governments' burden and uncertainty due to weather disasters (Ghesquiere and Mahul, 2007); (Melecky and Raddatz, 2011). Interest in public-private partnerships may evolve, e.g. between government, farmers, rural banks and insurers, in order to expedite agricultural development and resilience, e.g. by means of subsidies for start-up costs and peak risk (Collier *et al.*, 2009); (Mahul and Stutley, 2010) (Table 10-8). Previously implemented systems have suffered from adverse selection and moral hazard (Makki and Somwaru, 2001); (Glauber, 2004), suggesting an improved design is needed. For instance, group policies that foster mutual monitoring, programs or legislative actions that encourage purchase of insurance may increase participation rates. Further, insurance pools can diversify weather risks across larger regions, reduce premiums and improve access to external risk capital (Mendoza, 2009); (Hochrainer and Mechler, 2011); (Biener and Eling, 2012); (IPCC, 2012).

In least developed countries, domestic insurance markets are rare. Climate change-related disaster risk management was proposed for inclusion in the adaptation regime of the UNFCCC. Besides prevention, insurance is a central element in these concepts, partly funded from an UNFCCC adaptation fund according to the principles of "equity and […] common but differentiated responsibilities and respective capabilities" (UNFCCC Art.3.1); (Warner and Spiegel, 2009); (Linnerooth-Bayer *et al.*, 2009); (IPCC, 2012) (Table 10-8).

For insurance systems in developing markets, challenges include adequate public-privated partnership framing, improved risk assessment, with sufficient detail and appropriate dynamics, development of markets and regulation, and scaling-up of successful schemes. Regulatory requirements for risk-based capital, and access to reinsurance and securitization markets further contribute to a resilient insurance system.

10.7.7. Financial Services

The financial industry apart from insurance is vulnerable to both slow-onset changes and to more frequent and/or intensive weather-related disasters. Equity investors potentially face a higher exposure than debt investors, due to exit conditions and a focus on longer-term returns in equity markets, but ultimately the impact on debt investors depends on the exposure of credit collateral to climate change (Stenek *et al.*, 2010). In the short-to medium term, the financial sector is better sheltered from climate change due to high capital mobility, an ability to hedge against a range of business risks, an aptitude for the development of new products to cater for changing demand in particular with respect to risk transfers and invest in growing markets (Oliver Wyman, 2007); (Whalley and Yuan, 2009). In the longer-term, some risks associated with climate change will be more difficult to diversify in particular for financial institutions with local reach.

There are few papers on the impact of climate change on the financial sector (other than insurance). Surveys agree with earlier views (AR3, WGII, 8.4.) that climate change is perceived as a material threat by few bankers and asset managers. There is growing awareness of climate change impacts, as illustrated by increasing membership of sector initiatives such as the Carbon Disclosure Project, the UN Principles for Responsible Investment or the Global Reporting Initiative, potentially influencing the responsiveness of the sector to climate change (Brimble and Stewart, 2009). However, only a few financial institutions have systematically factored in climate change into their risk management and analytical framework (Cogan, 2008); (Furrer *et al.*, 2012).

While direct physical impact (i.e. damage to financial infrastructure) is not seen to be a material issue, this may change in the future in light of the exposure of major financial centres to rising sea levels and the reliance on complex IT infrastructure. Moreover, there is an increasing share of equity allocated to infrastructure and real estate that is more long-term oriented and could face higher maintenance and adaptation requirements (Stenek *et al.*, 2010); (Mercer, 2011).

Indirect impacts may become material over the next few decades, for example, value losses of assets/loan portfolios as a result of physical damage. Regulatory and reputational effects, together with liability and litigation risks linked to climate change are of concern too (Cogan, 2008); (Mercer, 2011); (Furrer *et al.*, 2012). However, legitimacy concerns linked to climate change (as reflected by clients) are insufficient, overshadowed by the financial crisis, or mitigated by the size and influence of the financial sector (Brimble and Stewart, 2009).

It is difficult to quantify how significant the impact of climate change will be for the industry. While it is not probable that climate change alone will affect the liquidity or financial capacity of an institution, the financial performance of both equity and debt markets could be weakened by a variety of factors including changes in market conditions through climate driven price variations, higher capital and operating expenditure or aggravation of country risk but also regulatory drivers, e.g. higher capital reserve requirements to cover higher on-and off-balance-sheet exposures (Stenek *et al.*, 2010).

10.7.8. Summary

More frequent or more severe extreme weather events, and increased uncertainty about such hazards, would lead to higher insurance premiums and reduced cover in several regions, to the detriment of the insured, and perhaps to reduced profitability of insurers, and to the detriment of their shareholders. Improvements in risk management, product innovation, financial innovation and better regulation would partially alleviate these impacts.

10.8. Services Other than Tourism and Insurance

Other service sectors of the economy include waste management, wholesale and retail trade, engineering, government, education, defense and health. Contributions to the economy vary substantially by country; however, overall worldwide economic activity related to government accounts for approximately 30% of global expenditures.

10.8.1. Sectors Other than Health

The literature on the impact of climate change on other sectors of the economy is sparse (see Appendix A). Few studies have evaluated the possible impacts of climate change, and particularly the economic impacts, on these sectors. (Tamiotti *et al.*, 2009) conducted a qualitative assessment of climate and trade. (Travers and Payne, 1998) and (Subak *et al.*, 2000) find that weather affects retail, mostly through transfers in the economy. (Sabbioni *et al.*,

2009) note that climate change may require a greater effort to protect cultural heritage. Chapter 12 discusses the impact of climate change on violent conflict, which has implications for military expenditures.

10.8.2. Health

Climate change-related alterations in weather patterns, particularly extreme weather and climate events, have the potential to affect the health sector through impacts on infrastructure and the delivery of health care services from changing demand. Increased demands for services put additional burdens on public health and health care personnel and supplies, with potential economic consequences. For example, hydrologic disasters (floods and wet mass movements) in 2011 were associated with 20% (140 million) of all reported disaster deaths and 19% of total damages (Guha - Sapir *et al.*, 2012).

Health care facilities are priority infrastructure that can be damaged by weather and climate events, compromising critical resources required for patient treatment; physical damage and destruction of equipment and buildings; and possibly requiring evacuation of critical care patients, with attendant risks for the patients (Carthey *et al.*, 2009). Adverse impacts on transportation (such as flooded roads) can further affect access and evacuation. The ability of health care facilities to properly care for the affected and for those with ongoing health issues requiring medication or treatment may be compromised by very large events that affect multiple health care facilities. Areas projected to experience increases in extreme events could consider additional “surge capacity” to manage such events without interruption of service (Banks *et al.*, 2007; Hess *et al.*, 2009).

Although the proportion of individuals seeking medical treatment during a disaster is typically a small subset of the total number of those affected, the additional burden on health care facilities can be significant (Hess *et al.*, 2009). Six weather and climate events that struck the US between 2000 and 2009 were estimated to have increased health care costs by US$740 million, reflecting more than 760,000 encounters with the health care system (Knowlton *et al.*, 2011). Hospitalizations, with attendant costs, can increase from cases of heat stress, heat stroke, and acerbations of cardiorespiratory diseases and other health conditions during heatwaves (e.g. (Astrom *et al.*, 2013; Lin *et al.*, 2012), and from the adverse health impacts of other extreme events (Chapter 11.4.1; 11.4.2). For example, one trauma center in the U.S. found a 5% increase in hourly admissions for each approximately 5°C increase in temperature (Rising *et al.*, 2006). Individuals looking for an air-conditioned location during high ambient temperatures can further increase hospital visits (Carthey *et al.*, 2009).

Climate change is projected to increase the burden of major worldwide causes of childhood mortality, including malnutrition, diarrheal diseases, and malaria (Chapter 11.5.1; 11.5.2; 11.6.1). Any increase in health burdens or risks would increase the demands for public health services (e.g. surveillance and control programs) and the demands for health care and relevant supplies (e.g. antimalarials, insecticide treated bednets, oral rehydration). Studies estimating the costs of additional cases of climate-sensitive health outcomes focus on the costs of treatment, typically omitting the costs of providing additional health services, implementing new policies, and health actions in other sectors (Hutton, 2011). Because most climate change-related cases of adverse health outcomes are projected to occur in low-income countries, treatment costs will primarily be borne by families where governments provide limited health care (WHO, 2004). Time off from work to care for sick children could affect productivity.

Public and private health expenditures account for approximately 10% of global GDP (http://data.worldbank.org/indicator/SH.XPD.TOTL.ZS). A systematic analysis of developing country government expenditures on health from domestic sources estimated that from 1995 to 2006, public financing of health in constant US$ increased nearly 100%; this was a product of rising GDP, slight decreases in the share of GDP spent by government, and increases in the share of government spending on health (Lu *et al.*, 2010). The results varied by region, with shares of government expenditures on health increasing in many regions but decreasing in many sub-Saharan African countries. Development assistance for health rose from about US$8 billion (in constant 2007 US$) in 1995 to nearly $19 billion in 2005 (Ravishankar *et al.*, 2009). Domestic government spending on health was negatively affected by development assistance to governments and positively effect when assistance was to the non-governmental sector (Lu *et al.*, 2010).

Estimates of the costs of treating future cases of adverse health outcomes from climate change are in the range of billions of US$ annually (Ebi, 2008; Pandey, 2010). An estimate of the worldwide costs in 2030 of additional cases of malnutrition, diarrheal disease, and malaria due to climate change, assuming no population or economic growth, emissions reductions resulting in stabilization at 750 ppm CO_2 equivalent in 2210, and current costs of treatment in developing countries, estimated treatment costs without adaptation could be $4-12 billion worldwide, depending on assumptions of the sensitivity of these health outcomes to climate change (Ebi, 2008). The costs for additional infrastructure and health care workers were not estimated, nor were the costs of additional public health services, such as surveillance and monitoring. The costs were estimated to be unevenly distributed, with most of the costs borne by developing countries, particularly in South East Asia and Africa, to address the projected approximately 3-5% increase in the number of cases of diarrheal disease and malaria from the 2002 baseline (Markandya and Chaibai, 2009). The prevalence of these diseases have since declined (http://apps.who.int/gho/data/node.main.14?lang=en; Chapter 11.1.1), although there is considerable uncertainty in mortality data from many low-income countries because of the low proportion of deaths covered by vital registration programs (Byass *et al.*, 2013).

A second global estimate assumed UN population projections, strong economic growth, updated projections of the current health burden of diarrheal diseases and malaria, two climate scenarios, and updated estimates of the costs of malaria treatment (Pandey, 2010). In 2010, the average annual adaptation costs for treating diarrheal disease and malaria were estimated to be $3-5 billion, with the costs expected to decline over time with improvement in basic health services. Over the period 2010-2050, the average annual costs were estimated to be around $2 billion, with most of the costs related to treating diarrheal disease; the largest burden is expected to be in Sub-Saharan Africa. The differences in costs from (Ebi, 2008) are primarily due to a reduction in the baseline burden of disease and lower costs for malaria treatment.

(Watkiss and Hunt, 2012) estimated the health impacts of climate change in Europe in 2071-2100 using physical and monetary metrics, taking socioeconomic change into consideration. Temperature-related mortality during winter and summer due to climate change included positive and negative effects, with welfare costs (and benefits) of up to $130 billion annually, with impacts unevenly distributed across countries. Assumptions about acclimatization influenced the size of the health impacts. The welfare costs for salmonellosis were estimated at potentially several hundred million Euro annually, and those for the mental health impacts associated with coastal flooding due to climate change were up to approximately $2 billion annually.

Estimated additional health care costs for climate change-related cases of malaria are similar in Southern Africa (van Rensburg and Blignaut, 2002). Ranges for (low-high) additional cost scenarios for the prevention and treatment of malaria in South Africa in 2025 were estimated to be approximately $280 - $3,764 million. Estimates for Botswana and Namibia are $9- $124 million and $13- $177 million, respectively. The high cost scenario for Namibia is about 4.6% of GDP. The climate change-related malaria inpatient and outpatient treatments costs at the end of the century (2080-2100) in 25 African countries[1] indicated that even marginal changes in temperature and precipitation could affect the number of malaria cases, with increases in most countries and decreases in others (Egbendewe-Mondzozo et al. 2011). The end of century treatment costs as a proportion of annual 2000 health expenditures per 1,000 people would increase in the vast majority of countries, with increases of more than 20% in inpatient treatment costs for Burundi, Cote D'Ivoire, Malawi, Rwanda, and Sudan.

[FOOTNOTE 1: Algeria, Benin, Botswana, Burkina, Burundi, Central African Republic, Chad, Cote D'Ivoire, Djibouti, Egypt, Ethiopia, Ghana, Guinea, Malawi, Mali, Mauritania, Morocco, Niger, Rwanda, South Africa, Sudan, Togo, Uganda, Tanzania, Zimbabwe.]

The costs of treating cases of cholera in Tanzania due to climate change in 2030 were estimated to be in the range of 0.32 – 1.4 % of GDP (Trærup *et al.*, 2011), and there would be costs for treating additional cases of diarrhea and malaria in India in 2030, depending on the emission scenario (Ramakrishnan, 2011).

(Bosello *et al.*, 2006) used a computable general equilibrium model to study the economic impacts of climate-change-induced changes in mortality and morbidity due to cardiovascular and respiratory diseases, malaria, diarrhea, schistosomiasis, and dengue fever. They considered the effects on labor productivity and demand for health care, and found that health and welfare impacts have the same sign. The economy-wide health impacts were greater than simple aggregation of the costs of the individual health outcomes. Increased health problems were associated with an expansion of the public sector at the expense of the private sector.

Estimates of the impacts of climate change on worker productivity, assuming current work practices, primarily through heat stress, indicate that productivity has already declined during the hottest and wettest seasons in parts of Africa and Asia, with more than half of afternoon hours projected to be lost to the need for rest breaks in 2050 in South East Asia and up to a 20% loss in global productivity in 2100 under RCP4.5 (Chapter 11.6.2; (Dunne *et al.*, 2013; Kjellstrom *et al.*, 2013; Kjellstrom *et al.*, 2009). Alternate workpractices may offer some relief from a health perspective, but would *likely* lead to significantly decreased productivity (Chapter 11).

10.9. Impacts on Markets and Development

Prior sections of this chapter present the direct impacts of climate change on the economy sector by sector. There are, however, also indirect impacts, from the one sector on the rest of the economy (10.9.1) and on economic growth and development (10.9.2).

10.9.1. Effects of Markets

There are three channels through which economic impact diffuse. First, outputs of one sector are used as inputs to other sectors. For example, a change in crop yields would affect the food-processing industry. Second, products compete for the consumers' finite budget. If, for example, food becomes more expensive, consumer would shift to cheaper food but also spend less money on other goods and services. Third, sectors compete for the primary factors of production (labor, capital, land, water). If, besides more fertilizers and irrigation, more labor is needed in agriculture to offset a drop in crop yields, less labor is available to produce other goods and services. Firms and households react to changes in relative prices, domestically and internationally. Ignoring these effects would lead to biased estimates of the impacts of climate change.

General equilibrium analysis describes how climate change impacts in one sector propagate to the rest of the economy, how impacts in one country influence other countries, and how macroeconomic conditions affect each impact (Ginsburgh and Keyzer, 1997). General equilibrium models can provide a comprehensive and internally consistent analysis of the medium-term impact of climate change on economic activity and welfare. However, these models necessarily make a number of simplifying assumptions, particularly with regard to the rationality of consumers and producers and the absence of market imperfections. Other types of economic models have yet to be applied to the estimation of indirect economic effects of climate change.

Computable general equilibrium models have long been used to study the wider economic implications of changes in crop yields (Kane *et al.*, 1992). (Yates and Strzepek, 1998) show for instance that the impact of a reduced flow of the Nile on the economy of Egypt is much more severe without international trade than with, because trade would allow Egypt to focus on water-extensive production for export and import its food.

Older studies focused on the impact of climate change on patterns of specialization and trade, food prices, food security and welfare (Darwin and Kennedy, 2000; Darwin, 2004; Kane *et al.*, 1992; Reilly *et al.*, 1994; Winters *et al.*, 1998; Yates and Strzepek, 1998). This has been extended to land use (Lee, 2009; Ronneberger *et al.*, 2009), water use (Calzadilla *et al.*, 2011; Kane *et al.*, 1992), and multiple stresses (Reilly *et al.*, 2007). General equilibrium models have also been used to estimate the value of improved weather forecasts (Arndt and Bacou, 2000), a form of adaptation to climate change. Computable general equilibrium analysis has also been used to study selected impacts other than agriculture, notably sea level rise (Bosello *et al.*, 2007b; Darwin and Tol, 2001), tourism (Berrittella *et al.*, 2006; Bigano *et al.*, 2008), human health (Bosello *et al.*, 2006) and energy (see 10.2).

(Bigano *et al.*, 2008) study the joint, global impact on tourism and coasts in the 21st century, finding that changes in tourist demand dominate the welfare impacts of sea level rise. (Kemfert, 2002) and (Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) estimate the joint, global effect on the world economy(Eboli *et al.*, 2010b) of a range of climate change impacts in the 21st century, but conflate general equilibrium and growth effects. (Aaheim *et al.*, 2010) analyze the economic effects of impacts of climate change on agriculture, forestry, fishery, energy demand, hydropower production, and tourism on the Iberian Peninsula. They find positive impacts on output in some sectors (agriculture, electricity) negative impacts in other sectors (forestry, transport) and negligible ones in others (manufacturing, services). (Ciscar *et al.*, 2011) study the combined impact on agriculture, coasts, river floods and tourism in the current European economy. They find an average welfare loss of 0.2-1.0% (depending on the SRES scenario) but there are large regional differences with losses in Southern Europe and gains in Northern Europe.

The following initial conclusions emerge. First, markets matter. Impacts are transmitted across locations—with local, regional and global impacts-- and across multiple sectors of the economy. For instance, landlocked countries are affected by sea level rise because their agricultural land increases in value as other countries face erosion and floods. Second, consumers and producers are often affected differently. The price increases induced by a reduction in production may leave producers better off while hurting consumers. Third, the distribution of the direct impacts can be very different than the distribution of the indirect effects. For instance, a loss of production may be advantageous to an individual company or country if the competition loses more. Fourth, a loss of productivity or productive assets in one sector leads to further losses in the rest of the economy. Fifth, markets offer options for adaptation, particularly possibilities for substitution. This changes the size, and sometimes the sign of the impact estimate.

10.9.2. Aggregate Impacts

Since AR4, four new estimates of the global aggregate impact on human welfare of moderate climate change were published (Bosello *et al.*, 2012; Maddison and Rehdanz, 2011; Roson and van der Mensbrugghe, 2012), including two estimates for warming greater than 3°C. Estimates agree on the size of the impact (small relative to economic growth) but disagree on the sign (Figure 10-1). Climate change may be beneficial for moderate climate change but turn negative for greater warming. Impacts worsen for larger warming, and estimates diverge. The new estimates have slightly widened the uncertainty about the economic impacts of climate.

Welfare impacts have been estimated with different methods, ranging from expert elicitation to econometric studies and simulation models. Different studies include different aspects of the impacts of climate change, but no estimate is complete; most experts speculate that excluded impacts are on balance negative (Füssel, 2010; Tol, 2008; Yohe, 2008). Estimates across the studies reflect different assumptions about intersectoral, interregional and intertemporal interactions, about adaptation, and about the monetary values of impacts. Aggregate estimates of costs mask significant differences in impacts across sectors, regions, countries and populations. Relative to their income, economic impacts are higher for poorer people.

[INSERT FIGURE 10-1 HERE
Figure 10-1: Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR5 are highlighted as diamonds; see Table 10.B.1.]

10.9.3. Social Cost of Carbon

The social cost of carbon (SCC) monetizes the expected welfare impacts of a marginal increase in carbon dioxide emissions in a given year (i.e., the welfare loss associated with an additional tonne of CO_2 emitted), aggregated across space, time, and probability (Tol, 2011). Figure 10-2 shows estimates published before AR4 and since, using the kernel density estimator by (Tol, 2013), extending the data with new estimates by (Anthoff and Tol, 2013b; Hope and Hope, 2013; Hope, 2013; Interagency Working Group on the Social Cost of Carbon, 2013). Central estimates of the social cost of carbon have fallen slightly for all pure rates of time preference and the uncertainty has tightened, particularly for studies that use a pure rate of time preference of zero. See Table 10-9. For comparison, the EU ETS price in July 2013 was about $21/tC.

[INSERT TABLE 10-9 HERE
Table 10-9: Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (N; number of studies in brackets).]

Uncertainty in SCC estimates is high due to the uncertainty in underlying total damage estimates (see 10.9.2), uncertainty about future emissions, future climate change, future vulnerability and future valuation. The spread in estimates is also high due to disagreement regarding the appropriate framework for aggregating impacts over time (discounting), regions (equity weighing), and states of the world (risk aversion).

Quantitative analyses have shown that SCC estimates can vary by at least ~2x depending on assumptions about future demographic conditions (Interagency Working Group on the Social Cost of Carbon, 2010), at least ~3x due to the incorporation of uncertainty (Kopp *et al.*, 2012), and at least ~4x due to differences in discounting (Tol, 2011) or alternative damage functions (Ackerman and Stanton, 2012).

Concerns have been raised that the uncertainty about climate change is so large that the SCC would be unbounded (Weitzman, 2009), but this result is sensitive to assumptions about the utility function (Buchholz and Schymura, 2012; Millner, 2013; Nordhaus, 2011) and disappears when climate policy is formulated as balancing the risks of climate change against those of mitigation policy (Anthoff and Tol, 2013a; Hwang *et al.*, 2013).

[INSERT FIGURE 10-2 HERE
Figure 10-2: Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).]

10.9.4. Effects on Growth

10.9.4.1. The Rate of Economic Growth

Climate change will also affect economic growth and development, but our understanding is limited. (Fankhauser and Tol, 2005) investigate four standard models of economic growth and three transmission mechanisms: economic production, capital depreciation, and the labor force. They find that, in three models, the fall in economic output is slightly larger than the direct impact on markets while in the 4th model (which emphasizes human capital accumulation) indirect impacts are 1.5 times as large. The difference can be understood as follows. In the three models, the impacts of climate change crowd out consumption and investment in physical capital, while in the fourth model investment in human capital is also crowded out; lower investment implies slower growth. (Hallegatte, 2005) reaches a similar conclusion. (Hallegatte and Thery, 2007; Hallegatte and Ghil, 2008; Hallegatte and Dumas, 2009) highlight that the impact of climate change through natural hazards on economic growth can be amplified by market imperfections and the business cycle. Additionally, (Eboli *et al.*, 2010a; Eboli *et al.*, 2010b) use a multi-sector, multi-region growth model, and find that the impact of climate change would lead to a 0.3% reduction of global GDP in 2050. Regional impacts are more pronounced, ranging from -1.0% in developing countries to +0.4% in Australia and Canada. In contrast, (Garnaut, 2008) finds -2.1% for Australia; the difference is mainly due to impacts on infrastructure (cf. Section 10.4). Sectoral results are varied too, with output changes ranging from +0.5% for power generation (to meet increased demand to air conditioning) to -0.7% for natural gas (as demand for space heating falls).

Using a biophysical model of the human body's ability to do work, (Kjellstrom *et al.*, 2009) find that by the end of the century climate change may reduce labor productivity by 11-27% in the humid (sub)tropics (depending on the SRES scenario; see Chapter 11 for further discussion). Assuming an output elasticity of labor of 0.8, this would reduce economic output in the affected sectors (involving heavy manual labor without air conditioning) by 8-22%. Although structural changes in the economy may well reduce the dependence on manual labor and air conditioning would be an effective adaptation, even the ameliorated impact would have a substantial, but as yet unquantified, impact on economic growth.

There are also statistical analyses of the relationship between climate and economic growth. (Barrios *et al.*, 2010) find that the decline in rainfall in the 20th century partly explains the economies of Sub-Saharan Africa have grown more slowly than those of other developing regions. (Brown *et al.*, 2011) corroborate this. (Dell *et al.*, 2012) find that, in the second half of the 20th century, anomalously hot weather slowed down economic growth in poor countries, in both the agricultural and the industrial sectors. (Dell *et al.*, 2009) find that one degree of warming would reduce income by 1.2% in the short run, and by 0.5% in the long run. The difference is due to adaptation. (Horowitz, 2009) finds a much larger effect: a 3.8% drop in income in the long run for one degree of warming. The impact of natural disasters on economic growth in the long-term is disputed, with studies reporting positive effects (Skidmore and Toya, 2002), negative effects (Raddatz, 2009), and no discernible effects (Cavallo *et al.*, 2013).

10.9.4.2. Poverty Traps

Poverty is concentrated in the tropics and subtropics. This has led some analysts to the conclusion that a tropical climate is one in a complex of causes of poverty (which itself is a cause of poverty). We here focus on national economies, while Chapter 13 discusses groups of people in poverty. (Gallup *et al.*, 1999) emphasize the link between climate, disease, and poverty while (Masters and McMillan, 2001) focus on climate, agricultural pests, and poverty. Other studies (Acemoglu *et al.*, 2001; Acemoglu *et al.*, 2002; Easterly and Levine, 2003) argue that climatic influence on development disappears if differences in human institutions (the rule of law, education, etc) are accounted for. However, (Van der Vliert, 2008) demonstrates that climate affects human culture and thus institutions, but this has yet to be explored in the economic growth literature. (Brown *et al.*, 2011) find that weather affects economic growth in Sub-Saharan Africa – particularly, drought decelerates growth. (Jones and Olken, 2010) find that exports from poor countries fall during hot years. (Bloom *et al.*, 2003) find limited support for an impact of climate (rather than weather) on past growth in a single-equilibrium model, but strong support in a multiple-equilibrium model: Hot and wet conditions and large variability in rainfall reduce long-term growth in poor countries (but not in hot ones) and increase the probability of being poor.

(Galor and Weil, 1996) speculate about the existence of a climate-health-poverty trap. (Bonds *et al.*, 2010; Bretschger and Valente, 2011; Gollin and Zimmermann, 2012; Ikefuji and Horii, 2012; Strulik, 2008) posit theoretical models and offer limited empirical support, while (Tang *et al.*, 2009) offers more rigorous empirical evidence. This is further supported by yet-to-be-published analyses (Gollin and Zimmermann, 2008; Ikefuji *et al.*, 2010). Climate-related diseases such as malaria and diarrhea impair children's cognitive and physical development. This contributes to poverty in their later life so that there are limited means to protect their own children against these diseases. Furthermore, high infant mortality may induce parents to have many children so that the investment in education is spread thin. An increase in infant and child mortality and morbidity due to climate change could thus trap more people in poverty.

(Ikefuji and Horii, 2012; Zimmerman and Carter, 2003) build a model in which the risk of natural disasters causes a poverty trap: At higher risk levels, households prefer assets with a safe but low return. (Carter *et al.*, 2007) find empirical support for this model at the household level, but (van den Berg, 2010) concludes the natural disaster itself has no discernible impact on investment choices. At the macro-economic level, natural disasters disproportionally affect the growth rate of poor countries (Noy, 2009).

(Devitt and Tol, 2012) construct a model with a conflict-poverty trap, and show that climate change may exacerbate this. (Bougheas *et al.*, 1999; Bougheas *et al.*, 2000) show that more expensive infrastructure, for example because of frequent repairs after natural disasters, slows down economic growth and that there is a threshold infrastructure cost above which trade and specialization do not occur, suggesting another mechanism through which climate could cause a poverty trap. The implications of climate change have yet to be assessed.

10.9.5. Summary

In sum, estimates of the aggregate economic impact of climate change are relative small but with a large downside risk. Estimates of the incremental damage per tonne of carbon dioxide emitted vary by two orders of magnitude, with the assumed discount rate the main driver of the differences between estimates. The literature on the impact of climate and climate change on economic growth and development has yet to reach firm conclusions. There is agreement that climate change would slow economic growth, by a little according to some studies and by a lot according to other studies. Different economies will be affected differently. Some studies suggest that climate change may trap more people in poverty.

10.10. Summary; Research Needs and Priorities

Table 10-10 summarizes the main findings. For each of the sectors discussed above, it gives the main climate drivers, the relationship between climate and impact (limited to less than linear, linear, and more than linear), the sign of the impacts (where needed split by economic actor), drivers other than climate change, and the relative importance of climate change.

[INSERT TABLE 10-10 HERE
Table 10-10: Summary of findings.]

Evaluating the economic aspects of the impacts has emerged as an active research area. Initial work has developed in a few key economic sectors and through economy wide economic assessments. Data, tools and methods continue to evolve to address additional sectors and more complex interactions among the sectors in the economic systems and a changing climate.

Based on a comprehensive assessment across economic sectors, few key sectors have been subject to detailed research. Multiple aspects of energy impacts have been assessed, but others remain to be evaluated, particularly economic impact assessments of adaptation both on existing and future infrastructure, but also the costs and benefits for future systems under differing climatic conditions. Studies focused on the impacts of climate change on the energy sector indicate both potential benefits and detrimental impacts across developed and developing countries. In energy supply, the deployment of extraction, transport and processing infrastructure, power plants and other installations are expected to proceed rapidly in developing countries in the coming decades to satisfy fast growing demand for energy. Designing newly deployed facilities with a view to projected changes in climate attributes and extreme weather patterns would require targeted inquiries into the impacts of climate change on the energy related resource base, conversion and transport technologies.

The economics of climate change impacts on transportation systems and their role in overall economic activity have yet to be well understood. For water related sectors, improved estimation of flood damages to economic sectors, research on economic impacts of ecosystems, rivers, lakes and wetlands, ecosystems service, and tourism and recreation are needed. Economic assessments of adaptation strategies such as water savings technologies, particularly for semi-arid and arid developing countries, are also needed. Further, detailed studies are needed of the integrated impact of climate change on all water-dependent economic sectors, as existing studies do not examine competitiveness between water uses among sectors and economic productivity.

Although both tourism and recreation are sensitive to climate change, the literature on tourism is far more extensive. Current studies either have a rudimentary representation of the effect of weather and climate but a detailed representation of substitution between holiday destination and activities, or a detailed representation of the immediate impact of climate change but a rudimentary representation of alternatives to the affected destinations or activities.

Considerable research has been developed related to climate change impacts on insurance; however, only limited research is available on observed and projected changes in insured climate-related losses. To advance such research, climate science and risk research communities need to be better integrated. Additionally, only few quantitative projection studies exist on regional markets including scenarios of changing hazard properties, exposure, vulnerability and adaption status, regulation, and availability of risk-based capital to indemnify disaster losses. Little research is available on the implications of climate change for banking/investment activities, in particular regarding the direct exposure of financial infrastructure. But also indirect effects through value losses in loan portfolios and assets as a result of physical damage and regulatory/reputational effects, together with liability and litigation risks, are underinvestigated.

Little literature exists on potential climate impacts on other economic sectors, such as mining, manufacturing, and services (apart from health, insurance and tourism); in particular assessments of whether these sectors are indeed sensitive to climate and climate change.

The spillover effects of the impacts of climate change in one sector on other markets are understood in principle, but the number of quantitative studies is too few to place much confidence in the numerical results. Similarly, the impact of climate and climate change on economic growth and development is not well understood, with some studies pointing to a small or negligible effect and other studies arguing for a large or dominant effect. A limited set of studies have evaluated the aggregate economic impact of climate change up to 3°C annual mean temperature rise, while only one study has evaluated larger temperature scenarios; suggesting considerable new analysis is warranted to improved confidence in the conclusions and investigation of a broader suite of RCPs.

Frequently Asked Questions

FAQ 10.1: Why are key economic sectors vulnerable to climate change? *[to be placed after Section 10.1]*
Many key economic sectors are affected by long-term changes in temperature, precipitation, sea level rise, and extreme events, all of which are impacts of climate change. For example, energy is used to keep buildings warm in winter and cool in summer. Changes in temperature would thus affect energy demand. Climate change also affects energy supply through the cooling of thermal plants, through wind, solar and water resources for power, and through transport and transmission infrastructure. Water demand increases with temperature but falls with rising carbon dioxide concentrations as carbon dioxide fertilization improves the water use efficiency plant respiration. Water supply depends on precipitation patterns and temperature, and water infrastructure is vulnerable to extreme weather, while transport infrastructure is designed to withstand a particular range of weather conditions, and climate change would expose this infrastructure to weather outside historical design criteria. Recreation and tourism are weather-dependent. As holidays are typically planned in advance, tourism depends on the *expected* weather and will thus be affected by climate change. Health care systems are also impacted, as climate change affects a number of diseases and thus the demand for and supply of health care.

FAQ 10.2: How does climate change impact insurance and financial services? *[to be placed in Section 10.7]*
Insurance buys financial security against, among other perils, weather hazards. Climate change, including changed weather variability, is anticipated to increase losses and loss variability in various regions through more frequent and/or intensive weather disasters. This will challenge insurance systems to offer coverage for premiums that are still affordable, while at the same time requiring more risk-based capital. Adequate insurance coverage will be challenging in low and middle-income countries. Other financial service activities can be affected depending on the exposure of invested assets/loan portfolios to climate change. This exposure includes not only physical damage but also regulatory/reputational effects, liability and litigation risks.

FAQ 10.3: Are other economic sectors vulnerable to climate change too? *[to be placed in Section 10.8]*
Economic activities such as agriculture, forestry, fisheries and mining are exposed to the weather and thus vulnerable to climate change. Other economic activities, such as manufacturing and services, largely take place in controlled environments and are not really exposed to climate change. However, markets connect sectors so that the impacts of climate change spill over from one activity to all others. The impact of climate change on economic development and growth also affects all sectors.

Cross-Chapter Box

Box CC-WE: The Water-Energy-Food/Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between countries, regions and production systems. Energy technologies (e.g. biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber 2008; McMahon and Price, 2011; Macknick *et al*., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Asano et al., 2006; Khan and Hanjra, 2009; USEPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012) *(robust evidence, high agreement)*. Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Sung et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Sections 10.2.2 10.3.4, 25.7.4; van Vliet et al., 2012; Davies et al., 2013) *(robust evidence, high agreement)*. Water for biofuels, for example, under the IEA Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (WEC, 2010; Sattler et al., 2012) *(medium evidence, high agreement)*. Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) *(robust evidence, high agreement).*

Water may require significant amounts of energy for lifting, transport and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly– electricity use (kWhr/m^3 of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012).

The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (Smit and Nasr, 1992; Jimenez, 1996; Wichelns et al., 2007; Raschid-Sally and Jayakody, 2008) *(medium confidence)*. More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita et al, 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) *(high confidence)*.

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) *(robust evidence, high agreement)*. Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (Sections 25.4.3 and 25.6.2, Box 25-10) *(medium evidence, high agreement)*. Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity and other factors (see Figure WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this report.

The interconnectivity of food/fiber, water, land use, energy and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel-food-land use-water-GHG mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type and use requirements, energy requirements and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use and climate change is increasingly recognized as critical to effective climate resilient pathway decision making *(medium evidence, high agreement)*, although tools to support local- and regional-scale assessments and decision-support remain very limited.

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APPENDICES

Appendix 10.A. Industrial Classification

International Standard Industrial Classification (ISIC) of All Economic Activities, Rev.4, the outline of Chapter 10, and nil returns in a literature search on Scopus.

- A - Agriculture, forestry and fishing (10.5)
  - 01 - Crop and animal production, hunting and related service activities
  - 02 - Forestry and logging
  - 03 - Fishing and aquaculture
- B - Mining and quarrying (10.5)
  - 05 - Mining of coal and lignite
  - 06 - Extraction of crude petroleum and natural gas
  - 07 - Mining of metal ores
  - 08 - Other mining and quarrying
    - Climate change impact & quarrying: No results*
  - 09 - Mining support service activities
- C – Manufacturing (10.5, except C19)
  - 10 - Manufacture of food products
    - Climate change impact & food products: No results*
    - Climate change impact & food processing: No results*
  - 11 - Manufacture of beverages
    - Climate change impact & beverages: No results*
  - 12 - Manufacture of tobacco products
    - Climate change impact & tobacco: No results*
  - 13 - Manufacture of textiles
    - Climate change impact & textiles: No results*
  - 14 - Manufacture of wearing apparel
    - Climate change impact & apparel: No results*
  - 15 - Manufacture of leather and related products
    - Climate change impact & leather: No results*
  - 16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
    - Climate change impact & wood: No results*
  - 17 - Manufacture of paper and paper products
    - Climate change impact & pulp paper: No results*
  - 18 - Printing and reproduction of recorded media
    - Climate change impact & printing: No results*

        - Climate change impact & recorded media: No results*
    - 19 - Manufacture of coke and refined petroleum products (10.2)
    - 20 - Manufacture of chemicals and chemical products
        - Climate change impact & chemical production: No results*
    - 21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations
        - Climate change impact & pharmaceutical: No results*
    - 22 - Manufacture of rubber and plastics products
        - Climate change impact & rubber: No results*
        - Climate change impact & plastic: No results*
    - 23 - Manufacture of other non-metallic mineral products
        - Climate change impact & cement: No results*
        - Climate change impact & glass: No results*
    - 24 - Manufacture of basic metals
        - Climate change impact & steel: No results*
        - Climate change impact & iron: No results*
        - Climate change impact & alumina: No results*
        - Climate change impact & aluminum: No results*
    - 25 - Manufacture of fabricated metal products, except machinery and equipment
        - Climate change impact & metal: No results*
    - 26 - Manufacture of computer, electronic and optical products
        - Climate change impact & equipment: No results*
    - 27 - Manufacture of electrical equipment
        - Climate change impact & equipment: No results*
    - 28 - Manufacture of machinery and equipment n.e.c.
        - Climate change impact & equipment: No results*
        - Climate change impact & machinery: No results*
    - 29 - Manufacture of motor vehicles, trailers and semi-trailers
        - Climate change impact & vehicle: No results*
    - 30 - Manufacture of other transport equipment
        - Climate change impact & equipment: No results*
    - 31 - Manufacture of furniture
        - Climate change impact & furniture: No results*
    - 32 - Other manufacturing
    - 33 - Repair and installation of machinery and equipment
        - Climate change impact & equipment: No results*
        - Climate change impact & machinery: No results*
- D - Electricity, gas, steam and air conditioning supply (10.2)
    - 35 - Electricity, gas, steam and air conditioning supply
- E - Water supply; sewerage, waste management and remediation activities
    - 36 - Water collection, treatment and supply (10.3)
    - 37 – Sewerage (10.3)
    - 38 - Waste collection, treatment and disposal activities; materials recovery (10.8)
    - 39 - Remediation activities and other waste management services (10.8)
- F – Construction (10.5)
    - 41 - Construction of buildings
    - 42 - Civil engineering
    - 43 - Specialized construction activities
- G - Wholesale and retail trade; repair of motor vehicles and motorcycles (10.8)
    - 45 - Wholesale and retail trade and repair of motor vehicles and motorcycles
    - 46 - Wholesale trade, except of motor vehicles and motorcycles
    - 47 - Retail trade, except of motor vehicles and motorcycles
- H - Transportation and storage (10.4)
    - 49 - Land transport and transport via pipelines
    - 50 - Water transport

    - 51 - Air transport
    - 52 - Warehousing and support activities for transportation
    - 53 - Postal and courier activities
- I - Accommodation and food service activities (10.6)
    - 55 - Accommodation
    - 56 - Food and beverage service activities
- J - Information and communication (10.8)
    - 58 - Publishing activities
    - 59 - Motion picture, video and television programme production, sound recording and music publishing activities
    - 60 - Programming and broadcasting activities
    - 61 - Telecommunications
    - 62 - Computer programming, consultancy and related activities
    - 63 - Information service activities
- K - Financial and insurance activities (10.7)
    - 64 - Financial service activities, except insurance and pension funding
    - 65 - Insurance, reinsurance and pension funding, except compulsory social security
    - 66 - Activities auxiliary to financial service and insurance activities
- L - Real estate activities (10.8)
    - 68 - Real estate activities
- M - Professional, scientific and technical activities (10.8)
    - 69 - Legal and accounting activities
    - 70 - Activities of head offices; management consultancy activities
    - 71 - Architectural and engineering activities; technical testing and analysis
    - 72 - Scientific research and development
    - 73 - Advertising and market research
    - 74 - Other professional, scientific and technical activities
    - 75 - Veterinary activities
- N - Administrative and support service activities (10.8 except N79)
    - 77 - Rental and leasing activities
    - 78 - Employment activities
    - 79 - Travel agency, tour operator, reservation service and related activities (10.6)
    - 80 - Security and investigation activities
    - 81 - Services to buildings and landscape activities
    - 82 - Office administrative, office support and other business support activities
- O - Public administration and defence; compulsory social security (10.8)
    - 84 - Public administration and defence; compulsory social security
- P – Education (10.8)
    - 85 - Education
- Q - Human health and social work activities (10.8)
    - 86 - Human health activities
    - 87 - Residential care activities
    - 88 - Social work activities without accommodation
- R - Arts, entertainment and recreation (10.6)
    - 90 - Creative, arts and entertainment activities
    - 91 - Libraries, archives, museums and other cultural activities
    - 92 - Gambling and betting activities
    - 93 - Sports activities and amusement and recreation activities
- S - Other service activities (10.8)
    - 94 - Activities of membership organizations
    - 95 - Repair of computers and personal and household goods
    - 96 - Other personal service activities
- T - Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use (10.8)

    - 97 - Activities of households as employers of domestic personnel
    - 98 - Undifferentiated goods- and services-producing activities of private households for own use
- U - Activities of extraterritorial organizations and bodies (10.8)
    - 99 - Activities of extraterritorial organizations and bodies

*No results = no results for the impact of climate change on this particular economic activity. There may be results for the impact of climate change on a related activity, or for the impact of the activity on climate change.

Appendix 10.B. Estimates of the Total and Marginal Economic Impact of Climate Change

Table 10.B.1: Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.
[NB: See tables file for content.]

Table 10-1: Main projected impacts of climate change and extreme weather events on energy supply and the related adaptation options.

Tech	Changes in climatic or related attributes	Possible impacts	Adaptation options
Thermal and nuclear power plants	Increasing air temperature	Reduces efficiency of thermal conversion by 0.1-0.2% in the USA; by 0.1-0.5% in Europe where the capacity loss is estimated in the range of 1-2%/1°C temperature increase, accounting for decreasing cooling efficiency and reduced operation level/shutdown	Siting at locations with cooler local climates where possible
	Changing (lower) precipitation and increasing air temperature increases temperature and reduces the availability of water for cooling	Less power generation; annual average load reduction by 0.1-5.6% depending on scenario	Use of non-traditional water sources (e.g., water from oil and gas fields, coal mines and treatment, treated sewage); Re-use of process water from flue gases (can cover 25-37% of the power plants cooling needs), coal drying, condensers (dryer coal has higher heating value, cooler water enters cooling tower),, flue-gas desulphurization; Using ice to cool air before entering the gas turbine increases efficiency and output, melted ice used in cooling tower; Condenser mounted at the outlet of cooling tower to reduce evaporation losses (by up to 20%). Alternative cooling technologies: dry cooling towers, regenerative cooling, heat pipe exchangers; Costs of retrofitting cooling options depend on depend on features of existing systems, distance to water, required additional equipment, estimated at US$250,000-500,000/MW
	Increasing frequency of extreme hot temperatures	Exacerbating impacts of warmer conditions: reduced thermal and cooling efficiency; limited cooling water discharge; overheating buildings; self-ignition of coal stockpiles	Cooling of buildings (air conditioning) and of coal stockpiles (water spraying)
	Drought: reduced water availability	Exacerbating impacts of warmer conditions, reduced operation and output, shutdown	Same as reduced water availability under gradual CC
Hydropower	Increase/decrease in average water availability	Increased/reduced power output	Schedule release to optimize income
	Changes in seasonal and inter-annual variation in inflows (water availability)	Shifts in seasonal and annual power output; floods and lost output in the case of higher peak flows	Soft: adjust water management Hard: build additional storage capacity, improve turbine runner capacity
	Extreme precipitation causing floods	Direct and indirect (by debris carried from flooded areas) damage to dams and turbines, lost output due to releasing water through by-pass channels	Soft: adjust water management Debris removal Hard: increase storage capacity
Solar energy	Increasing mean temperature	Improving performance of TH (especially in colder regions), reducing efficiency of PV and CSP with water cooling; PV efficiency drops by ~0.5%/1°C temperature increase for crystalline Si and thin-film modules as well, but	

		performance varies across types of modules, with thin film modules performing better; Long-term exposure to heat causes faster aging	
	Changing cloudiness	Increasing unfavourable (reduced output), decreasing beneficial (increased output) for all types, but evacuated tube collectors for TH can use diffuse insolation. CSP more vulnerable (cannot use diffuse light)	Apply rougher surface for PV panels that use diffuse light better; optimize fixed mounting angle for using diffuse light, apply tracking system to adjust angle for diffuse light conditions; Install/increase storage capacity
	Hot spells	Material damage for PV, reduced output for PV and CSP; CSP efficiency decreases by 3-9% as ambient temperature increases from 30 to 50°C and drops by 6% (tower) to 18% (trough) during the hottest 1% of time	Cooling PV panels passively by natural ail flows or actively by forced air or liquid coolants
	Hail	Material damage to TH: evacuated tube collectors are more vulnerable than flat plate collectors; Fracturing as glass plate cover, damage to photoactive material	Flat plate collectors: using reinforced glass to withstand hailstones of 35mm (all of 15 tested) or even 45 mm (10 of 15 tested); only 1 in 26 evacuated tube collectors withstood 45mm hailstones Increase protection to current standards or beyond them
Wind power	Windiness: total wind resource (multi-year annual mean wind power densities); *likely* to remain within ±50% of current values in Europe and North America; within ±25% of 1979-2000 historical values in contiguous USA	Change in wind power potential	Site selection
	Wind speed extremes: gust, direction change, shear	Structural integrity from high structural loads; fatigue, damage to turbine components; reduced output	Turbine design, lidar-based protection

Sources: (Sieber, 2013), (Parkpoom *et al.*, 2005), (Feeley III *et al.*, 2008; Förster and Lilliestam, 2009; Hoffmann *et al.*, 2010; Linnerud *et al.*, 2011; Mukheibir, 2013; NETL (National Energy Technology Laboratory), 2007; Ott and Richter, 2008; Williams, 2013), (Markoff and Cullen, 2008; Schaefli *et al.*, 2007),(Droogers, 2009). (Bloom *et al.*, 2008; Christensen and Busuioc, 2007; DOE, 2007; EPA, 2001; Haugen and Iversen, 2008; Honeyborne, 2009; Kurtz *et al.*, 2009; Kurtz *et al.*, 2011; Leckebusch *et al.*, 2008; Norton, 2006; Patt *et al.*, 2013; Pryor *et al.*, 2006; Pryor and Barthelmie, 2010; Pryor and Barthelmie, 2013; Pryor and Barthelmie, 2011; Pryor and Schoof, 2010; Sailor *et al.*, 2008; SPF, 2009; Walter *et al.*, 2006).
Notes: TH: thermal heating; PV: photovoltaic; CSP: concentrating solar power.

Table 10-2: Main impacts of climate change and extreme weather events on pipelines and the electricity grid.

Tech	Changes in climatic or related attribute	Impacts	Adaptation options
Pipelines	Melting permafrost	Destabilizing pillars, obstructing access for maintenance and repair	Adjust design code and planning criteria, install disaster mitigation plans
	Increasing high wind, storms, hurricanes	Damage to offshore and onshore pipelines and related equipment, spills; lift and blow heavy objects against pipelines, damage equipment	Enhance design criteria, update disaster preparedness
	Flooding caused by heavy rain, storm surge or sea-level rise	Damage to pipelines, spills	Siting (exclude flood plains), water proofing
Electricity grid	Increasing average temperature	Increased transmission line losses	Include increasing temperature in the design calculation for maximum temperature/rating
	Increasing high wind, storms, hurricanes	Direct mechanical damage to overhead lines, towers, poles, substations, flashover caused by live cables galloping and thus touching or getting too close to each other; indirect mechanical damage and short circuit by trees blown over or debris blown against overhead lines	Adjust wind loading standards, reroute lines alongside roads or across open fields, vegetation management, improved storm and hurricane forecasting
	Extreme high temperatures	Lines and transformers may overheat and trip off; flashover to trees underneath expanding cable	Increase system capacity, increase tension in the line to reduce sag, add external coolers to transformers
	Combination of low temperature, wind and rain, ice storm	Physical damage (including collapse) of overhead lines and towers caused by ice build-up on them	Enhance design standard to withstand larger ice and wind loading, reroute lines alongside roads or across open fields, improve forecasting of ice storms impacts on overhead lines and on transmission circuits

Sources: (Bayliss, 1996; Cruz and Krausmann, 2013; Hines *et al.*, 2009; Krausmann and Mushtaq, 2008; Reed, 2008; Winkler *et al.*, 2010),(Vlasova and Rakitina, 2010), (Ward, 2013), (McColl, 2012).

Table 10-3: Economy-wide implications of impacts of climate change and extreme weather on the energy sector.

Study	Model Type	Climate Impacts Modelled	Energy/Economic Impacts	Regions	Sectors Studied
(Bosello *et al.*, 2009)	IAM	Rising temperatures/ changing demand for energy; impacts from 4 other sectors/events (Global, 2001 - 2050)	Change in GDP in 2050 due to rising temperatures and changing energy demand: 0% to 0.75% (+1.2°C); -0.1% to 1.2% (+3.1°C)	14	4
(Jorgenson *et al.*, 2004)	CGE	Rising temperatures/ changing demand for energy; climate impacts from 3 other sectors (USA, 2000 - 2100)	Optimistic adaptation: 4% to 6.7% higher energy productivity per year (2000 – 2100); Output from electricity: -6% in 2050; GDP is +0.7% (aggregate all sectors, avg annual 2000 – 2100) Pessimistic adaptation: 0.5% to 2.2% lower energy productivity per year; Output from electricity: +2% in 2050; GDP is -0.6% (aggregate impact all sectors)	1	35
(Bosello *et al.*, 2007a)	CGE	Rising temperatures/ changing demand for energy (Global, 2050)	Change in GDP in 2050 (perfect competition): -0.297% to 0.027%; Change in GDP in 2050 (imperfect competition): -0.303% to 0.027%	8	1
(Aaheim *et al.*, 2009)	CGE	Change in precipitation -> share of hydro power; rising temperatures/ changing demand for energy ; impacts from 4 other sectors (Western Europe, 2071 – 2100)	Impact from all sectors in 2100: GDP in cooler regions: -1% to -0.25% GDP in warmer regions: -3% to -0.5% Adaptation can mitigate 80% to 85% of economic impact	8	11
(Boyd and Ibarraran, 2009)	CGE	Drought scenario affecting hydro plus 3 other sectors (Mexico, 2005 - 2026)	Generation output in 2026: -2.1% Refining output: -10.1% Coal output: -7.8% NG output: -2% Crude oil output: +1.7% GDP: -3% With adaptation: Generation output in 2026: 0.24%% Refining output: 1.36%% Coal output: 1.09%% NG output: 0.34%% Crude oil output: 0.22% GDP: 0.33%	1	2
(Jochem *et al.*, 2009)	PE/ CGE	Rising temperatures/ changing demand for energy; Change in technical potential of renewables; Change in rainfall -> change in hydro; High temperatures -> water temperatures exceeding regulatory limits (Europe); High temperatures -> greater electric grid losses and lower thermal efficiency; generic extreme events -> reduced capital stock in CGE model (EU27+2, 2005 – 2050)	GDP (Europe): -50 billion € p.a. in 2035 GDP (Europe): -240 billion € p.a. in 2050 GDP (EU regions): -0.1% to -0.4% in 2035 GDP (EU regions): -0.6% to -1.3% in 2050 Jobs (Europe): -380K in 2035 Jobs (Europe): -1 million in 2050	25	1

(Eboli *et al.*, 2010a; Eboli *et al.*, 2010a)	CGE	Rising temperatures/ changing demand for energy; climate impacts in 4 other sectors modelled (Global, 2002 - 2100)	By 2100, change in GDP due to climate impacts on energy demand vary by country between ~ -0.15% and 0.7%. USA and Japan were negative and all other countries positive. Overall economic impact from all sectors is neutral to positive for developed countries and negative for developing.	8	17
(Golombek *et al.*, 2011)	PE	Rising temperatures/ changing demand for energy; Rising temp/ reduced thermal efficiency; change in water inflow (Western Europe, 2030)	Net impact on the price of electricity is a 1% increase. Generation decreases by 4%	13	4
(de Lucena *et al.*, 2010)	PE	Changing precipitation -> Change in hydro production; rising temp -> lower NG thermal efficiency; rising temperature -> change in demand for energy (Brazil, 2010 - 2035)	New generating capacity needed to produce additional 153 – 162 TWh per year. Capital investment of $48 to $51 billion, which is equivalent to 10 years of capital expenditures in Brazil’s long-term energy plan. $6.9 to $7.2 billion in additional operating expenses in years with worst-case hydro production	1	11
(Bye *et al.*, 2008)	PE	Water shortages (Nordic countries, hypothetical 2 year period)	Water shortage scenarios can lead to a 100% increase in electricity prices at peak demand over a 2 year period. Higher prices lead to marginal reductions in demand (~ 1% - 2.25%).	4	1
(Koch *et al.*, 2012)	PE	High temperatures -> water temperatures exceeding regulatory limits (Berlin, 2010 - 2050)	Thermal plant outages amounting to 60 million EURO for plants in Berlin through 2050	1	1
(Gabrielsen *et al.*, 2005)	Econometric	Rising temperatures/ changing demand for energy; change in water inflow; change in wind speeds (Nordic countries, 2000 - 2040)	Net change in electricity supply in 2040: 1.8%. Change in electricity demand: 1.4%. Change in electricity price: -1.0%	4	1
(UNDP, 2011)	PE	Damage Case 1 (DC1): Hotter in Both Winter and Summer – Decreased demand for heating and increased demand for cooling; Damage Case 2 (DC2): Colder in Both Winter and Summer – Increased demand for heating and decreased demand for cooling,; Damage Case 3 (DC3): Colder in the Winter and Hotter in the Summer – Increased demand for heating and increased demand for cooling.(Macedonia, 2009 – 2030)	Change in electricity demand in residential and commercial sectors: DC1: 3.5% DC2: 0,3% DC3: 8% Change in electricity system cost: DC1: 0,8% DC2: 0.06% DC3: 1.74%	9	5
(DOE, 2009)	PE	Drought scenario (Western Electric Coordinating Council, USA, 2010 – 2020)	In 2020, 3.7% reduction in coal generation; 43.4% increase in NG gen; 29.3% reduction in hydro gen. Production cost increase of $3.5 billion. Average monthly electricity prices up 8.1% (Nov) to 24.1% (Jul).	1	1

Note: The regions indicated in the ‘Regions’ column vary in size and are model-specific.

Table 10-4: Observed normalized insured losses from weather hazards (trends significant at the 10% level are indicated as a trend).

Region / peril accounted for in normalized insured property losses	Observation period	Trend in insured losses - otherwise specified (aggregation mode)	References
World / all weather-related	1990-2008	No trend (annual aggregates)	[1]
Australia / aggregate of bushfire, flood, hailstorm, thunderstorm, tropical cyclone	1967-2006	No trend (annual aggregates)	[7]
West Germany / all weather-related West Germany / floods West Germany / convective events West Germany / winter storms	1980-2008 1980-2008 1980-2008 1980-2008	Positive trend (annual aggregates) No trend (annual aggregates) No trend (annual aggregates) Positive trend (annual aggregates)	[1]
Southwest Germany / hailstorm	1986-2004	Positive trends in annual frequency of days exceeding thresholds of daily damage claim counts. Increase in annual count of hail damage claims.	[8]
Spain / floods	1971-2008	No trend (annual aggregates)	[2]
USA / winter storms (ice storms, blizzards and snow storms)	1949-2003	Positive trend (pentade totals) Positive trend (average loss per state, pentade totals)	[3]
USA / all flood ("flood only" and floods specifically caused by convective storms, tropical cyclones, snow-melt)	1972-2006	Positive trend (annual aggregates)	[4]
USA / tropical cyclones	1949-2004	Increase (7-year totals) No statistical trend assessment.	[5]
USA / hailstorm	1951-2006	Focus on top-ten major hail storm losses of the period 1951-2006. Increase in frequency and loss in the 1992-2006 period as compared to 1951-1991. No statistical trend assessment.	[6]
USA east of 109° W / convective events (hail, heavy precipitation and flash flood, straight-line wind, tornado)	1970-2009 March to September	Standard deviation (variability) by a factor 1.65 greater for 1990-2009 than for 1970-1989. Mean annual loss by a factor 2.67 greater for 1990-2009 than for 1970-1989. Data: normalized insured loss exceeding US$ 150 million per event, annual aggregates.	[9]
USA / all weather-related USA / floods USA / convective events USA / winter storms USA / tropical cyclones USA / heat episodes USA / cold spells	1973-2008 1973-2008 1973-2008 1973-2008 1973-2008 1973-2008 1973-2008	Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) Positive trend (annual aggregates) No trend (annual aggregates)	[1]

References: [1] (Barthel and Neumayer, 2012); [2] (Barredo *et al.*, 2012); [3] (Changnon, 2007); [4] (Changnon, 2008); [5] (Changnon, 2009a); [6] (Changnon, 2009b); [7] (Crompton and McAneney, 2008); [8] (Kunz *et al.*, 2009); [9] (Sander *et al.*, 2013).

Table 10-5: Climate change projections of insured losses and/or insurance prices.

Hazard/ insurance line	**Region**	**Projected changes in future time slices relative to current climate (Spatial distribution and vulnerability of insured values assumed to be unchanged over time).**
Winter storm/ Homeowners' insurance	Europe	Projected increases in mean annual loss ratio lie in a range from one to two-digit percentages in time slices before and around 2050 for regions such as France, Belgium/Netherlands, UK/Ireland, Germany, and Poland, with larger increases at the end of the century. Southern European regions expect decreases, such as Portugal/Spain (A1B, A2) [4] [5] [8] [13] [14] [15] [19]. Currently rare and high annual loss ratios are projected to occur more often: today's 20-year, 10-year, and 5-year return periods appear strongly reduced by the end of the century for individual countries. For entire Europe they will be halved (A2) [16]. Accordingly, return periods will have higher loss levels associated [19] [10], e.g., the 25-year loss in Germany is expected to rise by 5% to 41% in 2041–2070 (A1B) [10] [8].
River flood, maritime flood, flash flood from rainfall, melting snow/ Property and business interruption insurances	Europe, North America	Germany: projected increases in mean annual insured flood loss according to a seven-member dynamical downscaling ensemble mean (B1, A1B, A2) are 84% (2011-2040), 91% (2041-2070), and 114% (2071-2100) [7]. United Kingdom: projected increases in mean annual insured flood loss are 8% (for a +2°C rise in global mean temperature) and 14% (for a +4°C rise), with the one-in-hundred-year loss higher by 18% and 30%, respectively [4]. Norway, Canada: losses from heavy precipitation in property and business interruption insurances in four city areas in Canada are projected to rise by 13% (2016-2035), 20% (2046-2065), and 30% (2081-2100) in a five member ensemble mean (IS92a, A2/B2, A2). In three counties across southern Norway precipitation and snowmelt insurance losses are expected to be higher by 10% to 21% (A2) and 17% to 32% (B2) at the end of the century [9;3]. The Netherlands: expected annual property loss with an assumed flood insurance system is projected to lie by 125% higher in 2040 relative to 2015 (corresponding to 24 cm sea level rise) and by 1,784% higher in 2100 (85cm sea level rise) [1].
Tropical cyclones/ Foremost property insurance lines	North America, Asia	U.S.A.: three of four GCMs driving a specific tropical cyclone and loss model entail increasing insured hurricane losses over time (A1B) [6]. Two GCM outputs at coarser resolution for the ende of the century produce contrarious results of prolonged (ECHAM5/MPIOM A2) versus shortened (MRI/JMA A1B) return periods of current loss levels [17]. Analogously, a wide range of model projections is reflected in price levels of Florida's hurricane wind insurance that are projected to change by -20% to +5% (2020s) and -28% to +10% (2040s) (under the assumptions of strained reinsurance capacity and current adaptation) [12;18]. These approaches demonstrate uncertainty in the sign of change. China: projected increases of insured typhoon losses are 20% (for a +2°C rise in global mean temperature) and 32% (for a +4°C scenario), with the one in hundred-year loss higher by 7% and 9%, respectively [4].
Hailstorm/ Homeowners' insurance/ Agricultural insurances	Europe	The Netherlands: losses from outdoor farming insurance and greenhouse horticulture insurance are projected to increase by 25% to 29% and 116% to 134%, respectively, for a +1°C rise in global mean temperature. For a +2°C scenario, projected increases will be higher at 49% to 58% and 219% to 269%, respectively (statistical model) [2]. Germany: projected increases in mean annual loss ratios from homeowners' insurance due to hail are 15% (2011 – 2040) and 47% (2041 – 2070) (A1B, statistical model) [8].
Storms, pests, diseases/ Paddy rice insurance	Asia	Japan: paddy rice insurance payouts are projected to decrease by 13% at the end of the century, on the basis of changes in standard yield and yield variability [11].

References: [1] (Aerts and Botzen, 2011); [2] (Botzen *et al.*, 2010b); [3] (Cheng *et al.*, 2012); [4] (Dailey *et al.*, 2009); [5] (Donat *et al.*, 2011); [6] (Emanuel, 2011); [7] (German Insurance Association (Gesamtverband der Deutschen Versicherungswirtschaft), 2011); [8] (Gerstengarbe *et al.*, 2013); [9] (Haug *et al.*, 2011); [10] (Held *et al.*, 2013); [11] (Izumi *et al.*, 2008); [12] (Kunreuther *et al.*, 2012); [13] (Leckebusch *et al.*, 2007); [14] (Pinto *et al.*, 2007); [15] (Pinto *et al.*, 2009); [16] (Pinto *et al.*, 2012); [17] (Raible *et al.*, 2012); [18] (Ranger and Niehoerster, 2012); [19] (Schwierz *et al.*, 2010).

Table 10-6: Fundamental supply-side challenges and sensitivities.

Challenges that might increase in the climate change context	**Example / Explanation**
Failure to reflect temporal changes in hazard condition in risk management	After the devastating 2004 and 2005 hurricane seasons, the losses of Florida's homeowners' insurance accumulated since 1985 exceeded the cumulative direct premiums earned by 31%. Consequences of the upswing and peak in hurricane activity: one insurer liquidated, two seized by regulation due to insolvency; reduced coverage availability in high-risk areas [9].
Misguided incentives additionally increasing risk	US National Flood Insurance Program (NFIP) allows for a vicious circle of built-up areas already existing within flood plains pressing authorities to construct or improve protecting levees which in turn lead to even more development attracted by NFIP premium discounts, although exposed to extreme flooding events [11;22]. Additionally, older properties situated within flood plains and accounting for 16% of losses in the period 1978-2008 pay premiums substantially below the risk-adequate level [1;6;7;11;14;15]. In this respect, premium incentives to reduce residual flood risk are missing. Policyholders residing in flood plains where flood cover was made precondition for mortgage drop the cover after only two to four years, accounting for missing insurance penetration and insufficient built-up of NFIP risk capital [11;14;15]. All these features, among others, account for the fact that NFIP has continuously been running a cumulative operating deficit, reaching more than US$ 20bn in 2006, after the big hurricanes [6;7;14;15].
Non-quantifiable uncertainties increasing risk	There is ambiguity as to what degree climate change may modify regional weather hazards – model projections are not unequivocal [2;3], and there is uncertainty about prospects of post-disaster regulatory/jurisdictional pressures, e.g. to extend claims payments beyond the original coverage [9]. Such uncertainties materialize in risk-based capital loadings [12].
Liability insurance impacted by new climate risk	Chances of success for claims based on CO_2 emissions in the USA seem small, due to legal obstacles [4;5;8;18], even though allocation schemes to overcome these hurdles are being discussed [17;20]. Defense costs could be covered by liability insurance [21]. CO_2 emissions were declared pollution (US Supreme Court/EPA). Existing and future regulation on limits for CO_2 emissions could continue to displace liability claims for CO_2 emissions and at the same time create new liability risks in case of non-compliance. These risks have not yet been adequately taken into account, somewhat similar to the early stages of environmental liability claims in the U.S.A. in the twentieth century [10;16]. The Supreme Court of Virginia ruled in 2012 that coverage under liability insurance for claims based on CO_2 emissions and defense costs depends on the specific occurrence-definition underlying the contract (e.g., if the cover pertains to accident, warming due to CO_2 emissions and resulting damage does not match this definition) [19].
Share of insurance in national risk financing	In the years following weather-related disasters countries with high insurance penetration show almost no impact on sovereign deficit and increasing economic output (GDP), whereas low-penetration countries experience substantially rising government deficit and missing positive change in output [13;21]. The absence of developed insurance systems, as is the case in many middle- and low-income countries, translates into greater macroeconomic vulnerability than with developed insurance systems.

References: [1] (Burby, 2006) [2] (Charpentier, 2008); [3] (Collier *et al.*, 2009); [4] (Ebert, 2010); [5] (Faure and Peeters, 2011); [6] (GAO, 2010); [7] (GAO, 2011); [8] (Gerrard, 2007); [9] (Grace and Klein, 2009); [10] (Hecht, 2008); [11] (Kousky and Kunreuther, 2010); [12] (Kunreuther *et al.*, 2009); [13] (Melecky and Raddatz, 2011); [14] (Michel-Kerjan, 2010); [15] (Michel-Kerjan and Kunreuther, 2011); [16] (Mills, 2009); [17] (Patton, 2011); [18] (Stewart and Willard, 2010); [19] (Supreme Court of Virginia, U.S.A., 2012); [20] (Taylor and Tollin, 2009); [21] (von Peter *et al.*, 2012); [22] (Zahran *et al.*, 2009).

Table 10-7: Products and systems responding to changes in weather risks.

Response option	**Example/Explanation**
Risk-adjusted premiums convey the risk to the insureds, encouraging them to adaptive measures	Flood hazard insurance zoning systems, e.g. HORA (Austria), SIGRA (Italy), and ZÜRS (Germany), hamper development in high-risk zones by allocating adequately high premiums [26]. Prior to Germany's disastrous River Elbe flood in 2002, 48.5% of insured households had obtained information on flood mitigation or were involved in emergency networks and 28.5% implemented one of several mitigation measures compared with 33.9% and 20.5%, respectively, of uninsured households [42]. However, perceptions that motivate flood insurance uptake range from risk awareness [9] to pure peer group expectation [32] - the latter might blur the role of the risk-premiums-nexus in some societal contexts.
Conditions of insurance policies incentivizing vulnerability reduction	Premium discounts for compliance with local building codes or other prevention options [27;45]; share of the insured in claims payment by deductibles or upper coverage limits, and exclusion of systematically affected property [1;7;8;10;11;15;21]; long-term natural-hazard insurance tied to the property and linked to mortgages and loans granted for prevention measures [27;28;36]. The latter is contested by modelled high risk capital requirements and ambiguity loadings, rendering multiyear policies relatively expensive and less flexible for the insurance market [34].
Amplifying factors in large disaster losses included in risk models	Evacuation and systemic economic catastrophe impacts, adversely affecting regional workforce and repair capacity, or knock-on catastrophes following initial catastrophes, e.g. long-term flooding following hurricane landfall [38].
Diversifying large disaster risk across securitization markets	Following the hurricane disasters of 2004 and 2005, securitisation instruments, e.g. catastrophe bonds, industry loss warranties and sidecars, acquired greater prominence, and have been recovering again from the market break in 2008 [16;18;20]. Investors in insurance linked securities are attracted by the lack of correlation to typical financial market risks (e.g., currency risks), and the well defined loss-per-index structure. The higher transparency relative to other asset-backed securities, such as mortgage-backed securities, contributed to the better performance of catastrophe bonds following the financial crisis of 2007/2008 [16;18]. As bonds typically cover large losses, the basis risk, i.e. suffering damage without parametric triggering, is reduced [44]; further reduction may be feasible by optimizing index measurements [16]. Weather derivatives are further instruments used to transfer risks to the capital markets [17;27;37]. Also multiple-trigger "hybrid" products are available, combining a parametric trigger-based catastrophe bond with a trigger-based protection against a simultaneous drop in stock market prices, thereby hedging against a double hit from direct disaster loss and losses incurred by the asset management side [5;18].
Index-based weather crop insurance products	Agricultural insurances predominantly cover crop, but also livestock, forestry, aquaculture, and greenhouses. Main products are indemnity-based crop insurance (covers for single perils and multiple peril events), and index-based crop insurance [41]. The latter is available in 40% of middle-income countries, with enlarged systems beyond pilot implementation in India and Mexico, and growth in China [23;33;40;46]. Risk-based price signals may better foster adaptation if schemes are coupled with access to advanced technology, e.g. drought-resistant seed [4;15;23;33]. Various index definitions (cumulative rainfall, area-yield, etc.) and applications exist or have been proposed [4;29;30;31]. Adjusting to uncertain regional changes in temporal hazard condition is a basic challenge with climate change [14;24;29].
Improvements in index-based weather insurance	Basis risk, i.e. weak correlation between index and damage, can be reduced if the index scheme is applied to an area-yield trigger in a region with homogeneous production potential (e.g., based on a sample) and/or to the uppermost disaster risk layer only [14;15;22]. It can be better absorbed if index insurance works at aggregate level, e.g. to cover crop-credit portfolios, cooperatives or informal networks [43], and if satellite-based remote-sensing technology can be used to establish plot identification, yield estimation and loss assessment [22]. Satellite-based forage estimation is already used for livestock index insurance in East Africa [13]. Pooling local schemes across climate regions under one cooperative parent organization, thus realizing central management, economics of scale and risk diversification, can reduce capital requirements and advance performance [6;12;35]. The disaster risk layer and high start-up costs (weather-data collection, risk modelling, education) necessitate subsidies from the state or donors [15;33].
Sovereign insurance schemes	Economic theory about the public sector's risk neutrality argues (i) that risks borne publicly render the social cost of risk-bearing insignificant and (ii) that disaster loss is seen small in comparison with a government's portfolio of diversified assets [3]. This theory proved inadequate if applied to relatively vulnerable small-sized middle to low-income countries [19],

	thereby rehabilitating sovereign insurance. For the Caribbean scheme CCRIF, that pools states, the reduction in premium cost per country is expected to be 45–50% [29]. Similar pooling schemes are being developed (e.g., African Risk Capacity, Pacific Catastrophe Risk Insurance Pilot) [2;39]. Pooling natural catastrophe risks across an array of megacities has also been proposed [25].

References: [1] (Aakre *et al.*, 2010); [2] (Wilcox *et al.*, 2010); [3] (Arrow and Lind, 1970) [4] (Barnett *et al.*, 2008) [5] (Barrieu and Loubergé, 2009) [6] (Biener and Eling, 2012); [7] (Botzen and van den Bergh, 2008) [8] (Botzen and van den Bergh, 2009); [9] (Botzen and van den Bergh, 2012); [10] (Botzen *et al.*, 2009) [11] (Botzen *et al.*, 2010a) [12] (Candel, 2007); [13] (Chantarat *et al.*, 2013); [14] (Clarke and Grenham, 2012); [15] (Collier *et al.*, 2009); [16] (Cummins, 2012); [17] (Cummins and Mahul, 2009); [18] (Cummins and Weiss, 2009); [19] (Ghesquiere and Mahul, 2007); [20] (Guy Carpenter, 2011); [21] (Hecht, 2008); [22] (Herbold, 2013b); [23] (Hess and Hazell, 2009); [24] (Hochrainer *et al.*, 2010); [25] (Hochrainer and Mechler, 2011); [26] (Kron, 2009); [27] (Kunreuther *et al.*, 2009); [28] (Kunreuther and Michel-Kerjan, 2009); [29] (Leblois and Quirion, 2011); [30] (Leiva and Skees, 2008); [31] (Linnerooth-Bayer and Mechler, 2009); [32] (Lo, 2013); [33] (Mahul and Stutley, 2010); [34] (Maynard and Ranger, 2012); [35] (Meze-Hausken *et al.*, 2009); [36] (Michel-Kerjan and Kunreuther, 2011); [37] (Michel-Kerjan and Morlaye, 2008); [38] (Muir-Wood and Grossi, 2008); [39] (The World Bank, 2013); [40] (Prabhakar *et al.*, 2013); [41] (Swiss Re, 2013a); [42] (Thieken *et al.*, 2006); [43] (Trærup, 2012); [44] (Van Nostrand and Nevius, 2011); [45] (Ward *et al.*, 2008); [46] (Zhu, 2011).

Table 10-8: Governance, public-private partnerships, and insurance market regulation.

Structural element	**Example/Explanation**
Public-private arrangements involving government intervention on the non-diversifiable disaster risk portion	Systems with government intervention range from ex ante risk financing design, such as public monopoly natural hazard insurance (e.g. Switzerland, with inter-cantonal pool) or compulsory forms of coverage to maximize the pool of insureds (e.g. Spain, France, with unlimited state guarantee on top), to ex post financing design, such as taxation-based governmental relief funds (e.g. Austria, Netherlands). In between these boundaries rank predominantly private insurance markets, in several countries combined with governmental post-disaster ad hoc relief (e.g. Germany, Italy, UK, Poland, USA) [13]; see also [1;3;4;10;11;12;14].
Care for people who cannot afford insurance	Either by funds outside the insurance system, e.g. insurance vouchers, or by premium subsidies (particularly for the catastrophic risk portion) [1;6;14;17].
Public-private partnership to expedite agricultural development	Insurance improve the farmers' creditworthiness that in turn strengthens their adaptive capacity. For instance, by means of loans farmers can step from low-yield to higher-yield cropping systems [2;8;9].
Concepts for adaptation-oriented climate change risk management frameworks linked to UNFCCC	Risk prevention and risk reduction often are the starting points that can absorb many of the smaller weather risks, and various forms of insurance, including international coordination, are meant to cover all of the remaining risks [7;15;16]. A global framework, where the wealthy agree to pool risks with the most vulnerable, equals social insurance that is different from a risk-based share in insurance funds [5].

References: [1] (Aakre *et al.*, 2010); [2] (Barnett *et al.*, 2008); [3] (Botzen and van den Bergh, 2008); [4] (Bruggeman *et al.*, 2010); [5] (Duus-Otterström and Jagers, 2011); [6] (Kunreuther *et al.*, 2009); [7] (Linnerooth-Bayer *et al.*, 2009); [8] (Linnerooth-Bayer *et al.*, 2011); [9] (Mahul and Stutley, 2010); [10] (Monti, 2012); [11] (Paudel, 2012); [12] (Schwarze and Wagner, 2007); [13] (Schwarze *et al.*, 2011); [14] (Van den Berg and Faure, 2006); [15] (Warner and Spiegel, 2009); [16] (Warner *et al.*, 2012); [17] ().

Table 10-9: Selected statistical characteristics of the social cost of carbon: average (Avg) and standard deviation (SD), both in dollar per tonne of carbon, and number of estimates (N; number of studies in brackets).

	Post-AR4			Pre-AR4			All studies		
	Avg	SD	N	Avg	SD	N	Avg	SD	N
0%	270	233	97	745	774	89	585	655	142
1%	181	260	88	231	300	49	209	284	137
3%	33	29	35	45	39	42	40	36	186
All	241	233	462 (35)	565	822	323 (49)	428	665	785 (84)

Sources: See Appendix 10.B.

Table 10-10: Summary of findings.

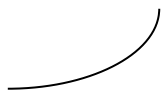
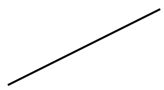
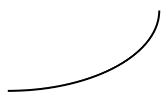
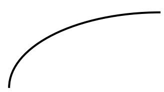
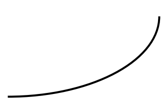
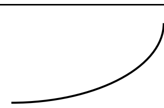
Sector	**CC Drivers**	**Sensitivity to CC**	**Sign**	**Other Drivers**	**Relative Impact of CC to Other Drivers**
Winter tourism	Temperature Snow		Negative	Population Lifestyle Income Aging	Much less
Summer tourism	Temperature Rainfall Cloudiness		Negative for suppliers in low altitudes and latitudes Positive for suppliers in high altitudes and latitudes Neutral for tourists	Population Income Lifestyle Aging	Much less
Cooling demand	Temperature Humidity Hot Spells		Positive for suppliers Negative for consumers	Population Income Energy Prices Technology Change	Less
Heating demand	Temperature Humidity Cold spells		Negative for suppliers Positive for consumers	Population Income Energy Prices Technology Change	Less
Health services	Temperature Precipitation		Positive for suppliers Negative for consumers	Aging Income Diet/Lifestyle	Less
Water infrastructure and services	Temperature Precipitation Storm Intensity Seasonal Variability		Negative for water users Positive for suppliers Spatially heterogeneous	Population Income Urbanization Regulation	Less in developing countries Equal in developed countries
Transportation	Temperature Precipitation Storm Intensity Seasonal Variability Freeze/Thaw Cycles		Negative for all users Positive for transport construction industry	Population Income Urbanization Regulation Mode Shifting Consumer and Commuter Behavior	Much less in developing countries Less in developed countries
Insurance	Floods Wind Storms Hail Drought Temperature		Negative for consumers Neutral for suppliers	Population Income Regulation Product Innovation	Less or equal in developing countries Equal or more in developed countries

Table 10.B.1: Estimates of the welfare loss due to climate change (as equivalent income loss in percent); estimates of the uncertainty are given in bracket as standard deviations or 95% confidence intervals.

Study	**Warming (˚C)**	**Impact (%GDP)**	**Method**	**Coverage**
(Nordhaus 1994b)	3.0	-1.3	Enumeration	Agriculture, energy demand, sea level rise
(Nordhaus 1994a)	3.0	-4.8 (-30.0 to 0.0)	Expert elicitation	Total welfare
(Fankhauser 1995)	2.5	-1.4	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, electricity demand, water resources, amenity, human health, air pollution, natural disasters
(Tol 1995)	2.5	-1.9	Enumeration	Agriculture, biodiversity, sea level rise, human health, energy demand, water resources, natural disasters, amenity
(Nordhaus and Yang 1996)[a]	2.5	-1.7	Enumeration	Agriculture, energy demand, sea level rise
(Plamberk and Hope 1996)[a]	2.5	-2.5 (-0.5 to –11.4)	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, electricity demand, water resources, amenity, human health, air pollution, natural disasters
(Mendelsohn et al. 2000)[a]	2.5	0.0	Enumeration	Agriculture, forestry, sea level rise, energy demand, water resources
(Mendelsohn et al. 2000)[a]	2.5	0.1	Statistical	Agriculture, forestry, energy demand
(Nordhaus and Boyer 2000)	2.5	-1.5	Enumeration	Agriculture, sea level rise, other market impacts, human health, amenity, biodiversity, catastrophic impacts
(Tol 2002)	1.0	2.3 (1.0)	Enumeration	Agriculture, forestry, biodiversity, sea level rise, human health, energy demand, water resources
(Maddison 2003)[a]	2.5	-0.1	Statistical	Household consumption
(Rehdanz and Maddison 2005)[a]	1.0	-0.4	Statistical	Self-reported happiness
(Hope 2006a)[a]	2.5	-0.9 (-0.2 to 2.7)	Enumeration	Sea level rise, biodiversity, agriculture, forestry, fisheries, energy demand, water resources, amenity, human health, air pollution, natural disasters
(Nordhaus 2006)	3.0	-0.9 (0.1) -1.1 (0.1)	Statistical	Economic output
(Nordhaus 2008)	3.0	-2.5	Enumeration	Agriculture, sea level rise, other market impacts, human health, amenity, biodiversity, catastrophic impacts
(Maddison and Rehdanz 2011)[a]	3.2	-11.5	Statistical	Self-reported happiness
(Bosello et al. 2012)	1.9	-0.5	CGE	Energy demand; tourism; sea level rise; river floods; agriculture; forestry; human health
(Roson and van der Mensbrugghe 2012)	2.3 4.9	-1.8 -4.6	CGE	Agriculture, sea level rise, water resources, tourism, energy demand, human health, labor productivity

[a] Results aggregated by (Tol 2013).

The database on the marginal damage costs of carbon dioxide emissions and its growth rate can be found at: http://www.sussex.ac.uk/Users/rt220/marginaldamagecost.xlsx

The following papers are included in the database on the marginal damage costs of carbon dioxide emissions: (Ackerman and Munitz 2012;Ackerman and Stanton 2012;Anthoff et al. 2009b;Anthoff et al. 2009a;Anthoff et al. 2009c;Anthoff et al. 2011a;Anthoff et al. 2011b;Anthoff and Tol 2010;Anthoff and Tol 2011;Anthoff and Tol 2013;Ayres and Walter 1991;Azar 1994;Azar and Sterner 1996;Cai et al. 2012;Ceronsky et al. 2006;Ceronsky et al. 2011;Clarkson and Deyes 2002;Cline 1992;Cline 1997;Cline 2004;Downing et al. 1996;Downing et al. 2005;EPA and NHTSA 2009;Eyre et al. 1999;Fankhauser 1994;Guo et al. 2006;Haraden 1992;Haraden 1993;Hohmeyer 1996;Hohmeyer 2004;Hohmeyer and Gaertner 1992;Hope 2005a;Hope 2005b;Hope 2006a;Hope 2006b;Hope 2008a;Hope 2008b;Hope 2011;Hope 2013;Hope and Hope 2013;Hope and Maul 1996;Interagency Working Group on the Social Cost of Carbon 2013;Kemfert and Schill 2010;Link and Tol 2004;Maddison 1995;Manne 2024;Marten 2011;Mendelsohn 2004;Narita et al. 2009;Narita et al. 2010;Newell and Pizer 2003;Nordhaus 2010;Nordhaus 1982;Nordhaus 1991;Nordhaus 1993;Nordhaus 1994b;Nordhaus 2008;Nordhaus and Boyer 2000;Nordhaus and Popp 1997;Nordhaus and Yang 1996;Parry 1993;Pearce 2003;Peck and Teisberg 1993;Penner et al. 1992;Perrissin Fabert et al. 2012;Plambeck and Hope 1996;Reilly and Richards 1993;Roughgarden and Schneider 1999;Schauer 1995;Sohngen 2010;Stern et al. 2006;Stern and Taylor 2007;Tol 1999;Tol 2005;Tol 2010;Tol 2012;Uzawa 2003;Wahba and Hope 2006;Waldhoff et al. 2011)

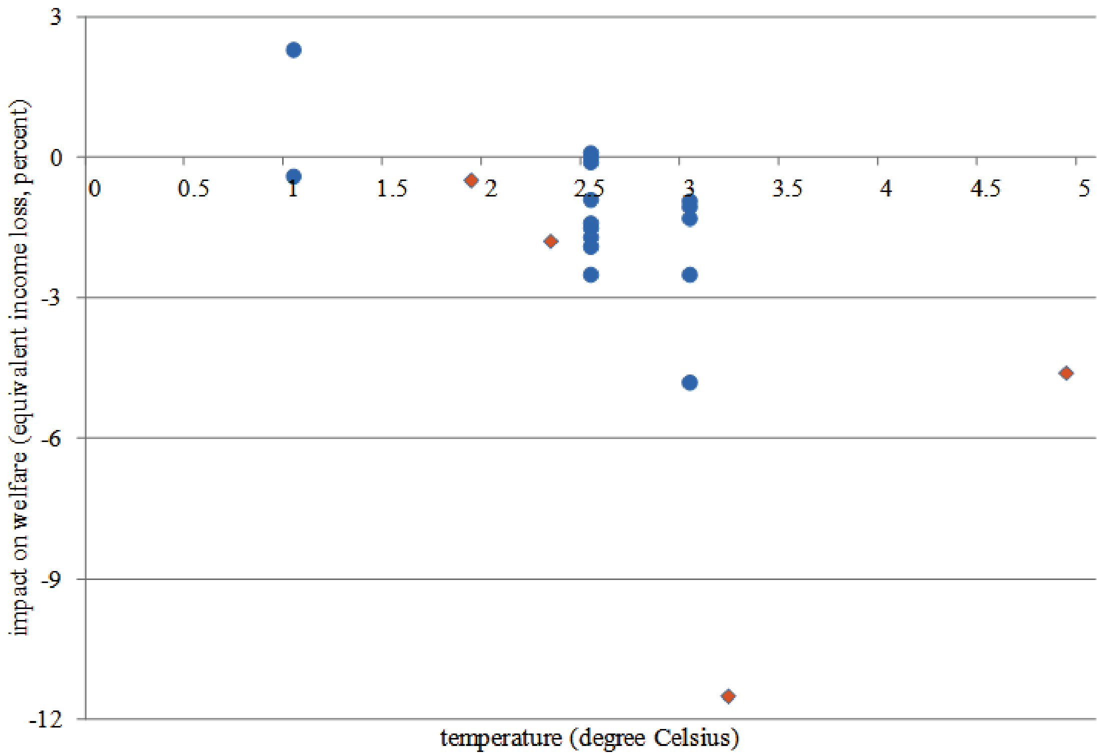


Figure 10-1: Estimates of the total impact of climate change plotted against the assumed climate change (proxied by the increase in the global mean surface air temperature); studies published since IPCC AR5 are highlighted as diamonds; see Table 10.B.1.

[Illustration to be redrawn to conform to IPCC publication specifications.]

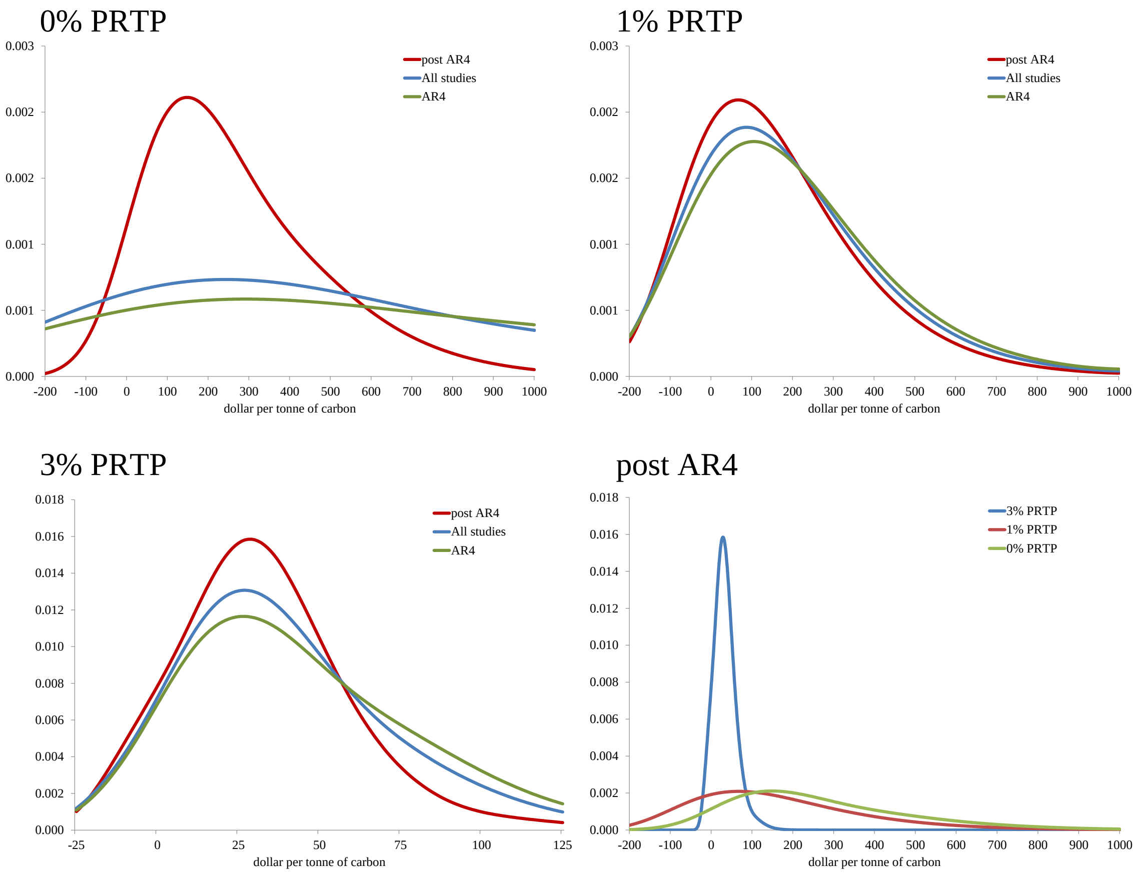


Figure 10-2: Kernel densities of the social cost of carbon for all studies and studies before or after AR4 for three alternative pure rates of time preference (PRTP).
[Illustration to be redrawn to conform to IPCC publication specifications.]

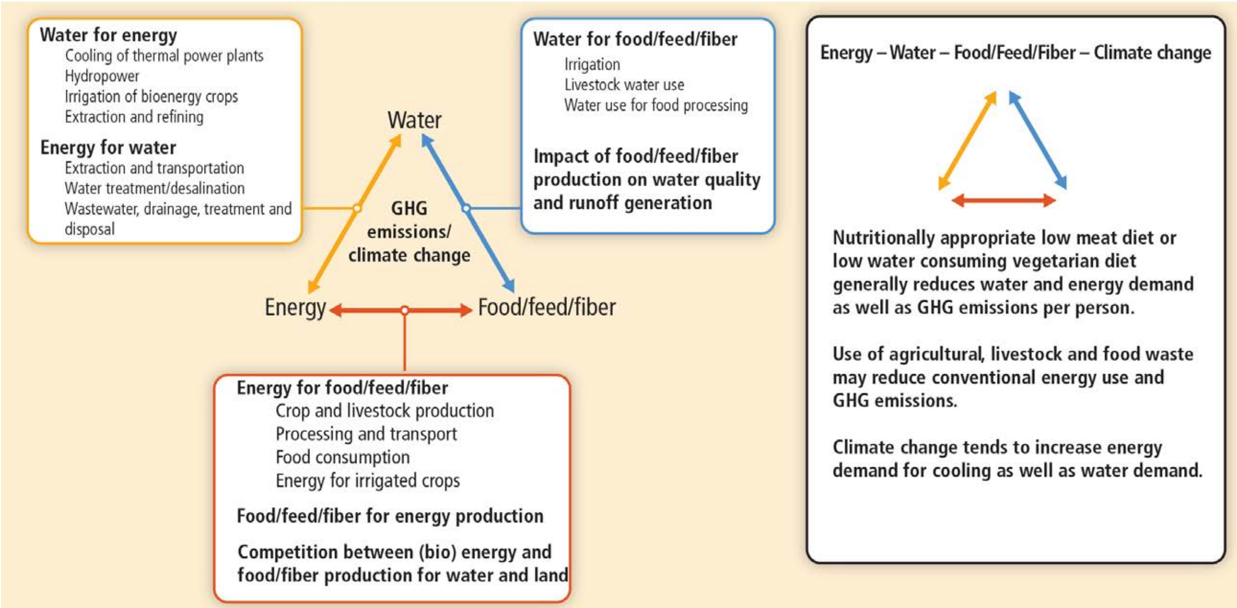


Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

Chapter 11. Human Health: Impacts, Adaptation, and Co-Benefits

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Contents

Chapter Boxes

Frequently Asked Questions

Executive Summary

The health of human populations is sensitive to shifts in weather patterns and other aspects of climate change (*very high confidence*). These effects occur directly, due to changes in temperature and precipitation and occurrence of heat waves, floods, droughts, and fires. Indirectly, health may be damaged by ecological disruptions brought on by climate change (crop failures, shifting patterns of disease vectors), or social responses to climate change (such as displacement of populations following prolonged drought). Variability in temperatures is a risk factor in its own right, over and above the influence of average temperatures on heat-related deaths. [11.4] Biological and social adaptation is more difficult in a highly variable climate than one that is more stable. [11.7]

Until mid-century climate change will act mainly by exacerbating health problems that already exist *[very high confidence]*. New conditions may emerge under climate change *[low confidence]*, and existing diseases (e.g. food-borne infections) may extend their range into areas that are presently unaffected *[high confidence]*. But the largest risks will apply in populations that are currently most affected by climate-related diseases. Thus, for example, it is expected that health losses due to climate change-induced under-nutrition will occur mainly in areas that are already food-insecure. [11.3]

In recent decades, climate change has contributed to levels of ill-health (*likely*) though the present world-wide burden of ill-health from climate change is relatively small compared with other stressors on health and is not well quantified. Rising temperatures have increased the risk of heat-related death and illness *(likely)*. [11.4] Local changes in temperature and rainfall have altered distribution of some water-borne illnesses and disease vectors, and reduced food production for some vulnerable populations *[medium confidence]*. [11.5, 11.6]

If climate change continues as projected across the RCP scenarios until mid-century, the major increases of ill-health compared to no climate change will occur through:

- Greater risk of injury, disease, and death due to more intense heat waves and fires *[very high confidence]* [11.4]
- Increased risk of under-nutrition resulting from diminished food production in poor regions *[high confidence]* [11.6]
- Consequences for health of lost work capacity and reduced labor productivity in vulnerable populations *[high confidence]* [11.6]
- Increased risks of food- and water-borne diseases *[very high confidence]* and vector-borne diseases *[medium confidence]* [11.5]
- Modest improvements in cold-related mortality and morbidity in some areas due to fewer cold extremes *[low confidence]*, geographical shifts in food production, and reduced capacity of disease-carrying vectors due to exceedance of thermal thresholds *[medium confidence]*. These positive effects will be out-weighed, world-wide, by the magnitude and severity of the negative effects of climate change *[high confidence]*. [11.4, 11.5, 11.6]

Impacts on health will be reduced, but not eliminated, in populations that benefit from rapid social and economic development *[high confidence]*, particularly among the poorest and least healthy groups *[very high confidence]*.

[11.4, 11.6, 11.7] Climate change is an impediment to continued health improvements in many parts of the world. If economic growth does not benefit the poor, the health effects of climate change will be exacerbated.

In addition to their implications for climate change, essentially all the important Climate Altering Pollutants (CAPs) other than CO_2 have near-term health implications *[very high confidence*]. In 2010, more than 7% of the global burden of disease was due to inhalation of these air pollutants [*high confidence*]. [Box 11-4]

Some parts of the world already exceed the international standard for safe work activity during the hottest months of the year. The capacity of the human body to thermoregulate may be exceeded on a regular basis, particularly during manual labour, in parts of the world during this century. In the highest Representative Concentration Pathway, RCP8.5, by 2100 some of the world's land area will be experiencing 4-7 degree higher temperatures due to anthropogenic climate change [WG1, Figure SPM.7]. If this occurs, the combination of high temperatures and high humidity will compromise normal human activities, including growing food or working outdoors, raising doubt about the habitability of some areas, for parts of the year *[high confidence]*. [11.8]

The most effective adaptation measures for health in the near-term are programs that implement basic public health measures such as provision of clean water and sanitation, secure essential health care including vaccination and child health services, increase capacity for disaster preparedness and response, and alleviate poverty *[very high confidence*]. [11.7] In addition, there has been progress since AR4 in targeted and climate-specific measures to protect health, including enhanced surveillance and early warning systems. [11.7]

There are opportunities to achieve co-benefits from actions that reduce emissions of CAPs and at the same time improve health. Among others, these include:

- Reducing local emissions of health-damaging and climate-altering air pollutants from energy systems, through improved energy efficiency, and a shift to cleaner energy sources *[very high confidence]* [11.9]
- Providing access to reproductive health services (including modern family planning) to improve child and maternal health through birth spacing and reduce population growth, energy use, and consequent CAP emissions over time *[medium confidence]* [11.9]
- Shifting consumption away from animal products, especially from ruminant sources, in high-meat-consumption societies toward less CAP-intensive healthy diets *[medium confidence]* [11.9]
- Designing transport systems that promote active transport and reduce use of motorized vehicles, leading to lower emissions of CAPs and better health through improved air quality and greater physical activity *[high confidence]* [11.9].

There are important research gaps regarding the health consequences of climate change and co-benefits actions, particularly in low-income countries. There are now opportunities to use existing longitudinal data on population health to investigate how climate change affects the most vulnerable populations. Another gap concerns the scientific evaluation of the health implications of adaptation measures at community and national levels. A further challenge is to improve understanding of the extent to which taking health co-benefits into account can offset the costs of GHG mitigation strategies.

11.1. Introduction

This chapter examines what is known about the effects of climate change on human health and, briefly, the more direct impacts of Climate-Altering Pollutants (CAPs, see glossary) on health. We review diseases and other aspects of poor health that are sensitive to weather and climate. We examine the factors that influence the susceptibility of populations and individuals to ill-health due to variations in weather and climate, and describe steps that may be taken to reduce the impacts of climate change on human health. The chapter also includes a section on health "co-benefits." Co-benefits are positive effects on human health that arise from interventions to reduce emissions of CAPs or vice versa.

This is a scientific assessment based on best available evidence according to the judgment of the authors. We searched the English-language literature up to August 2013, focusing primarily on publications since 2007. We drew primarily (but not exclusively) on peer-reviewed journals. Literature was identified using a published protocol (Hosking and Campbell-Lendrum, 2012) and other approaches, including extensive consultation with technical experts in the field. We examined recent substantial reviews (for instance (Bassil and Cole, 2010; Gosling *et al.*, 2009; Hajat *et al.*, 2010; Huang *et al.*, 2011; McMichael, 2013b; Stanke *et al.*, 2013)), to check for any omissions of important work. In selecting citations for the chapter, we gave priority to publications that were recent (since AR4), comprehensive, added significant new findings to the literature, included areas or population groups that have not previously been well-described or were judged to be particularly policy-relevant in other respects.

We begin with an outline of measures of human health, the major driving forces that act on health world-wide, recent trends in health status, and health projections for the remainder of this century.

11.1.1. Present State of Global Health

The Fourth Assessment Report pointed to dramatic improvement in life expectancy in most parts of the world in the 20th Century, and this trend has continued through the first decade of the 21st century (Wang, 2012). Rapid progress in a few countries (especially China) has dominated global averages, but most countries have benefited from substantial reductions in mortality. There remain sizable and avoidable inequalities in life expectancy within- and between-nations in terms of education, income and ethnicity (Beaglehole and Bonita, 2008) and in some countries, official statistics are so patchy in quality and coverage that it is difficult to draw firm conclusions about health trends (Byass, 2010). Years lived with disability have tended to increase in most countries (Salomon *et al.*, 2012).

If economic development continues as forecast, it is expected that mortality rates will continue to fall in most countries; WHO estimates the global burden of disease (measured in Disability Adjusted Life Years per capita) will decrease by 30% by 2030, compared with 2004 (World Health Organization, 2008a; World Health Organization, 2008b). The underlying causes of global poor health are expected to change substantially, with much greater prominence of chronic diseases and injury, nevertheless the major infectious diseases of adults and children will remain important in some regions, particularly Sub-Saharan Africa and South Asia (Hughes *et al.*, 2011).

11.1.2. Developments since AR4

The relevant literature has grown considerably since publication of AR4. For instance, the annual number of MEDLINE citations on climate change and health doubled between 2007 and 2009 (Hosking and Campbell-Lendrum, 2012). In addition, there have been many reviews, reports and international assessments that do not appear in listings such as MEDLINE but include important information nevertheless, for instance, the World Development Report 2010 (World Bank, 2010) and the 2011 UN Habitat report on cities and climate change (United Nations Human Settlements Programme, 2011). Since AR4, there have been improvements in the methods applied to investigate climate change and health. These include more sophisticated modeling of possible future impacts (for example, work linking climate change, food security, and health outcomes) (Nelson *et al.*, 2010) and new methods to model the effects of heat on work capacity and labor productivity (Kjellstrom *et al.*, 2009b). Other developments include coupling of high-quality, longitudinal mortality data sets with down-scaled meteorological data, in low-income settings (for instance, through the INDEPTH Network) (see Box 11-1).

_____ START BOX 11-1 HERE _____

Box 11-1. Weather, Climate, and Health –
a Long-Term Observational Study in African and Asian Populations

Given the dearth of scientific evidence of the relationship between weather/climate and health in low- and middle-income countries, we report on a project that spans sub-Saharan Africa and Asia. The INDEPTH Network currently includes 43 surveillance sites in 20 countries. Using standardized health and demographic surveillance systems, member sites have collected up to 45 years information on births, migration and deaths. Currently, there are about 3.2 million people under surveillance (Sankoh and Byass, 2012).

To study relationships between weather and health, the authors obtained daily meteorological data for 12 INDEPTH populations between 2000 and 2009, and projected future climate changes to 2100 under the A1B, A3, and B1 scenarios (Hondula *et al.*, 2012). The authors concluded the health of all the populations would be challenged by the new climatic conditions, especially later in the century. In another study from the Network, Diboulo *et al.* (2012) examined the relation between weather and all-cause mortality data in Burkina Faso. Relations between daily temperature and mortality were similar to those reported in many high-income settings, and susceptibility to heat varied by age and gender.

_____ END BOX 11-1 HERE _____

Since AR4, studies of the ways in which policies to reduce GHG emissions may affect health, or vice versa, leading to so-called "co-benefits" in the case of positive outcomes for either climate or health, have multiplied (Haines *et al.*, 2009).

Much has been written on links between climate, socioeconomic conditions and health, for example related to occupational heat exposure (Kjellstrom *et al.*, 2009b) and malaria (e.g., Béguin *et al.*, 2011; Gething *et al.*, 2010) There is also growing appreciation of the social upheaval and damage to population health that may arise from the interaction of large-scale food insecurity, population dislocation, and conflict (see Chapter 12).

11.1.3. Non-Climate Health Effects of Climate-Altering Pollutants (CAPs)

CAPs affect health in other ways than through climate change, just as CO_2 creates non-climate effects such as ocean acidification. The effects of rising CO_2 levels on calcifying marine species are well documented and the risks for coral reefs are now more closely defined than they were at the time of the AR4 (see Chapter 30). There are potential implications for human health, such as under-nutrition in coastal populations that depend on local fish stocks, but, so far, links between health and ocean acidification have not been closely studied (Kite-Powell *et al.*, 2008). CAPs such as black carbon and tropospheric ozone have substantial, direct, negative effects on human health (Wang *et al.*, 2013). (See 11.5.3 and Box 11-3.) Although CO_2 is not considered a health-damaging air pollutant at levels experienced outside particular occupational and health-care settings, one study has reported a reduction in mental performance at 1000 ppm and above, within the range that all of humanity would experience in some extreme climate scenarios by 2100 (Satish *et al.*, 2012).

11.2. How Climate Change Affects Health

There are three basic pathways by which climate change affects health (Figure 11-1), and these provide the organization for the chapter:

- Direct impacts, which relate primarily to changes in the frequency of extreme weather including heat, drought, and heavy rain [11.4]
- Effects mediated through natural systems, for example, disease vectors, water-borne diseases, and air pollution [11.5]
- Effects heavily mediated by human systems, for example, occupational impacts, undernutrition, and mental stress [11.6].

[INSERT FIGURE 11-1 HERE
Figure 11-1: Conceptual diagram showing three primary exposure pathways by which climate change affects health: directly through weather variables such as heat and storms; indirectly through natural systems such as disease vectors; and pathways heavily mediated through human systems such as undernutrition. The yellow box indicates the moderating influences of local environmental conditions on how climate change exposure pathways are manifest in a particular population. The orange box indicates that the extent to which the three categories of exposure translate to actual health burden is moderated by such factors as background public health and socioeconomic conditions, and adaptation measures. The green arrows at the bottom indicate that there may be feedback

mechanisms, positive or negative, between societal infrastructure, public health, and adaptation measures and climate change itself. As discussed later in the chapter, for example, some measures to improve health also reduce emissions of climate-altering pollutants, thus reducing the extent and/or pace of climate change as well as improving local health. Credit: E. Garcia, UC Berkeley.]

The negative effects of climate change on health may be reduced by improved health services, better disaster management, and poverty alleviation, although the cost and effort may be considerable [11.7]. The consequences of large magnitude climate change beyond 2050, however, would be much more difficult to deal with [11.8]. Although there are exceptions, to a first approximation climate change acts to exacerbate existing patterns of ill-health, by acting on the underlying vulnerabilities that lead to ill-health even without climate change. Thus, before pursuing the three pathways in Figure 11-1, we summarize what is known about vulnerability to climate-induced illness and injury.

11.3. Vulnerability to Disease and Injury due to Climate Variability and Climate Change

In the IPCC assessments, vulnerability is defined as the propensity or predisposition to be adversely affected (see Chapter 19 and Glossary). In this section, we consider causes of vulnerability to ill-health associated with climate change and climate variability, including individual and population characteristics and factors in the physical environment.

We have outlined the causes of vulnerability separately, but in practice causes combine, often in a complex and place-specific manner. There are some factors (such as education, income, health status and responsiveness of government) that act as generic causes of vulnerability. For example, the quality of governance – how decisions are made and put into practice – affects a community's response to threats of all kinds (Bowen *et al.*, 2012). (See Chapter 12.) The background climate-related disease rate of a population is often the best single indicator of vulnerability to climate change - doubling of risk of disease in a low disease population has much less absolute impact than doubling of the disease when the background rate is high. (Note that here, and elsewhere in the chapter, we treat "risk" in the epidemiological sense: the probability that an event will occur.) But the precise causes of vulnerability, and therefore the most relevant adaptation capacities, vary greatly from one setting to another. For example, severe drought in Australia has been linked to psychological distress – but only for those residing in rural and remote areas (Berry *et al.*, 2010). The link between high ambient temperatures and increased incidence of salmonella food poisoning has been demonstrated in many places (e.g. (Zhang *et al.*, 2010)), but the lag varies from one country to another, suggesting that the mechanisms differ. Deficiencies in food storage may be the critical link in some places, food handling problems may be most important elsewhere (Kovats *et al.*, 2004).

The 2010 World Development Report concluded that all developing regions are vulnerable to economic and social damage resulting from climate change – but for different reasons (World Bank, 2010). The critical factors for Sub-Saharan Africa, for example, are the current climate stresses (in particular, droughts and floods) that may be amplified in parts of the region under climate change, sparse infrastructure and high dependence on natural resources (see Chapter 22). Asia and the Pacific, on the other hand, are distinguished by the very large number of people living in low-lying areas prone to flooding (see Chapters 24 and 29).

11.3.1. Geographic Causes of Vulnerability

Location has an important influence on the potential for health losses caused by climate change (Samson *et al.*, 2011). Those working outdoors in countries where temperatures in the hottest time of the year are already at the limits of thermal tolerance for part of the year will be more severely affected by further warming than workers in cooler countries (Kjellstrom *et al.*, 2013). The inhabitants of low-lying coral atolls are very sensitive to flooding, contamination of fresh water reservoirs due to sea level rise, and salination of soil, all of which may have important effects on health (Nunn, 2009). Rural populations that rely on subsistence farming in low rainfall areas are at high risk of under-nutrition and water-related diseases if drought occurs, although this vulnerability may be modified strongly by local factors, such as access to markets and irrigation facilities (Acosta-Michlik *et al.*, 2008). Living in rural and remote areas may confer increased risk of ill-health because of limited access to services and generally higher levels of social and economic disadvantage (Smith, 2008). Populations that are close to the present limits of transmission of vector-borne diseases are most vulnerable to changes in the range of transmission due to rising temperatures and altered patterns of rainfall, especially when disease control systems are weak (Lozano-Fuentes *et al.*, 2012; Zhou *et al.*, 2008). In cities, those who live on urban heat islands are at greater risk of ill-health due to extreme heat events (Stone *et al.*, 2010; Uejio *et al.*, 2011).

11.3.2. Current Health Status

Climate extremes may promote the transmission of certain infectious diseases and the vulnerability of populations to these diseases will depend on the baseline levels of pathogens and their vectors. In the United States, as one example, arboviral diseases such as dengue are rarely seen after flooding, compared with the experience in other parts of the Americas. The explanation lies in the scarcity of dengue (and other pathogenic viruses) circulating in the population, before the flooding (Keim, 2008). On the other hand, the high prevalence of HIV infection in many populations in Sub-Saharan Africa will tend to multiply the health risks of climate change, due to the interactions between chronic ill-health, poverty, extreme weather events and undernutrition (Ramin and McMichael, 2009). Chronic diseases such as diabetes and ischemic heart disease magnify the risk of death or severe illness associated with high ambient temperatures (Basu and Ostro, 2008; Sokolnicki *et al.*, 2009).

11.3.3. Age and Gender

Children, young people, and the elderly are at increased risk of climate-related injury and illness (Perera, 2008). For example, adverse effects of malaria, diarrhea, and undernutrition are presently concentrated amongst children, for reasons of physiological susceptibility (Michon *et al.*, 2007). In principle, children are thought to be more vulnerable to heat-related illnesses, due to their small body mass to surface area ratio, but evidence of excess heat-related mortality in this age group is mixed (Basu and Ostro, 2008; Kovats and Hajat, 2008). Maternal antibodies acquired *in utero* provide some protection against dengue fever in the first year of life, but if infection does occur in infants it is more likely to provoke the severe hemorrhagic form of illness (Ranjit and Kissoon, 2011). Children are generally at greater risk when food supplies are restricted: households with children tend to have lower than average incomes, and food insecurity is associated with a range of adverse health outcomes amongst young children (Cook and Frank, 2008).

Older people are at greater risk from storms, floods, heat-waves and other extreme events (Brunkard *et al.*, 2008), in part because they tend to be less mobile than younger adults and so find it more difficult to avoid hazardous situations and also because they are more likely to live alone in some cultures. Older people are also more likely to suffer from health conditions that limit the body's ability to respond to stressors such as heat and air pollution (Gamble *et al.*, 2013).

The relationship between gender and vulnerability is complex. Worldwide, mortality due to natural disasters, including droughts, floods and storms, is higher among women than men (World Health Organization, 2011). However there is variation regionally. In the United States, males are at greater risk of death following flooding (Jonkman and Kelman, 2005). A study of the health effects of flooding in Hunan province, China, also found an excess of flood deaths among males, often related to rural farming (Abuaku *et al.*, 2009). In Canada's Inuit population males are exposed to dangers associated with insecure sea ice, while females may be more vulnerable to the effects of diminished food supplies (Pearce *et al.*, 2011). In the Paris 2003 heat wave, excess mortality was greater among females overall, but there were more excess deaths among men in the working age span (25 – 64) possibly due to differential exposures to heat in occupational settings (Fouillet *et al.*, 2006). In Bangladesh, females are more affected than males by a range of climate hazards, due to differences in prevalence of poverty, undernutrition and exposure to water-logged environments (Neelormi *et al.*, 2009). The effect of food insecurity on growth and development in childhood may be more damaging for girls than boys (Cook and Frank, 2008).

Pregnancy is a period of increased vulnerability to a wide range of environmental hazards, including extreme heat (Strand *et al.*, 2012) and infectious diseases such as malaria, foodborne infections and influenza (Van Kerkhove *et al.*, 2011).

11.3.4. Socioeconomic Status

The poorest countries and regions are generally most susceptible to damage caused by climate extremes and climate variability (Malik *et al.*, 2012), but wealthy countries are not immune, as shown by the deaths resulting from bushfires in Australia in 2009 (Teague *et al.*, 2010). Also, rapid economic development may increase the risks of climate-related health issues. For instance, changes in Tibet, China including new roads and substantial in-migration may explain (along with above-average warming) the appearance and establishment in Lhasa of *Culex pipiens*, a mosquito capable of transmitting the West Nile virus (Liu *et al.*, 2013b).

A review of global trends in tropical cyclones 1970-2009 found that mortality risk at country-level depended most strongly on three factors: storm intensity, quality of governance, and levels of poverty (Peduzzi *et al.*, 2012). Individuals and households most vulnerable to climate hazards tend to be those with relatively low socioeconomic status (Friel *et al.*, 2008). A study of the impacts of flooding in Bangladesh found that household risk reduced with increases in both average income and number of income sources. Poorer households were not only more severely affected by flooding, but they took preventive action less often, and received assistance after flooding less frequently than did more affluent households (Brouwer *et al.*, 2007).

In many countries, race and ethnicity are powerful markers of health status and social disadvantage. Black Americans have been reported to be more vulnerable to heat-related deaths than other racial groups in the United States (Basu and Ostro, 2008). This may be due to a higher prevalence of chronic conditions such as over-weight and diabetes (Lutsey *et al.*, 2010), financial circumstances (for instance, lower incomes may restrict access to air conditioning during heat-waves) (Ostro *et al.*, 2010), or community-level characteristics such as higher local crime rates or disrupted social networks (Browning *et al.*, 2006). Indigenous peoples who depend heavily on local resources, and live in parts of the world where climates are changing quickly, are generally at greater risk of economic losses and poor health. Studies of the Inuit people, for example, show that rapid warming of the Canadian Arctic is jeopardizing hunting and many other day-to-day activities, with implications for livelihoods and well-being (Ford, 2009).

11.3.5. Public Health and Other Infrastructure

Populations that do not have access to good quality health care and essential public health services are more likely to be adversely affected by climate variability and climate change (Frumkin and McMichael, 2008). Harsh economic conditions in Europe since 2008 led to cutbacks in health services in some countries, followed by a resurgence of climate-sensitive infectious diseases including malaria (Karanikolos *et al.*, 2013). The condition of the physical infrastructure that supports human settlements also influences health risks (this includes supply of power, provision of water for drinking and washing, waste management and sanitation: see Chapter 8). In Cuba, a country with a well-developed public health system, dengue fever has been a persistent problem in the larger cities, due in part to the lack of a constant supply of drinking water in many neighbourhoods (leading to people storing water in containers that are suitable breeding sites for the disease vector, *A. aegypti*) (Bulto *et al.*, 2006). In New York, daily mortality spiked after a city-wide power failure in August 2003, due in part to increased exposure to heat (Weis, 2011).

11.3.6. Projections for Vulnerability

Population growth is linked to climate change vulnerability. If nothing else changes, increasing numbers of people in locations that are already resource-poor and are affected by climate risks will magnify harmful impacts. Virtually all the projected growth in populations will occur in urban agglomerations, mostly in large, low latitude hot countries in which a high proportion of the workforce is deployed outdoors with little protection from heat. About 150 million people currently live in cities affected by chronic water shortages and by 2050, unless there are rapid improvements in urban environments, the number will rise to almost a billion (McDonald *et al.*, 2011). Under a "business as usual" scenario with mid-range population growth, the OECD projects that about 1.4 billion people will be without access to basic sanitation in 2050 (OECD, 2012). The age structure of the population also has implications for vulnerability (see Figure 11-2). The proportion aged over 60, world-wide, is projected to increase from about 10% presently to about 32% by the end of the century (Lutz *et al.*, 2008). The prevalence of overweight and obesity, which is associated with relatively poor heat tolerance, has increased almost everywhere in the last 20 years, and in many countries the trend continues upwards (Finucane *et al.*, 2011). It has been pointed out that the Sahel region of Africa may be particularly vulnerable to climate change because it already suffers so much stress from population pressure, chronic drought, and governmental instability (Diffenbaugh and Giorgi, 2012; Potts and Henderson, 2012).

[INSERT FIGURE 11-2 HERE
Figure 11-2: Increasingly frequent heat extremes will combine with rapidly growing numbers of older people living in cities – who are particularly vulnerable to extreme heat. Countries are shaded according to the expected proportional increase in urban populations aged over 65 by the year 2050. Bar graphs show how frequently the maximum daily temperature that would have occurred only once in 20 years in the late 20th century is expected to occur in the mid-21st century, with lower numbers indicating more frequent events. Results are shown for 3 different "SRES" scenarios (Blue = B1; Green = A1B, Red = A2), as described in the IPCC Special Report on Emissions Scenarios, and based on 12 global climate models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). Coloured boxes show the range in which 50% of the model projections are contained, and whiskers show the maximum and minimum projections from all models. Source: World Health Organization and World Meteorological Organization, 2012.]

Future trends in social and economic development are critically important to vulnerability. For instance, countries with a higher Human Development Index (HDI) (a composite of life expectancy, education, literacy and GDP per capita) are less affected by the floods, droughts and cyclones that take place (Patt *et al.*, 2010). Therefore policies that boost health, education, and economic development should reduce future vulnerability. Overall, there have been substantial improvements in HDI in the last 30 years, but this has been accompanied by increasing inequalities between and within countries, and has come at the cost of high consumption of environmental resources (UNDP, 2011).

11.4. Direct Impacts of Climate and Weather on Health

11.4.1. Heat and Cold – Related Impacts

Although there is ample evidence of the effects of weather and climate on health, there are few studies of the impacts of climate change itself. (An example: Bennett *et al* (2013) reported that the ratio of summer to winter deaths in Australia increased between 1968 and 2010, in association with rising annual average temperatures.) The issue is scale, since climate change is defined in decades. Robust studies require not only extremely long-term data series on climate and disease rates, but also information on other established or potential causative factors, coupled with statistical analysis to apportion changes in health states to the various contributing factors. Wherever risks are identified, health agencies are mandated to intervene immediately, biasing long-term analyses.

Nevertheless, the connection between weather and health impacts is often sufficiently direct to permit strong inferences about cause and effect (Sauerborn and Ebi, 2012). Most notably, the association between hot days (commonly defined in terms of the percentiles of daily maximum temperature for a specified location) and increases in mortality is very robust (Honda *et al*., 2013). The IPCC Special Report on Extreme Events (SREX) concludes that it is *very likely* that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale. If there has been an increase in daily maximum temperatures, then it follows, in our view, that the number of heat-related deaths is *likely* to have also increased. For example, Christidis *et al* (2012) concluded that it is "extremely likely (probability greater than 95%)" that anthropogenic climate change at least quadrupled the risk of extreme summer heat events in Europe in the decade 1999-2008. The 2003 heat wave was one such record event: therefore the probability that particular heat wave can be attributed to climate change is 75% or more, and on this basis it is *likely* the excess mortality attributed to the heat wave (about 15,000 deaths in France alone (Fouillet *et al.*, 2008)) was caused by anthropogenic climate change.

The rise in minimum temperatures may have contributed to a decline in deaths associated with cold spells, however the influence of seasonal factors other than temperature on winter mortality suggests that the impacts on health of more frequent heat extremes greatly outweigh benefits of fewer cold days (Ebi and Mills, 2013; Kinney *et al.*, 2012). Quantification, globally, remains highly uncertain, as there are few studies of the large developing country populations in the tropics, and these point to effects of heat, but not cold, on mortality (Hajat *et al.*, 2010). There is also significant uncertainty over the degree of physiological, social or technological adaptation to increasing heat over long time periods.

11.4.1.1. Mechanisms

The basic processes of human thermoregulation are well-understood. If the body temperature rises above 38°C ("heat exhaustion"), physical and cognitive functions are impaired; above 40.6°C ("heat stroke"), risks of organ damage, loss of consciousness, and death increase sharply. Detailed exposure-response relationships were described long ago (Wyndham, 1969), but the relationships in different community settings and for different age/sex groups are not yet well established. The early studies are supported by more recent experimental and field studies (Parsons, 2003; Ramsey and Bernard, 2000) and meta-analysis (Bouchama *et al.*, 2007), that show significant effects of heat stress as body temperatures exceed 40°C, and heightened vulnerability in individuals with pre-existing disease.

At high temperatures, displacement of blood to the surface of the body may lead to circulatory collapse. Indoor thermal conditions, including ventilation, humidity, radiation from walls or ceiling and the presence or absence of air-conditioning are important in determining whether adverse events occur, but these variables are seldom well-measured in epidemiological studies (Anderson *et al.*, 2012). Biological mechanisms are less evident for other causes of death, such as suicide, that are sometimes related to high temperature (Kim *et al.*, 2011; Likhvar *et al.*, 2011; Page *et al.*, 2007).

Heat waves refer to a run of hot days; precisely how many days, and how high the temperatures must rise, are defined variously (Kinney *et al.*, 2008). Some investigators have reported that mortality increases more during heat waves than would be anticipated solely on the basis of the short-term temperature mortality relationship (Anderson and Bell, 2011; D'Ippoliti *et al.*, 2010), although the added effect is relatively small in some series, and most evident with prolonged heat waves (Gasparrini and Armstrong, 2011). Because heat waves are relatively infrequent compared with the total number of days with temperatures greater than the optimum for that location, the effects of heat waves are only a fraction of the total impact of heat on health. Some studies have shown larger effects of heat and heat waves earlier in the hot season (Anderson and Bell, 2011; Rocklov *et al.*, 2011). This may be testament to the importance of acclimatisation and adaptive measures, or may result from a large group in the population that is more susceptible to heat early in the season (Rocklov *et al.*, 2009; Rocklov *et al.*, 2011).

The extreme heat wave in Europe in 2003 led to numerous epidemiological studies. Reports from France (Fouillet *et al.*, 2008) concluded that most of the extra deaths occurred in elderly people (80% of those who died were above 75 years). Questions were raised at the time as to why this event had such a devastating effect (Kosatsky, 2005). It is still not clear, but one contributing factor may have been the relatively mild influenza season the year before. Recent studies have found that when the previous year's winter mortality is low, the effect of summer heat is increased (Ha *et al.*, 2011; Rocklov and Forsberg, 2009) because mild winters may leave a higher proportion of vulnerable people (Stafoggia *et al.*, 2009). Most studies of heat have been in high-income countries, but there has been work recently in low- and middle-income countries, suggesting heterogeneity in vulnerability by age groups and socio-economic factors similar to that seen in higher-income settings (Bell *et al.*, 2008; McMichael *et al.*, 2008; Pudpong and Hajat, 2011).

Numerous studies of temperature-related morbidity, based on hospital admissions or emergency presentations, have reported increases in events due to cardio-vascular, respiratory and kidney diseases (Hansen *et al.*, 2008; Knowlton *et al.*, 2009; Lin and Chan, 2009) and the impact has been related to the duration and intensity of heat (Nitschke *et al.*, 2011).

There is evidence now that both average levels and variability in temperature are important influences on human health. The standard deviation of summer temperatures was associated with survival time in a US cohort study of persons aged over 65 years with chronic disease who were tracked from 1985-2006 (Zanobetti *et al.*, 2012). Greater variability was associated with reduced survival. A study that modeled separately projected increases in temperature variability and average temperatures for six cities for 2070-2099 found that, with one exception, variability had an effect (increased deaths) over and above what was estimated from the rise in average temperatures (Gosling *et al.*, 2009). Relevant to 11.5, rapid changes in temperature may also alter the balance between humans and parasites, increasing opportunities for new and resurgent diseases. The speed with which organisms adapt to changes in temperatures is, broadly speaking, a function of mass, and laboratory studies have shown that microbes respond more quickly to a highly variable climate than do their multi-cellular hosts (Raffel *et al.*, 2012).

Health risks during heat extremes are greater in people who are physically active (e.g. manual labourers). This has importance for recreational activity outdoors and it is relevant especially to the impacts of climate change on occupational health (11.6.2) (Ebi and Mills, 2013; Kjellstrom *et al.*, 2009a).

Heat also acts on human health through its effects, in conjunction with low rainfall, on fire risk. In Australia in 2009, record high temperatures, combined with long-term drought, caused fires of unprecedented intensity and 173 deaths from burns and injury (Teague *et al.*, 2010). Smoke from forest fires has been linked elsewhere with increased mortality and morbidity (Analitis *et al.*, 2012) (see 11.5.3.2).

11.4.1.2. Near-Term Future

The climate change scenarios modeled by WG1 project rising temperatures and an increase in frequency and intensity of heat waves (2.6.1 and chapter 1 of this report) in the near-term future, defined as roughly midway through the 21st century, or the era of climate responsibility (see SPM). It is uncertain how much acclimatization may mitigate the effects on human health (Baccini *et al.*, 2011; Bi and Parton, 2008; Hanna *et al.*, 2011; Honda *et al.*, 2013; Maloney and Forbes, 2011; Peng *et al.*, 2011; Wilkinson *et al.*, 2007; Wilkinson *et al.*, 2007). In New York, it was estimated that acclimatization may reduce the impact of added summer heat in the 2050s by roughly a quarter (Knowlton *et al.*, 2007). In Australia, the number of “dangerously hot” days, when core body temperatures may increase by ≥ 2ºC and outdoor activity is hazardous, is projected to rise from the current 4-6 days per year to 33-45 days per year by 2070 (with SRES A1FI) for non-acclimatized people. Among acclimatized people, an increase from 1-5 days per year to 5-14 days per year is expected (Hanna *et al.*, 2011).

For reasons given above, it is not clear whether winter mortality will decrease in a warmer, but more variable, climate (Ebi and Mills, 2013; Kinney *et al.*, 2012). Overall, we conclude that the increase in heat-related mortality by mid-century will outweigh gains due to fewer cold periods, especially in tropical developing countries with limited adaptive capacities and large exposed populations (Wilkinson *et al.*, 2007). A similar pattern has been projected for temperate zones. A study of three Quebec cities, based on SRES A2 and B2, extended to 2099, showed an increase in summer mortality that clearly outweighed a small reduction in autumn deaths, and only slight variations in winter and spring (Doyon *et al.*, 2008). Another study in Brisbane, Australia, using years of life lost as the outcome, found the gains associated with fewer cold days were less than the losses caused by more hot days, when warming exceeded 2ºC. (Huang *et al.*, 2012). A similar trend is reported in the United Kingdom (Health Protection Agency, 2012) and in New York City (Knowlton *et al.*, 2007).

11.4.2. Floods and Storms

Floods are the most frequently occurring type of natural disaster (Guha-Sapir *et al.*, 2011). In 2011, six of the 10 biggest natural disasters were flood events, when considered in terms of both number affected (112 million people) and number of deaths (3,140 people) (Guha-Sapir *et al.*, 2011). Globally, the frequency of river flood events has been increasing, as well as economic losses, due to the expansion of population and property in flood plains (chapter 18). There is little information on health trends attributable to flooding, except for mortality and there are large differences in mortality risk between countries (UNISDR, 2011). Mortality from flooding and storm events is generally declining, but there is good evidence that mortality risks first increase with economic development before declining (De Haen and Hemrich, 2007; Kellenberg and Mobarak, 2008; Patt *et al.*, 2010). For instance, migration to slums to coastal cities may increase population exposure at a greater pace than can be compensated for by mitigation measures (see chapter 10 on urban risks). Severe damaging floods in Australia in 2010-2011 and in the Northeastern United States in 2012 indicate that high-income countries may still be affected (Guha-Sapir *et al.*, 2011).

11.4.2.1. Mechanisms

Flooding and windstorms adversely affect health through drowning, injuries, hypothermia, infectious diseases (e.g. diarrhoeal disease, leptospirosis, vector-borne disease, cholera) (Jakubicka *et al.*, 2010; Schnitzler *et al.*, 2007). Since AR4, more evidence has emerged on the long term (months-years) implications of flooding for health. Flooding and storms may have profound effects on peoples' mental health (Neria, 2012). The prevalence of mental health symptoms (psychological distress, anxiety and depression) was two to five times higher among individuals who reported flood water in the home compared to non-flooded individuals (2007 flood in England and Wales)(Paranjothy *et al.*, 2011). In the United States, signs of hurricane-related mental illness were observed in a follow-up of New Orleans' residents almost two years after Hurricane Katrina (Kessler *et al.*, 2008).

The attribution of deaths to flood events is complex; most reports of flood deaths include only immediate traumatic deaths, which means that the total mortality burden is under-reported (Health Protection Agency, 2012). There is some uncertainty as to whether flood events are associated with a longer-term (6-12 months) effect on mortality in the flooded population. No persisting effects were observed in a study in England and Wales (Milojevic *et al.*, 2011), but longer-term increases in mortality were found in a rural population in Bangladesh (Milojevic *et al.*, 2012).

11.4.2.2. Near-Term Future

Under most climate change scenarios, it is expected that more frequent intense rainfall events will occur in most parts of the world in the future (IPCC, 2012). If this happens, floods in small catchments will be more frequent, but the consequence is uncertain in larger catchments (See Chapter 3). In terms of exposure, it is expected that more people will be exposed to floods in Asia, Africa and Central and South America (Chapter 3). Also, increases in intense tropical cyclones are *likely* in the late 21st century (WG1 Table SPM.1). It has been estimated conservatively that around 2.8 billion people were affected by floods between 1980-2009, with over 500,000 deaths (Doocy *et al.*, 2013). On this basis we conclude it is *very likely* that health losses caused by storms and floods will increase this century if no adaptation measures are taken. What is not clear is how much of this projected increase can be attributed to climate change. Dasgupta *et al.* (2009) developed a spatially explicit mortality model for 84 developing countries and 577 coastal cities. They modelled 1:100 year storm-surge events, and assessed future impacts under climate change, accounting for sea level rise and a 10% increase in event intensity. In the 84 developing countries, an additional 52 million people and 30,000 km^2 of land were projected to be affected by 2100.

11.4.3. Ultraviolet Radiation

Ambient UV levels and maximum summertime day temperatures are related to the prevalence of non-melanoma skin cancers and cataracts in the eye. In one study in the United States, the number of cases of squamous cell carcinoma was 5.5% higher for every 1°C increment in average temperatures, and basal cell carcinoma was 2.9% more common with every 1°C increase. These values correspond to an increase in the effective UV dose of 2% for each 1°C (van der Leun *et al.*, 2008). However, exposure to the sun has beneficial effects on synthesis of Vitamin D, with important consequences for health. Accordingly the balance of gains and losses due to increased UV exposures vary with location, intensity of exposure and other factors (such as diet) that influence Vitamin D levels (Lucas *et al.*, 2013). Studies of stratospheric ozone recovery and climate change project that ultraviolet radiation levels at Earth's surface will generally return to pre-1980 levels by mid-century, and may diminish further by 2100, although there is high uncertainty around the projections (Correa *et al.*, 2013). On the other hand, higher temperatures in countries with temperate climates may result in an increase in the time which people spend outdoors (Belanger *et al.*, 2009) and lead to additional UV-induced adverse effects.

11.5. Ecosystem-Mediated Impacts of Climate Change on Health Outcomes

11.5.1. Vector-Borne and Other Infectious Diseases

Vector-borne diseases (VBDs) refer most commonly to infections transmitted by the bite of blood-sucking arthropods such as mosquitoes or ticks (Wong, Harris, Rodriguez-Galindo, & Johnson, 2013). These are some of the best-studied diseases associated with climate change, due to their widespread occurrence and sensitivity to climatic factors (Bangs *et al.*, 2006; Bi *et al.*, 2007; Halide and Ridd, 2008; Wu *et al.*, 2009). Table 11-1 summarizes what is known about the influence of weather and climate on selected VBDs.

[INSERT TABLE 11-1 HERE
Table 11-1: The association between different climatic drivers and the global prevalence and geographic distribution of selected vector-borne diseases observed over the period 2008-2012. Among the vector borne diseases shown here, only dengue fever was associated with climate variables at both the global and local levels (*high confidence*), while malaria and hemorrhagic fever with renal syndrome showed a positive association at the local level (*high confidence*).]

11.5.1.1. Malaria

Malaria is mainly caused by five distinct species of plasmodium parasite (*Plasmodium falciparum, Plasmodium vivax, Plasmodium malariae, Plasmodium ovale, Plasmodium knowlesi*), transmitted between individuals by Anopheline mosquitoes. In 2010 there were an estimated 216 million episodes of malaria worldwide, mostly amongst children under 5 years in the African Region (World Health Organization, 2010). The number of global malaria deaths was estimated to be 1,238,000 in 2010 (Murray *et al.*, 2012). Worldwide, there have been significant advances made in malaria control in the last 20 years (Feachem, 2011).

The influence of temperature on malaria development appears to be non-linear, and is vector-specific (Alonso *et al.*, 2011). Increased variations in temperature, when the maximum is close to the upper limit for vector and pathogen, tend to reduce transmission, while increased variations of mean daily temperature near the minimum boundary increase transmission (Paaijmans *et al.*, 2010). Analysis of environmental factors associated with the malaria vectors *Anopheles gambiae* and *A. funestus* in Kenya found that abundance, distribution, and disease transmission are affected in different ways by precipitation and temperature (Kelly-Hope *et al.*, 2009). There are lag-times according to the lifecycle of the vector and the parasite: a study in central China reported that malaria incidence was related to the average monthly temperature, the average temperature of the previous two months, and the average rainfall of the current month (Zhang *et al.*, 2012).

More work has been done since AR4 to elucidate the role of local warming on malaria transmission in the East African highlands, but this is hampered by the lack of time series data on levels of drug resistance and intensity of vector control programs. Earlier research had failed to find a clear increase in temperatures accompanying increases in malaria transmission, but new studies with aggregated meteorological data over longer periods have confirmed increasing temperatures since 1979 (Omumbo *et al.*, 2011; Stern *et al.*, 2011). The strongly non-linear response to temperature means that even modest warming may drive large increases in transmission of malaria, if conditions are otherwise suitable (Alonso *et al.*, 2011; Pascual *et al.*, 2006). On the other hand, at relatively high temperatures modest warming may reduce the potential of malaria transmission (Lunde *et al.*, 2013). One review (Chaves and Koenraadt, 2010) concluded that decadal temperature changes have played a role in changing malaria incidence in East Africa. But malaria is very sensitive also to socioeconomic factors and health interventions, and the generally more conducive climate conditions have been offset by more effective disease control activities. The incidence of malaria has reduced over much of East Africa (Stern *et al.*, 2011) although increased variability in disease rates has been observed in some high altitude areas (Chaves *et al.*, 2012).

At the global level, economic development and control interventions have dominated changes in the extent and endemicity of malaria over the last 100 years (Gething *et al.*, 2010). Although modest warming has facilitated malaria transmission (Alonso *et al.*, 2011; Pascual *et al.*, 2006), the proportion of the world's population affected by the disease has been reduced, largely due to control of *P. vivax* malaria in moderate climates with low transmission intensity. However, the burden of disease is still high and may actually be on the increase again, in some locations (World Health Organization, 2012). For instance, locally-transmitted malaria has re-emerged in Greece in association with economic hardship and cutbacks in government spending (Andriopoulos *et al.*, 2013; Danis *et al.*, 2011).

11.5.1.2. Dengue Fever

Dengue is the most rapidly spreading mosquito-borne viral disease, showing a 30-fold increase in global incidence over the past 50 years (World Health Organization, 2013). Each year there occur about 390 million dengue infections worldwide, of which roughly 96 million manifest with symptoms (Bhatt *et al.*, 2013). Three quarters of the people exposed to dengue are in the Asia-Pacific region, but many other regions are affected also. The first sustained transmission of dengue in Europe since the 1920s was reported in 2012 in Madeira, Portugal (Sousa *et al.*, 2012). The disease is associated with climate on spatial (Beebe *et al.*, 2009; Li *et al.*, 2011; Russell *et al.*, 2009), temporal (Descloux *et al.*, 2012; Earnest *et al.*, 2012; Gharbi *et al.*, 2011; Herrera-Martinez and Rodriguez-Morales, 2010; Hii *et al.*, 2009; Hsieh and Chen, 2009; Pham *et al.*, 2011) and spatiotemporal (Chowell *et al.*, 2008; Chowell *et al.*, 2011; Lai, 2011) scales.

The principal vectors for dengue, *Aedes aegypti* and *Ae. albopictus,* are climate-sensitive. Over the last two decades, climate conditions have become more suitable for *albopictus* in some areas (e.g. over central northwestern Europe) but less suitable elsewhere (e.g. over southern Spain) (Caminade *et al.*, 2012). Distribution of *Ae. albopictus* in northwestern China is highly correlated with annual temperature and precipitation (Wu *et al.*, 2011). Temperature, humidity and rainfall are positively associated with dengue incidence in Guangzhou, China, and wind velocity is inversely associated with rates of the disease (Li *et al.*, 2011; Lu and Lin, 2009). Several studies in Taiwan reported that typhoons remain an important factor affecting vector population and dengue fever (Hsieh and Chen, 2009; Lai, 2011). Typhoons result in extreme rainfall, high humidity and water pooling, and may generate fresh mosquito breeding sites. A study in Dhaka, Bangladesh reported increased rates of admissions to hospital due to dengue with both high and low river levels (Hashizume and Dewan, 2012). In some circumstances, it is apparent that heavy precipitation favors the spread of dengue fever, but drought can also be a cause if households store water in containers that provide suitable mosquito breeding sites (Beebe *et al.*, 2009; Padmanabha *et al.*, 2010).

_____ START BOX 11-2 HERE _____

Box 11-2. Case Study: An Intervention to Control Dengue Fever

Seasonality in dengue transmission is well established in many parts of the world, and transmission occurs mostly during the wettest months of the year (Chadee *et al.*, 2007; Gubler and Kuno, 1997). Figure 11-3 shows that about 80% of dengue fever cases in Trinidad were recorded during the wet season, a period when the *Ae. aegypti* mosquito population density was four to nine times higher than the dengue transmission threshold (Macdonald, 1956). This led to a control program that concentrated on reducing the mosquito population before the onset of the rains, by application of insecticides (temephos) into the water drums that serve as primary breeding sites of *Ae. aegypti* in the

Caribbean. The one-off treatment effectively controlled the mosquito populations for almost 12 weeks after which the numbers reverted to levels observed in the untreated control areas.

[INSERT FIGURE 11-3 HERE
Figure 11-3: a) Rainfall, temperature, Breteau index (number of water containers with *Ae. aegypti* larvae per 100 houses), and dengue fever cases, Trinidad (2002-2004). Rainfall was found to be significantly correlated with an increase in the *Ae. aegypti* population and dengue fever incidence, with a clearly defined “dengue season” between June and November over two years of the study. Source: (Chadee *et al.*, 2007). b) Efficacy of pre-seasonal treatment with temephos on *Ae. aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003). Evidence of the efficacy of the pre-seasonal larval control through focal treatment of *Ae. aegypti* population is provided. Treatment at the onset of the rainy season can effectively prevent the rapid increase in *Ae. aegypti* populations and therefore suppress the onset of dengue transmission. Source: Chadee, 2009.]

Climate scenarios that extend to 2071-2100 project changes in the intensity and frequency of rainfall events in the Caribbean (Campbell *et al.*, 2011). In these scenarios, there is greater variability in rainfall patterns during November to January, with the northern Caribbean region receiving more rainfall than in the southern Caribbean (Campbell *et al.*, 2011). There may be water shortages during drought periods, and flooding after episodes of heavy rainfall, both of which affect the breeding habitats of *Ae. aegypti* and *Ae. albopictus*. Vector control strategies will need to be planned and managed astutely to systematically reduce mosquito populations.

_____ END BOX 11-2 HERE _____

11.5.1.3. Tick-Borne Diseases

Tick-borne encephalitis (TBE) is caused by tick-borne encephalitis virus, and is endemic in temperate regions of Europe and Asia. Lyme disease is an acute infectious disease caused by the spirochaete bacteria *Borrelia burgdorferi* and is reported in Europe, the USA and Canada. *Borrelia* is transmitted to humans by the bite of infected ticks belonging to a few species of the genus *Ixodes* ("hard ticks"). Many studies have reported associations between climate and tick-borne diseases (Andreassen *et al.*, 2012; Estrada-Peña *et al.*, 2012; Jaenson *et al.*, 2012; Lukan *et al.*, 2010; Okuthe and Buyu, 2006; Tokarevich *et al.*, 2011).

In North America, there is good evidence of northward expansion of the distribution of the tick vector (*Ixodes scapularis*) in the period 1996-2004 based on an analysis of active and passive surveillance data (Ogden *et al.*, 2010). However, there is no evidence so far of any associated changes in the distribution in North America of human cases of tick-borne diseases.

There was a marked rise in TBE cases from the 1970s in central and eastern Europe. Spring-time daily maximum temperatures rose in the late 1980s, sufficient to encourage transmission of the TBE virus. For instance, in the Czech Republic, between 1970 and 2008, there were signs of lengthening transmission season and higher altitudinal range in association with warming (Kriz *et al.*, 2012). However variations in illness rates across the region demonstrate that climate change alone cannot explain the increase. Socioeconomic changes (including changes in agriculture and recreational activities) have affected patterns of disease in Europe (Randolph, 2010; Sumilo *et al.*, 2008). The complex ecology of tick-borne diseases such as Lyme disease and TBE make it difficult to attribute particular changes in disease frequency and distribution to specific environmental factors such as climate (Gray *et al.*, 2009).

11.5.1.4. Other Vector-Borne Diseases

Hemorrhagic fever with renal syndrome (HFRS) is a zoonosis caused by the Hanta virus, and leads to approximately 200,000 hospitalized cases each year. The incidence of this disease has been associated with temperature, precipitation, and relative humidity (Fang *et al.*, 2010; Liu *et al.*, 2011; Pettersson *et al.*, 2008). Plague, one of the oldest diseases known to humanity, persists in many parts of the world. Outbreaks have been linked to seasonal and inter-annual variability in climate (Holt *et al.*, 2009; MacMillan *et al.*, 2012; Nakazawa *et al.*, 2007; Stenseth *et al.*, 2006; Xu *et al.*, 2011). Chikungunya fever is a climate-sensitive mosquito-transmitted viral disease (Anyamba *et al.*, 2012), first identified in Africa, now present also in Asia, and the disease has recently emerged in parts of Europe (Angelini *et al.*, 2008). The incidence in China of Japanese encephalitis, another mosquito-borne viral disease, is correlated with temperature and rainfall, especially during the warmer months of the year (Bai *et al.*, 2013). In West Africa, outbreaks of Rift Valley Fever, an acute viral disease affecting humans and domestic animals, are linked to within-season variability in rainfall (Caminade *et al.*, 2011).

11.5.1.5. Near-Term Future

Using the A1B climate change scenario, Béguin *et al.* (2011) projected the population at risk of malaria to 2030 and 2050. With GDP *per capita* held constant at 2010 values, the model projected 5.2 billion people at risk in 2050, out of a predicted global population of 8.5 billion. Keeping climate constant, and assuming strong economic growth allied with social development ("best case"), the model projected 1.74 billion people at risk (approximately half the present number at risk) in 2050. Factoring in climate change would increase the "best case" estimate of the number of people at risk of malaria in 2050 to 1.95 billion, which is 200 million more than if disease control efforts were not opposed by higher temperatures and shifts in rainfall patterns.

There are no recent studies that project the return of established malaria to North America or Europe, where it was once prevalent. However suitable vectors for *P. vivax* malaria abound in these parts of the world, and recent experience in southern Europe demonstrates how rapidly the disease may re-appear if health services falter (Bonovas and Nikolopoulos, 2012).

A systematic review of research on the distribution of dengue and possible influence of climate change (Van Kleef *et al.*, 2010) concluded that the area of the planet that was climatically suitable for dengue would increase under most scenarios, but it was not possible to project the impact on disease incidence. Åström (Astrom *et al.*, 2012) estimated the population at risk out to the year 2050. The study was based on routine disease reports, surveys, population projections, estimates of GDP growth and the A1B scenario for climate change. Assuming high GDP growth that benefits all populations, the number exposed to dengue in 2050 falls to 4.46 billion, i.e. the adverse effects of climate change are balanced by the beneficial outcomes of development. This study considered only the margins of the geographic distribution of dengue (where economic development has its strongest effect) and did not examine changes in intensity of transmission in areas where the disease is already established.

Kearny (2009) used biophysical models to examine the potential extension of vector range in Australia. He predicted that climate change would increase habitat suitability throughout much of Australia. Changes in water storage as a response to a drier climate may be an indirect pathway, through which climate change affects mosquito breeding (Beebe *et al.*, 2009).

11.5.2. Food- and Water-Borne Infections

Human exposure to climate-sensitive pathogens occurs by ingestion of contaminated water or food, incidental ingestion during swimming or by direct contact with eyes, ears or open wounds. Pathogens in water may be zoonotic in origin, concentrated by bivalve shellfish (e.g., oysters) or deposited on irrigated food crops. Pathogens of concern include enteric organisms that are transmitted by the fecal oral route and also bacteria and protozoa that occur naturally in aquatic systems. Climate may act directly by influencing growth, survival, persistence, transmission or virulence of pathogens; indirect influences include climate-related perturbations in local ecosystems or the habitat of species that act as zoonotic reservoirs.

11.5.2.1. Vibrios

Vibrio is a genus of native marine bacteria that includes a number of human pathogens, most notably *V. cholerae* which causes cholera. Cholera may be transmitted by drinking water or by environmental exposure in seawater and seafood; other Vibrio species are solely linked to seawater and shellfish. These include *V. parahaemolyticus* and *V. vulnificus*, with *V. alginolyticus* emerging in importance (Weis, 2011). Risk of infection is influenced by temperature, precipitation and accompanying changes in salinity due to freshwater run-off, addition of organic carbon or other nutrients or changes in pH. These factors all affect the spatial and temporal range of the organism and also influence exposure routes (e.g. direct contact or via seafood). In countries with endemic cholera, there appears to be a robust relationship between temperature and the disease (Islam, 2009; Paz, 2009; Reyburn *et al.*, 2011). In addition, heavy rainfall promotes the transmission of pathogens when there is not secure disposal of fecal waste. An unequivocal positive relationship between Vibrio numbers and SST in the North Sea has been established by DNA analyses of formalin-fixed samples collected over a 44 year period (Vezzulli *et al.*, 2012). Cholera outbreaks have been linked to variations in temperature and rainfall, and other variables including sea and river levels, sea chlorophyll and cyanobacteria contents, Indian Ocean Dipole (IOD) and El Niño–Southern Oscillation (ENSO) events (Bompangue *et al.*, 2011; Constantin de Magny *et al.*, 2008; Hashizume, 2008; Reyburn *et al.*, 2011; Rinaldo *et al.*, 2012).

11.5.2.2. Other Parasites, Bacteria, and Viruses

Rates of diarrhea have been associated with high temperatures (Kolstad and Johansson, 2011). Mostly, however, the specific causes of the diarrheal illness are not known, nor the mechanism for the association with temperature. Exceptions include *Salmonella* and *Campylobacter*, among the most common zoonotic food and waterborne bacterial pathogens worldwide, which both show distinct seasonality in infection and higher disease rates at warmer temperatures. The association between climate (especially temperature) and non-outbreak (‘sporadic’) cases of salmonellosis may, in part, explain seasonal and latitudinal trends in diarrhea (Lake, 2009).

Among the enteric viruses, there are distinct seasonal patterns in infection that can be related indirectly to temperature. Enterovirus infections in the U.S. peak in summer and fall months (Khetsuriani *et al.*, 2006). After controlling for seasonality and interannual variations, hand, foot and mouth disease (caused by coxsackievirus A16 and enterovirus 71), shows a linear relationship with temperature in Singapore, with a rapid rise in incidence when the temperature exceeds 32°C (Hii *et al.*, 2011). However, it is not clear what the underlying driver is and if temperature is confounded by other seasonal factors.

Temperature is directly linked with risk of enteric disease in Arctic communities, since melt of the permafrost hastens transport of sewage (which is often captured in shallow lagoons) into groundwater, drinking water sources or other surface waters (Martin *et al.*, 2007). Additionally, thawing may damage drinking water intake systems (for those communities with such infrastructure) (Hess, 2008).

Rainfall has also been associated with enteric infections. Bacterial pathogens are more likely to grow on produce crops (e.g. lettuce) in simulations of warmer conditions (Liu *et al.*, 2013a), and become attached to leafy crops under conditions of both flooding and drought (Ge *et al.*, 2012). This latter pattern is reflected in patterns of illness (Bandyopadhyay *et al.*, 2012). Higher concentrations of enteric viruses have been reported frequently in drinking water and recreational water following heavy rainfall (Delpla *et al.*, 2009).

Worldwide, rotavirus infections caused about 450,000 deaths in children under 5 years old in 2008 (Tate *et al.*, 2012). There are seasonal peaks in the number of cases in temperate and subtropical regions but less distinct patterns are seen within 10° latitude of the equator (Cook *et al.*, 1990). Variations in the timing of peak outbreaks between countries or regions (Atchison *et al.*, 2010; Turcios *et al.*, 2006) and variations with time in the same country (Dey *et al.*, 2010) have been attributed to fluctuations in the number and seasonality of births (Pitzer *et al.*, 2009; Pitzer *et al.*, 2011). While vaccination against rotavirus is expected to reduce the total burden of disease, it may also increase seasonal variation (Pitzer *et al.*, 2011; Tate *et al.*, 2009).

Harmful algal blooms can be formed by (i) dinoflagellates that cause outbreaks of paralytic shellfish poisoning, ciguatera fish poisoning and neurotoxic shellfish poisoning; (ii) cyanobacteria that produce toxins causing liver, neurological, digestive and skin diseases; and (iii) diatoms that can produce domoic acid, a potent neurotoxin which is bioaccumulated in shellfish and finfish (Erdner *et al.*, 2008). Increasing temperatures promote bloom formation in both fresh water (Paerl *et al.*, 2011), and marine environments (Marques *et al.*, 2010). (See Chapter 5.) Increasing temperature favoured growth of toxic over non-toxic strains of *Microcystis* in lakes in the USA (Davis *et al.*, 2009). Projections of toxin-producing blooms in Puget Sound using an A1B scenario suggest that by the end of the century the "at risk" period may begin 2 months earlier and last up to 1 month longer than at present (Moore *et al.*, 2011).

11.5.2.3. Near-Term Future

Kolstad and Johansson (2011) projected an increase of 8-11% in the risk of diarrhea in the tropics and subtropics in 2039 due to climate change, using the A1B scenario and 19 coupled atmosphere-ocean climate models from CMIP3. This study did not account for future changes in economic growth and social development. Application of down-scaled climate change models showed that overflows of sewage into Chicago's watersheds would increase by 50-120% by 2100, as a result of more frequent and intense rainfall (Patz *et al.*, 2008). In Botswana, if hot, dry conditions begin earlier in the year, and are prolonged, as projected by down-scaled climate scenarios, the present dry season peak in diarrhoeal disease may be amplified (Alexander *et al.*, 2013). However the same analysis projected that incidence of diarrhoeal disease in the wet season would decline.

Zhou *et al.* (2008) studied the effect of climate on transmission of schistosomiasis due to *S. japonicum* in China. They concluded that an additional 784 thousand km^2 would become suitable for schistosomiasis transmission in China by 2050, as the mid-winter freezing line moves northwards (Figure 11-4).

[INSERT FIGURE 11-4 HERE
Figure 11-4: Effect of rising temperatures on the area in which transmission of *Schistosomiasis japonica* may occur. Green area denotes the range of schistosomiasis in China in 2000. The blue area shows the additional area suitable for disease transmission in 2050. Based on a biology-driven model including parasite (*Schistosoma japonicum*) and snail intermediate host (*Oncomelania hupensis*) and assuming average temperatures in China in mid-winter (January) increase by 1.6°C in 2050, compared with 2000. Adapted from Zhou *et al.*, 2008.]

Mangal *et al*. (2008) constructed a mechanistic model of the transmission cycle of another species, *S. mansoni,* and reported a peak in the worm burden in humans at an ambient temperature of 30°C, falling sharply as temperature rises to 35°C. The authors attribute this to the increasing mortality of both the snails and the water-borne intermediate forms of the parasite, and noted that worm burden is not directly linked to the prevalence of schistosomiasis.

11.5.3. Air Quality

Nearly all the non-CO_2 climate-altering pollutants (CAPs – see Chapters 7 and 8 of WGI) are health damaging, either directly or by contributing to secondary pollutants in the atmosphere. Thus, like the ocean acidification and ecosystem/ agriculture fertilization impacts of CO_2, the other CAPs have non-climate-mediated impacts, particularly on health. Although not reviewed in detail in this assessment, the health impacts of non-CO_2 CAPs are substantial globally. See Box 11-3.

_____ START BOX 11-3 HERE _____

Box 11-3. Health and Economic Impacts of Climate-Altering Pollutants (CAPs) Other than CO_2

Although other estimates of the global health impacts of human exposures to particle and ozone pollution have been published in recent years (e.g. (UNEP, 2011)), the most comprehensive was the Comparative Risk Assessment carried out as part of the 2010 Global Burden of Disease Project (Lim *et al.*, 2012). It found that the combined health impact of the household exposures to particle air pollution from poor combustion of solid cooking fuels, plus general ambient pollution, was about 6.8 million premature deaths annually, with about 5 percent overlapping, i.e., coming from the contribution to general ambient pollution of household fuels. It also found that about 150 thousand premature deaths could be attributed to ambient ozone pollution. Put into terms of disability-adjusted life years

(DALYs), particle air pollution was responsible for about 190 million lost DALYs in 2010, or about 7.6% of all DALYs lost. This burden puts particle air pollution among the largest risk factors globally, far higher than any other environmental risk and rivaling or exceeding all of the five dozen risk factors examined, including malnutrition, smoking, high blood pressure, and alcohol.

The economic impact of this burden is difficult to assess as evaluation methods vary dramatically in the literature. Most in the health field prefer to consider some version of a lost healthy life year as the best metric although the economics literature often uses willingness to pay for avoiding a lost life (Jamison *et al.*, 2006). Another difficulty is that any valuation technique that weights the economic loss according to local incomes per capita will value health effects in rich countries more than in poor countries, which would seem to violate some of the premises of a global assessment; see WGIII Chpt 3 for more discussion. Here, however, we will use the mean global income per capita (~ USD 10,000 in 2010) to scope out the scale of the impact globally without attempting to be specific by country or region.

The WHO CHOICE approach for evaluating what should be spent on health interventions indicates that one annual per capita income per DALY is a reasonable upper bound (World Health Organization, 2009a). This would imply that the total lost economic value from global climate-altering pollutants in the form of particles is roughly USD 1.9 trillion, in the sense that the world ought to be willing to pay this much to reduce it. This is about 2.7% of the global economy (approximately USD 70 trillion in 2010).

On the one hand, this shows that global atmospheric pollution already has a major impact on the health and economic well-being of humanity today, due mainly to the direct effects rather than those mediated through climate. If CO_2 is not controlled and climate change continues to intensify while air pollutant controls become more stringent, the climate impacts will become more prominent. The quite different time scales for the two types of impacts make comparisons difficult, however.

Air pollution reductions do not always promote the twin goals of protecting health and climate but can pose trade-offs. All particles are dangerous for health, for example, but some are cooling, such as sulfates, and some warming, such as black carbon (Smith *et al.*, 2009). Indeed elimination of all anthropogenic particles in the atmosphere, a major success for health, would have only a minor net impact on climate (WG1, Fig TS-6). As discussed in the co-benefits section below (11.9), there are nevertheless specific actions that will work toward both goals.

_____ END BOX 11-3 HERE _____

Although there is a large body of literature on the health effects of particulate air pollution (see Box 11-3), WGI indicates that there is little evidence that climate change, per se, will affect long-term particle levels in a consistent way (WG1, 11.3.5; Annex II). Thus, we focus here on chronic ozone exposures, which are found by WGI to be enhanced in some, but not all, scenarios of future climate change (WG1, TS.5.4.8).

11.5.3.1. Long-Term Outdoor Ozone Exposures

Tropospheric ozone is formed through photochemical reactions that involve nitrogen oxides (NO_x), carbon monoxide (CO), methane (CH_4), and volatile organic compounds (VOCs) in the presence of sunlight and elevated temperatures (WG1, Ch 8). Therefore, if temperatures rise, many air pollution models (Chang *et al.*, 2010; Ebi and McGregor, 2008; Polvani *et al.*, 2011; Tsai *et al.*, 2008) project increased ozone production especially within and surrounding urban areas (Hesterberg *et al.*, 2009). Enhanced temperature also accelerates destruction of ozone, and the net direct impact of climate change on ozone concentrations worldwide is thought to be a reduction (WG1 TS.5.4.8). Some WG1 (TS.5.4.8) scenarios, however, indicate tropospheric ozone may rise from additional methane emissions stimulated by climate change. Models also show that local variations can have a different sign to the global one (Selin *et al.*, 2009).

Even small increases in atmospheric concentrations of ground-level ozone may affect health (Bell *et al.*, 2006; Ebi and McGregor, 2008; Jerrett *et al.*, 2009). For instance, Bell *et al*. (2006) found that levels that meet the US EPA 8-

hour regulation (0.08 ppm over 8 hours) were associated with increased risk of premature mortality. There is a lack of association between ozone and premature mortality only at very low concentrations (from 0 to ~10 ppb) but the association becomes positive and approximately linear at higher concentrations (Bell *et al.*, 2006; Ebi and McGregor, 2008; Jerrett *et al.*, 2009). In an analysis of 66 United States cities with 18 years of follow-up (1982-2000), tropospheric ozone levels were found to be significantly associated with cardiopulmonary mortality (Smith *et al.*, 2009). See also the global review by WHO, which includes data from developing countries (World Health Organization, 2006).

11.5.3.2. Acute Air Pollution Episodes

Wildfires, which occur more commonly following heat waves and drought, release particulate matter and other toxic substances that may affect large numbers of people for days to months (Finlay *et al.*, 2012; Handmer *et al.*, 2012). During a fire near Denver (USA) in June 2009, 1-hour concentrations of PM_{10} and $PM_{2.5}$ reached 370 µg/m^3 and 200 µg/m^3, and 24-hour average concentrations reached 91 µg/m^3 and 44 µg/m^3, compared to the 24-hour WHO air quality guidelines for these pollutants of 50 µg/m^3 and 25 µg/m^3, respectively (Vedal and Dutton, 2006). One study of worldwide premature mortality attributable to air pollution from forest fires estimated there were 339,000 deaths per year (range 260,000 to 600,000) (Johnston *et al.*, 2012). The regions most affected are Sub-Saharan Africa and Southeast Asia (Johnston *et al.*, 2012).

Extremely high levels of PM_{10} were observed in Moscow due to forest fires caused by a heat wave in 2010. Daily mean temperatures in Moscow exceeded the respective long-term averages by 5°C or more for 45 days. Ten new temperature records were established in July and nine in August, based on measurements since 1885, and an anti-cyclone in the Moscow region prevented dispersion of air pollutants. The highest 24-h pollution levels recorded in Moscow during these conditions were between 430 and 900 µg/m^3 PM_{10} most days, but occasionally reached 1500 µg/m^3. The highest 24-h CO concentration was 30 mg/m^3 compared to the WHO AQG of 7 µg/m^3, and the levels of formaldehyde, ethyl benzene, benzene, toluene and styrene were also increased (State Environmental Institution “Mosecomonitoring”, 2010).

There may be an interaction of tropospheric ozone and heat waves. Dear *et al*. (2005) modeled the daily mortality due to heat and exposure to ozone during the European summer heat wave of 2003 and found that possibly 50% of the deaths could have been associated with ozone exposure rather than the heat itself.

11.5.3.3. Aeroallergens

Allergic diseases are common and are climate-sensitive. Warmer conditions generally favour the production and release of air-borne allergens (such as fungi and lower plant spores and pollen) and, consequently, there may be an effect on asthma and other allergic respiratory diseases, such as asthma and allergic rhinitis, as well as effects on conjunctivitis and dermatitis (Beggs, 2010). Children are particularly susceptible to most allergic diseases (Schmier and Ebi, 2009). Increased release of allergens may be amplified if higher CO_2 levels stimulate plant growth. Visual monitoring and experiments have shown that increases in air temperature cause earlier flowering of prairie tallgrass (Sherry *et al.*, 2007). Droughts and high winds may produce windborne dust and other atmospheric materials, which contain pollen and spores, and transport these allergens to new regions.

Studies have shown that increasing concentrations of grass pollen lead to more frequent ambulance calls due to asthma symptoms, with a time lag of 3-5 days (Heguy *et al.*, 2008). Pollen levels have also been linked to hospital visits with rhinitis symptoms (Breton *et al.*, 2006). A cross-sectional study in the three climatic regions of Spain documented a positive correlation between the rate of child eczema and humidity, and negative correlation between child eczema and air temperature or the number of sunshine hours (Suarez-Varela *et al.*, 2008).

11.5.3.4. Near-Term Future

It is projected by WGI that climate change could affect future air quality, including levels of photochemical oxidants and, with much less certainty, fine particles ($PM_{2.5}$). If this occurs, there will be consequences for human health (Bell *et al.*, 2007; Chang *et al.*, 2012; Dong *et al.*, 2011; Lepeule *et al.*, 2012; Meister *et al.*, 2012; West *et al.*, 2013). High temperatures may also magnify the effects of ozone (Jackson *et al.*, 2010; Ren *et al.*, 2008). Increasing urbanization, use of solid biomass fuels, and industrial development in the absence of emission controls could also lead to increases in ozone chemical precursors (Selin *et al.*, 2009; Wilkinson *et al.*, 2009).

Most post-2006 studies on the projected impacts of future climate change on air pollution-related morbidity and mortality have focused on ozone in Europe, the U.S. and Canada (see Table 11-S1; (Bell *et al.*, 2007; Selin *et al.*, 2009; Tagaris *et al.*, 2009)). Projections are rare for other areas of the world, notably the developing countries where air pollution is presently a serious problem and is expected to worsen unless controls are strengthened.

Higher temperatures may magnify the effects of air pollutants like ozone, although estimates of the size of this effect vary (Jackson *et al.*, 2010; Ren *et al.*, 2008). In general, all-cause mortality related to ozone is expected to increase in the US and Canada (Bell *et al.*, 2007; Cheng *et al.*, 2011; Jackson *et al.*, 2010; Tagaris *et al.*, 2009). Under a scenario in which present air quality legislation is rolled out everywhere, premature deaths due to ozone would be wound back in Africa, South Asia and East Asia. Under a maximum feasible CO_2 reduction scenario related to A2, it is projected that 460,000 premature ozone-related deaths could be avoided in 2030, mostly in South Asia (West *et al.*, 2007). All-cause mortality, however, is not the best metric for comparing air pollution health impacts across regions; given that background disease conditions vary so widely. HIV deaths and malaria deaths, which are prominent in Sub-Saharan Africa, for example, are not expected to increase from air pollution exposures in the same way as deaths from cardiovascular disease that dominate other regions.

A study that investigated regional air quality in the United States in 2050, using a down-scaled climate model (Goddard Institute for Space Studies, Global Climate Model), concluded there would be about 4000 additional annual premature deaths due to increased exposures to $PM_{2.5}$ (Tagaris *et al.*, 2009). Air pollutant-related mortality increases are also projected for Canada, but in this case they are largely driven by the effects of ozone (Cheng *et al.*, 2011). On the basis of the relation of asthma to air quality in the last decade (1999-2010), Thompson *et al*. (2012) anticipate that the prevalence of asthma in South Africa will increase substantially by 2050. Sheffield *et al*. (2011), applying the SRES A2 scenario, projected a median 7.3% increase in summer ozone-related asthma emergency department visits for children (0-17 years) across New York City by the 2020s compared to the 1990s.

11.6. Health Impacts Heavily Mediated through Human Institutions

11.6.1. Nutrition

Nutrition is a function of agricultural production (net of post-harvest wastes and storage losses), socioeconomic factors, such as food prices and access, and human diseases, especially those which affect appetite, nutrient absorption and catabolism (Black *et al.*, 2008; Lloyd *et al.*, 2011). All three may be influenced by climate but only agricultural production has been modeled in a climate impacts framework. Here we use the terms *undernutrition*, which is a health outcome, and *undernourishment*, which reflects national (post-trade) calories available for human consumption, and is expressed as estimated percent of the population receiving ‘insufficient’ calories. We do not use the term “malnutrition,” as it includes overnutrition, which is not considered here (except under co-benefits in 11.9). Undernutrition can be chronic, leading to stunting (low height for age) or acute, leading to wasting (low weight for height); underweight (low weight for age) is a combination of chronic and acute undernutrition.

11.6.1.1. Mechanisms

The processes through which climate change can affect human nutrition are complex (see chapter 7.2.2). Higher temperatures and changes in precipitation may reduce both the quantity and quality of food harvested (e.g. (Battisti and Naylor, 2009)). Lobell *et al*. (2011b) showed for African maize that for each degree above 30°C, yields decreased by 1% under optimal rainfall conditions and by 1.7 % under drought conditions. From their systematic review of more than a thousand studies, Knox *et al*. (2012) drew the conclusion that “climate change is a threat to crop productivity in areas that are already food insecure.” Grace *et al*. (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability as well as child stunting in Kenya. The authors conclude that climate change will increase the proportion of stunted children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial adaptation efforts, such as investment in education and agricultural technology. Rising temperatures may also affect food security through the impact of heat on productivity of farmers (see 11.6.2).

The magnitude of detected and predicted decline in land-based agricultural production due to increasing temperatures and changes in rainfall must be put in perspective to other changes, such as increase in harvests due to improved farming knowledge and technology, the amount of food fed to livestock, used for biofuels, consumed beyond baseline needs by the overnourished or wasted in other ways (Foley *et al.*, 2011). There is good evidence that local food price increases have negative effects on food consumption, and therefore on health (Green *et al.*, 2013). Against this background, the global food price fluctuates, though with a recently rising trend. While the main driver is higher energy costs, amplified by speculation (Piesse and Thirtle, 2009), there is growing evidence (Auffhammer, 2011) that extreme weather events, especially floods, droughts (Williams and Funk, 2011) and heat waves, may have contributed to higher prices. All else being equal, higher prices increase the number of malnourished people. See Chapter 7 for a more detailed discussion of the impact of climate change on food production.

11.6.1.2. Near-Term Future

Since AR4 at least four studies have been published which project the effect of climate change on undernourishment and undernutrition.

Nelson *et al*. (2010; 2009) conducted two studies using a crop simulation model (DSSAT) and a global agricultural trade model (IMPACT 2009) to estimate crop production (with and without CO_2 enrichment), calorie availability, child underweight, and adaptation costs. The first study (Nelson *et al.*, 2009) was carried out under the A2 emission scenario, using two GCMs (NCAR, CSIRO) and relative to a ‘no climate change’ future. The authors found that yields of most important crops would decline in developing countries by 2050, that per capita calorie availability would drop below levels that applied in the year 2000, and that child underweight would be ~20% higher (in the absence of carbon enrichment effects). That is, about 25 million children would be affected. (See Table 11-2). Of note, the underweight estimates do not account for possible improvements in socioeconomic conditions between 2000 and 2050. However it was estimated that substantial improvements would be necessary to counteract the effects of climate change. These included a 60% increase in yield growth (all crops) over baseline, 30% faster growth in animal numbers, and a 25% increase in the rate of expansion of irrigated areas. The second study by Nelson *et al.* used a wider range of socioeconomic and climate scenarios but health impacts were similar to the first study. Estimates of improved socioeconomic conditions were insufficient to fully offset the potential impacts of climate change: child underweight was estimated to be ~10% higher with climate change compared to a future without climate change.

[INSERT TABLE 11-2 HERE
Table 11-2: Number of under-nourished children less than 5 years of age (in millions) in 2000 and 2050, using the NCAR (National Center for Atmospheric Research) climate model (and the A2 scenario from AR4). Results assume no effect of heat on farmers’ productivity, and no CO_2 fertilization benefits. Adapted from (Nelson *et al.*, 2009).]

Lloyd *et al.* (2011) built a model for estimating future stunting driven by two principle inputs: estimates of undernourishment (i.e. ‘food-related’ causes of stunting) and socioeconomic conditions (i.e. ‘non-food related’ causes of stunting). The former were based on calorie availability estimates from Nelson *et al*. (2009), and the latter on GDP *per capita* projections and estimates of the Gini index for income distribution. They estimated that by 2050, under A2 emissions with moderate to high economic growth and compared to a future without climate change, there may be a relative increase of severe stunting of 31% to 55% across regions of Sub-Saharan Africa and 61% in South Asia. It should be noted here that severe stunting carries 3 to 4 times the mortality risk of moderate stunting. In a future without climate change, undernutrition was projected to decline, leading the authors to conclude that climate change would hold back efforts to reduce child undernutrition in the most severely affected parts of the world, even after accounting for the potential benefits of economic growth.

In addition to global studies, regional projections of the impacts of climate change on undernutrition have also been carried out since AR4. Grace *et al*. (2012) modeled the relationship between climate variables (temperature and precipitation), food production and availability as well as child stunting in Kenya. The authors conclude that climate change will increase the proportion of stunted children in countries such as Kenya that are dependent on rain-fed agriculture, unless there are substantial adaptation efforts, such as investment in education and agricultural technology.

Similarly, Jankowska *et al*. (Jankowska *et al.*, 2012) included climate, livelihood and health variables (stunting and underweight). The authors identified a link between type of livelihood and risk of undernutrition, and climate and stunting. Applying the model to Mali, the authors projected impacts to 2025 and estimated that nearly 6 million people may experience undernutrition due to changes in climate, livelihood and demography; three-quarter to one million of this number will be children under five.

In summary, we conclude that climate change will have a substantial negative impact on (i) per capita calorie availability, (ii) childhood undernutrition, particularly stunting and (iii) on undernutrition–related child deaths and DALYs lost in developing countries (high confidence).

11.6.2. Occupational Health

Since AR4, much has been written on the effects of heat on working people (Dunne *et al.*, 2013; Kjellstrom *et al.*, 2009a) and on other climate-related occupational health risks (Bennett and McMichael, 2010; Schulte and Chun, 2009).

11.6.2.1. Heat Strain and Heat Stroke

Worldwide, more than half of all non-household labor-hours occur outdoors, mainly in agriculture and construction (International Fund for Agricultural Development, 2010; International Labor Organization, 2013). Individuals who are obliged to work outside in hot conditions, without access to shade, or sufficient water, are at heightened risk of heat-strain (ICD code T.67, "heat exhaustion") and heat stroke. Health risks increase with the level of physical exertion. Agricultural and construction workers in tropical developing countries are therefore among the most exposed, but heat stress is also an issue for those working indoors in environments that are not temperature-controlled, and even for some workers in high-income countries such as the USA (Luginbuhl *et al.*, 2008). (See Figure 11-5). Moreover, at higher temperatures there is potential conflict between health protection and economic productivity (Kjellstrom *et al.*, 2011): as workers take longer rests to prevent heat stress, hourly productivity goes down (Sahu *et al.*, 2013).

[INSERT FIGURE 11-5 HERE
Figure 11-5: The 1980-2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Standard Organization standard (1989) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that Tmax goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health. Source: Lemke and Kjellstrom, 2012.]

11.6.2.2. Heat Exhaustion and Work Capacity Loss

There are international standards of maximum recommended workplace heat exposure and hourly rest time (e.g. (ISO, 1989; Parsons, 2003)) for both acclimatized and non-acclimatized people. In hot countries during the hot season, large proportions of the workforce are affected by heat, and the economic impacts of reduced work capacity may be sufficient to jeopardize livelihoods (Kjellstrom *et al.*, 2011; Kjellstrom *et al.*, 2009a; Kjellstrom and Crowe, 2011; Lecocq and Shalizi, 2007). Kjellstrom and Crow (2011) and Dunne *et al*. (Dunne *et al.*, 2013) report that loss of work productivity during the hottest and wettest seasons has already occurred, at least in Asia and Africa.

11.6.2.3. Other Occupational Health Concerns

In areas where vector-borne diseases, such as malaria and dengue fever, are common, people working in fields without effective protection may experience a higher incidence of these diseases when climatic conditions favour mosquito breeding and biting (Bennett and McMichael, 2010). Increasing heat exposure in farm fields during the middle of the day may lead to more work during dawn and dusk when some of the vectors are biting humans more actively. Exposure to heat affects psychomotor, perceptual, and cognitive performance (Hancock *et al.*, 2007) and increases risk of injuries (Ramsey, 1995). Extreme weather events and climate-sensitive infectious diseases also pose occupational risks to health workers, which may in turn undermine health protection for the wider population (World Health Organization, 2009b). Other mechanisms include elevated occupational exposures to toxic chemical solvents which evaporate faster at higher temperatures (Bennett and McMichael, 2010) and rising temperatures reducing sea ice and increasing risk of drowning in those engaged in traditional hunting and fishing in the Arctic (Ford *et al.*, 2008).

11.6.2.4. Near-Term Future

Projections have been made of the future effects of heat on work capacity (Dunne *et al.*, 2013; Kjellstrom *et al.*, 2009b). Temperature and humidity were both included, and the modeling took into account the changes in the workforce distribution relating to the need for physical activity. In Southeast Asia, in 2050, the model indicates that more than half the afternoon work hours will be lost due to the need for rest breaks (Kjellstrom *et al.*, 2013). By 2100, under RCP4.5, Dunne *et al*. (2013) project up to a 20% loss of productivity globally. There is an unfortunate trade-off between health impact and productivity, which creates risks for poor and disenfranchised laborers working under difficult working conditions and inflexible rules (Kjellstrom *et al.*, 2011; Kjellstrom *et al.*, 2009a; Sahu *et al.*, 2013).

11.6.3. Mental Health

Harsher weather conditions such as floods, droughts, and heat waves tend to increase the stress on all those who are already mentally ill, and may create sufficient stress for some who are not yet ill to become so (Berry *et al.*, 2010). Manifestations of disaster-related psychiatric trauma include severe anxiety reactions (such as post-traumatic stress) and longer-term impacts such as generalised anxiety, depression, aggression, and complex psychopathology (Ahern *et al.*, 2005; Ronan *et al.*, 2008). For slow-developing events such as prolonged droughts, impacts include chronic psychological distress and increased incidence of suicide (Alston and Kent, 2008; Hanigan *et al.*, 2012). Extreme weather conditions may have indirect effects on those with mental illness, through the impacts on agricultural productivity, fishing, forestry and other economic activities. Disasters such as cyclones, heat waves and major floods may also have destructive effects in cities. Here again, the mentally ill may be at risk: cities often feature zones of concentrated disadvantage where mental disorders are more common (Berry, 2007) and there is also higher risk of natural disasters (such as flooding).

In addition to effects of extreme weather events on mental health via the risk/disadvantage cycle, there may be a distressing sense of loss, known as 'solastalgia,' that people experience when their land is damaged (Albrecht *et al.*, 2007) and they lose amenity and opportunity.

11.6.4. Violence and Conflict

Soil degradation, freshwater scarcity, population pressures and other forces that are related to climate are all potential causes of conflict. The relationships are not straightforward, however, as many factors influence conflict and violence. The topic is reviewed closely in Chapter 12, which concludes that factors associated with risk of violent conflict, such as poverty and impaired state institutions, are sensitive to climate variability, but evidence of an effect of climate change on violence is contested. Also, it is noted that populations affected by violence are particularly vulnerable to the impacts of climate change on health and social well-being.

11.7. Adaptation to Protect Health

Climate change may threaten the progress that has been made in reducing the burden of climate-related disease and injury. The degree to which programs and measures will need modification to address additional pressures from climate change will depend on the current burden of ill-health, the effectiveness of current interventions, projections of where, when, and how the health burden could change with climate change, the feasibility of implementing additional programs, other stressors that could increase or decrease resilience, and the social, economic, and political context for intervention (Ebi *et al.*, 2006).

The scientific literature on adaptation to climate change has expanded since AR4, and there are many more national adaptation plans that include health, but investment in specific health protection activities is growing less rapidly. A review by the World Health Organization in 2012 estimated that commitments to health adaptation internationally amount to less than 1% of the annual health costs attributable to climate change in 2030 (World Health Organization Regional Office for Europe, 2013).

The value of adaptation is demonstrated by the health impacts of recent disasters associated with extreme weather and climate events, although not necessarily attributed with confidence to climate change itself. For example, approximately 500,000 people died when cyclone Bhola (category 3 in severity) hit East Pakistan (present day Bangladesh) in 1970. In 1991, a cyclone of similar severity caused about 140,000 deaths. In November 2007, cyclone Sidr (category 4) resulted in approximately 3,400 deaths; the population had grown by more than 30 million in the intervening period (Mallick *et al.*, 2005). Bangladesh achieved this remarkable reduction in mortality through effective collaborations between governmental and non-governmental organizations and local communities (Khan, 2008). Alongside improving general disaster education (greatly assisted by rising literacy rates, especially among women), the country deployed early warning systems and built a network of cyclone shelters. Early warning systems included high technology information systems and relatively simple measures such as training volunteers to distribute warning messages by bicycle.

Efforts to adapt to the health impacts of climate change can be categorized as incremental, transitional, and transformational actions (O'Brien *et al.*, 2012). Incremental adaptation includes improving public health and health care services for climate-related health outcomes, without necessarily considering the possible impacts of climate change. Transitional adaptation means shifts in attitudes and perceptions, leading to initiatives such as vulnerability mapping and improved surveillance systems that specifically integrate environmental factors. Transformational adaptation (see Chapter 16), which requires fundamental changes in systems, has yet to be implemented in the health sector.

11.7.1. Improving Basic Public Health and Health Care Services

Although the short time period since health adaptation options have been implemented means evidence of effectiveness in specifically reducing climate change-related impacts is currently lacking, there is abundant evidence of steps that may be taken to improve relevant public health functions (Woodward *et al.*, 2011). This is important because the present health status of a population may be the single most important predictor of both the future health impacts of climate change and the costs of adaptation (Pandey, 2010). Most health adaptation focuses on improvements in public health functions to reduce the current adaptation deficit, such as enhancing disease surveillance, monitoring environmental exposures, improving disaster risk management, and facilitating coordination between health and other sectors to deal with shifts in the incidence and geographic range of diseases (Woodward *et al.*, 2011).

Examples of incremental health care interventions include introduction of vaccination programs in the United States, after which seasonal outbreaks of rotavirus, a common climate-sensitive pathogen, were delayed and diminished in magnitude (Tate *et al.*, 2009). Post-disaster initiatives also are important. For example, an assessment of actions to improve the resilience of vulnerable populations to heat waves recommended staff planning over the summer period, cooling of health care facilities, training of staff to recognize and treat heat strain, and monitoring of those in the highest risk population groups (World Health Organization Regional Office for Europe, 2009). Ensuring essential medical supplies for care of individuals with chronic conditions, including effective post-disaster distribution, would increase the ability of communities to manage large-scale floods and storms. In Benin, one measure proposed as part of the national response to sea level rise and flooding is expanded health insurance arrangements, so that diseases such as malaria and enteric infections can be treated promptly and effectively (Dossou and Glehouenou-Dossou, 2007).

11.7.2. Health Adaptation Policies and Measures

Transitional adaptation moves beyond focusing on reducing the current adaptation deficit to considerations of how a changing climate could alter health burdens and the effectiveness of interventions (Frumkin *et al.*, 2008). For example, maintaining and improving food safety in the face of rising temperatures and rainfall extremes depends on effective interactions between human health and veterinary authorities, integrated monitoring of food-borne and animal diseases, and improved methods to detect pathogens and contaminants in food (Tirado *et al.*, 2010). Indicators of community functioning and connectedness also are relevant because communities with high levels of social capital tend to be more successful in disseminating health and related messages, providing support to those in need (Frumkin *et al.*, 2008).

Vulnerability Mapping

Vulnerability mapping is being increasingly used to better understand current and possible future risks related to climate change. For example, Reid *et al*. (2009) mapped community determinants of heat vulnerability in the U.S.A. The four factors explaining most of the variance were a combination of social and environmental factors, social isolation, prevalence of air conditioning, and the proportion of the population who were elderly or diabetic. Remote sensing technologies are now sufficiently fine-grained to map local vulnerability. For example, these technologies can be used to map surface temperatures and urban heat island effects at the neighborhood scale, indicating where city greening and other urban cooling measures could be most effective, and alerting public health authorities to populations that may be at greatest risk of heat waves (Luber and McGeehin, 2008). In another example, spatial modeling of geo-referenced climate and environmental information was used to identify characteristics of domestic malaria transmission in 2009-2012 in Greece, to guide malaria control efforts (Sudre *et al.*, 2013). Mapping at regional and larger scales may be useful to guide adaptation actions. In Portugal, modeling of Lyme disease indicates that future conditions will be less favorable for disease transmission in the south, but more favorable in the center and northern parts of the country (Casimiro *et al.*, 2006). This information can be used to modify surveillance programs before disease outbreaks occur. To capture a more complete picture of vulnerability, mapping exercises also could consider climate sensitivity and adaptation capacity, such as was done in an assessment of climate change and risk of poverty in Africa (Thornton *et al.*, 2008).

11.7.3. Early Warning Systems

Early warning systems have been developed in many areas to prevent negative health impacts through alerting public health authorities and the general public about climate-related health risks. Effective early warning systems take into consideration the range of factors that can drive risk and are developed in collaboration with end users.

Components of effective early warning systems include forecasting weather conditions associated with increased morbidity or mortality, predicting possible health outcomes, identifying triggers of effective and timely response plans that target vulnerable populations, communicating risks and prevention responses, and evaluating and revising the system to increase effectiveness in a changing climate (Lowe *et al.*, 2011). Heat wave early warning systems are being increasingly implemented, primarily in high-income countries. Of eight studies of the effectiveness of heat wave early warning systems or heat prevention activities to reduce heat-related mortality, seven reported fewer deaths during heat waves after implementation of the system (Chau *et al.*, 2009; Ebi *et al.*, 2004; Fouillet *et al.*, 2008; Palecki *et al.*, 2001; Tan *et al.*, 2007; Weisskopf *et al.*, 2002) ; only Morabito *et al.* (2012) was inconclusive. For example, in the summer of 2006, France experienced high temperatures with about 2,000 excess deaths. This was over 4,000 fewer deaths than was anticipated on the basis of what occurred in the 2003 heat wave. A national assessment attributed the lower than expected death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet *et al.*, 2008). A review of the heat wave early warning systems in the twelve European countries with such plans concluded that evaluations of the effectiveness of these systems is urgently needed to inform good practices, particularly understanding which actions increase resilience (Lowe *et al.*, 2011).

Early warning systems have been developed also for vector-borne and food-borne infections, although evidence of their effectiveness in reducing disease burdens is limited. In Botswana, an early warning system forecasts malaria incidence up to 4 months in advance based on observed rainfall; inter-annual and seasonal variations in climate are associated with outbreaks of malaria in this part of Africa. Model outputs include probability distributions of disease risk and measures of the uncertainty associated with the forecasts (Thomson *et al.*, 2006). A weather-based forecasting model for dengue, developed in Singapore, predicted epidemics 13 months ahead of the peak in new cases, which gave the national control program time to increase control measures (Hii *et al.*, 2012). A study of campylobacteriosis in the United States developed models of monthly disease risk with a very good fit in validation data sets (R^2 up to 80%) (Weisent *et al.*, 2010).

11.7.4. Role of Other Sectors in Health Adaptation

Other sectors, including ecosystems, water supply and sanitation, agriculture, infrastructure, energy and transportation, land use management, and others, play an important part in determining the risks of disease and injury resulting from climate change.

Within the context of the EuroHEAT project, a review of public health responses to extreme heat in Europe identified transport policies, building design, and urban land use as important elements of national and municipal heat wave and health action plans (World Health Organization Regional Office for Europe, 2009). A study examining well-established interventions to reduce the urban heat island effect (replacing bitumen and concrete with more heat-reflective surfaces, and introducing more green spaces to the city) estimated these would reduce heat-related emergency calls for medical assistance by almost 50% (Silva *et al.*, 2010). Urban green spaces lower ambient temperatures, improve air quality, provide shade, and may be good for mental health (van den Berg *et al.*, 2010). However, the extent to which changes in these factors reduce heat wave-related morbidity and mortality depend on location. A study in London, UK, found that built form and other dwelling characteristics more strongly influenced indoor temperatures during heat waves than did the urban health island effect (Oikonomou and Wilkinson, 2012).

A review of food aid programs indicates that a rapid response to the risk of child under-nutrition, targeted to those in greatest need, with flexible financing and the capacity to rapidly scale-up depending on need, may reduce damaging health consequences (Alderman, 2010). Community-based programs designed for other purposes can facilitate adaptation, including disaster risk management. In the Philippines, for example, interventions in low-income urban settings with the potential to reduce the harmful effects of climate extremes on health include savings schemes, small-scale loans, hygiene education, local control and maintenance of water supplies, and neighborhood level solid waste management strategies (Dodman *et al.*, 2010). It is important to note that climate change adaptation in other sectors may influence health in a positive manner (eg re-vegetation of watersheds to improve water quality), or on occasion, exacerbate health risks (eg urban wet-lands designed primarily for flood control may promote mosquito breeding) (Medlock and Vaux, 2011).

11.8. Adaptation Limits under High Levels of Warming

Most attempts to quantify health burdens associated with future climate change consider modest increases in global average temperature, typically less than 2° C. However, research published since AR4 raises doubt over whether it will be possible to limit global warming to 2°C above pre-industrial temperatures (Anderson and Bows, 2011; PriceWaterhouseCoopers, 2012; Rogelj *et al.*, 2009). It is therefore increasingly important to examine the likely health consequences of warming beyond 2°, including extreme warming of 4-6°C or higher. Predictions of this nature are limited by uncertainty about climatic as well as key, non-climatic determinants of health including the nature and degree of adaptation. Here, we instead focus primarily on physiological or ecological limits that constrain our ability to adapt and protect human health and wellbeing (Section 16.4.1).

It can be assumed that the increase in many important climate-related health impacts at increasingly higher levels of warming will be greater than simple linear increments; that is, that the health consequences of a 4°C temperature increase will be more than twice those of a +2°C world (see Figure 11-6). Nonlinear and threshold effects have been observed in the mortality response to extreme heat (Anderson and Bell, 2011; McMichael, 2013a), agricultural crop yields, as key determinants of childhood nutrition and development (Lobell *et al.*, 2011a; Schlenker and Roberts, 2009), and infectious diseases (Altizer *et al.*, 2006) , for example. These are also briefly elaborated here.

[INSERT FIGURE 11-6 HERE
Figure 11-6: Conceptual presentation of the health impacts from climate change and the potential for impact reduction through adaptation. Impacts are identified in eight health-related sectors based on assessment of the literature and expert judgments by authors of Chapter 11.The width of the slices indicates in a qualitative way the relative importance in terms of burden of ill-health globally at present and should not be considered completely independent. Impact levels are presented for the near-term era of committed climate change (2030-2040), in which projected levels of global mean temperature increases do not diverge substantially across emissions scenarios. For some sectors, e.g., vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Estimated impacts are also presented for the longer-term era of climate options (2080-2100), for global mean temperature increase of 4°C above preindustrial levels, which could potentially be avoided by vigorous mitigation efforts taken soon. For each timeframe, impact levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors.]

11.8.1. Physiological Limits to Human Heat Tolerance

In standard (or typical) conditions, core body temperatures will reach lethal levels under sustained periods of wet-bulb temperatures above about 35°C (Sherwood and Huber, 2010). Sherwood and Huber (2010) conclude that a global mean warming of roughly 7°C above current temperatures would create small land areas where metabolic heat dissipation would become impossible. An increase of 11-12°C would enlarge these zones to encompass most of the areas occupied by today’s human population.

The above analysis is likely a conservative estimate of an absolute limit to human heat tolerance because working conditions are hazardous at lower thresholds. The U.S. military, for example, suspends all physical training and strenuous exercise when the wet bulb globe temperature (WBGT) exceeds 32°C (Willett and Sherwood, 2012) while international labor standards suggest the time acclimatized individuals spend doing low intensity labor such as office work be halved under such conditions (Kjellstrom *et al.*, 2009a).[1] One estimate suggests global labor productivity will be reduced during the hottest months to 60% in 2100 and less than 40% in 2200 under the RCP 8.5 scenario in which global mean temperatures rise 3.4°C by 2100 and 6.2°C by 2200 relative to 1861-1960 (Dunne *et al.*, 2013). It is projected that tropical and mid-latitude regions including India, Northern Australia, Southeastern USA will be particularly badly affected (Dunne et al., 2013; Willett and Sherwood, 2012).

[FOOTNOTE 1: WBGT is a heat index closely related to the wet-bulb temperature that also incorporates measures of radiant heat from the Sun and evaporative cooling due to wind.]

11.8.2. Limits to Food Production and Human Nutrition

Agricultural crops and livestock similarly have physiological limitations in terms of thermal and water stress. For example, production of the staple crops maize, rice, wheat and soybean is generally assumed to face an absolute temperature limit in the range of 40-45°C (Teixeira *et al.*, 2011), while key phenological stages such as sowing to emergence, grain-filling, and seed set have maximum temperature thresholds near or below 35°C (Porter and Semenov, 2005; Porter and Gawith, 1999; Yoshida *et al.*, 1981). The existence of critical climatic thresholds and evidence of non-linear responses of staple crop yields to temperature and rainfall (Brázdil *et al.*, 2009; Lobell *et al.*, 2011b; Schlenker and Roberts, 2009) thus suggest that there may be a threshold of global warming beyond which current agricultural practices can no longer support large human civilizations, and the impacts on malnourishment and undernutrition described in Section 11.6.1 will become much more severe. However, current models to estimate the human health consequences of climate-impaired food yields at higher global temperatures generally incorporate neither critical thresholds nor nonlinear response functions (Lake *et al.*, 2012; Lloyd *et al.*, 2011), reflecting uncertainties about exposure-response relations, future extreme events, the scale and feasibility of adaptation, and climatic thresholds for other influences such as infestations and plant diseases. Extrapolation from current models nevertheless suggests that the global risk to food security becomes very severe under an increase of 4-6°C or higher in global mean temperature (*medium evidence, high agreement*) (Chapter 7, Executive Summary).

11.8.3. Thermal Tolerance of Disease Vectors

Substantial warming in higher-latitude regions will open up new terrain for some infectious diseases that are limited at present by low temperature boundaries, as already evidenced by the northward extensions in Canada and Scandinavia of tick populations, the vectors for Lyme disease and tick-borne encephalitis (Lindgren and Gustafson, 2001; Ogden *et al.*, 2006). On the other hand, the emergence of new temperature regimes that exceed optimal conditions for vector and host species will reduce the potential for infectious disease transmission and, with high enough temperature rise, may eventually eliminate some infectious diseases that exist at present close to their upper tolerable temperature limits. For example, adults of two malaria-transmitting mosquito species are unable to survive temperatures much above 40°C in laboratory experiments (Lyons *et al.*, 2012), although in the external world they may seek out tolerable microclimates. Reproduction of the malaria parasite within the mosquito is impaired at lesser raised temperatures (Paaijmans *et al.*, 2009). Larval development of *Aedes albopictus*, an Asian mosquito vector of dengue and chikungunya, also does not occur at or above 40°C (Delatte *et al.*, 2009).

11.8.4. Displacement & Migration under Extreme Warming

Weather extremes and longer term environmental change including sea level rise lead to both more people displaced and increase in populations that are effectively trapped (Section 12.4.1.2). This trend is expected to be more pronounced under extreme levels of warming (Section 16.5). Gemenne (2011) argues that the most significant difference between the nature of human migration in response to 4°C of warming relative to 2°C would be to remove many people's ability to choose whether to stay or leave when confronted with environmental changes. Health studies of refugees, migrants, and people in resettlement schemes suggest that forced displacement, in turn, is likely to lead to more adverse health impacts than voluntary migration or planned resettlement (McMichael *et al.*, 2012). The health risks associated with forced displacement include undernutrition; food- and water-borne illnesses; diseases related to overcrowding such as measles, meningitis and acute respiratory infections; sexually-transmitted diseases; increased maternal mortality; and mental health disorders (McMichael *et al.*, 2012).

11.8.5. Reliance on Infrastructure

Under severe climate regimes, societies may be able to protect themselves by enclosing places for living and working, first for their most vulnerable members: the young, old, ill, and manual laborers. This strategy will mean increased vulnerability to infrastructure failure and unreliable energy and water supplies. Electrical power outages have been linked to both accidental and disease-related deaths in temperate climates (Anderson and Bell, 2012), and failures in power supplies are more likely to occur during extreme weather events (Section 19.6.2.1). Large-scale reliance on air-conditioning under a significantly hotter climate regime would therefore pose a serious health risk.

11.9. Co-Benefits

Essentially every human activity affects (and is affected by) climate and health status in some way, but not all are strongly linked to either and even fewer strongly to both. Here we focus on measures to mitigate the atmospheric concentration of warming climate altering pollutants (CAPs) that also hold the potential to significantly benefit human health. These so-called co-benefits include health gains from strategies that are directed primarily at climate change, and mitigation of climate change from well-chosen policies for health advancement (Apsimon *et al.*, 2009; Haines *et al.*, 2007; Shindell *et al.*, 2012; Smith and Balakrishnan, 2009; UNEP, 2011). The literature on health co-benefits associated with climate change mitigation strategies falls into several categories (Smith and Balakrishnan, 2009; Smith *et al.*, 2009). These include: Reduce emissions of health-damaging pollutants, either primary or precursors to other pollutants in association with changes in energy production, energy efficiency, or control of landfills; Increase access to reproductive health services; Decrease meat consumption (especially from ruminants) and substitution of low-carbon healthy alternatives; Increase active transport particularly in urban areas; Increase urban green-space. In addition, although not discussed here, there are potential health side effects of mitigation measures, such as geoengineering, biofuel expansion, and carbon taxes that are potentially deleterious for human health (Tilman *et al.*, 2009). See WGII Ch 19. In Table 11-3, we summarize what is known about the main categories of co-benefits, but because of space limitation, we only provide additional detail for two of them below.

[INSERT FIGURE 11-7
Figure 11-7: Illustrative co-benefits comparison of the health and climate cost-effectiveness of selected household, transport, and power sector interventions (Smith and Haigler, 2008). Area of each circle denotes the total social benefit in international dollars from the combined value of carbon offsets (valued at 10$/t$CO_2$e) and averted DALYs [$7450/DALY, which is representative of valuing each DALY at the average world GDP (PPP) per capita in 2000]. The vertical bar shows the range of the cut offs for cost-effective and very cost-effective health interventions in India and China using the WHO CHOICE criteria (World Health Organization, 2003). This figure evaluates only a small subset of all co-benefits opportunities and thus should not be considered either current or complete. It does illustrate, however, the kind of comparisons that can help distinguish and prioritize options. Note that even with the log-log scaling, there are big differences among them. For other figures comparing the climate and health benefits of co-benefits actions including those in food supply and urban design, see Haines *et al*. (Haines *et al.*, 2009). See the original reference for details of the calculations in this figure (Smith and Haigler, 2008).]

[INSERT TABLE 11-3 HERE
Table 11-3: Examples of recent (post AR4) research studies on co-benefits of climate change mitigation and public health policies. For recent estimates of the global and regional burden of disease from the various risk factors involved, see Lim *et al.* (2012).]

11.9.1. Reduction of Co-Pollutants

Most of the publications related to CAPs and health-damaging pollutants refer to fuel combustion and fall into three major categories: 1) improvement in energy efficiency will reduce emissions of CO_2 and health-damaging pollutants, providing these gains are not outpaced by increases in energy demand, and the energy is derived from combustion of fossil fuels or non-renewable biomass fuels, either directly or through the electric power system; 2) increases of combustion efficiency (decreasing emission of incomplete combustion products) will have both climate and health benefits, even if there is no change in energy efficiency and/or fuel itself is renewable, because a number of the products of incomplete combustion are climate altering and nearly all are damaging to health (Smith and Balakrishnan, 2009); and 3) Increased use of non-combustion sources, such as wind, solar, tidal, wave and geothermal energy, would reduce emissions of warming CAPs and health damaging air pollutants, providing benefits for climate and health (Jacobson *et al.*, 2013).

Studies of the health co-benefits of reduction in air pollutants include sources that produce outdoor air pollution (Bell *et al.*, 2008) and household sources (Po *et al.*, 2011). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for a substantial percent of primary outdoor fine particle pollution as well, perhaps a quarter in India, for example (Lim *et al.*, 2012). In many parts of the world, household fuel (poorly combusted biomass and coal) is responsible for much fine particle outdoor air pollution and may contribute to long-range transport of hazardous air pollutants (Anenberg *et al.*, 2013). This indicates that reductions in emissions from household sources will yield co-benefits through the outdoor pollution pathway as well.

If interventions result in reductions in coal combustion, there are a range of other potential health benefits beyond reduction of particulate air pollution emissions, including reducing other types of health-damaging emissions and the human impacts from coal mining (Lockwood, 2012; Smith *et al.*, 2013).

Another category of air pollution co-benefits comes from controls on methane emissions that both reduce radiative forcing and potentially reduce human exposures to ambient ozone, for which methane is a precursor.

11.9.1.1. Outdoor Sources

Primary co-pollutants, such as particulate matter (PM) and carbon monoxide (CO) are those released at the point of combustion, while secondary co-pollutants, such as tropospheric ozone and sulfate particles, are formed downwind from the combustion source via atmospheric chemical interactions (Jerrett *et al.*, 2009) and can be transported long distances.

The burden of disease from outdoor exposures in a country may often be greater in populations with low socioeconomic status, both because of living in areas with higher exposures and because these populations often have worse health and are subjected to multiple additional negative environmental and social exposures (Morello-Frosch *et al.*, 2011).

11.9.1.2. Household Sources

Globally, the largest exposures from the pollutants from poor fuel combustion occur in the poorest populations. This is because household use of biomass for cooking is distributed nearly inversely with income. Essentially, no poor family can afford gas or electricity for cooking and very few families who can afford to do so, do not. Thus, the approximate 41% of all world households using solid fuels for cooking are all among the poor in developing countries (Bonjour *et al.*, 2013). Although biomass makes up the bulk of this fuel and creates substantial health impacts from products of incomplete combustion when burned in simple stoves (Lim *et al.*, 2012), probably the greatest health and largest climate impacts per household result from use of coal, which can also be contaminated with sulfur and a range of toxic elements as well (Edwards *et al.*, 2004; Zhang and Smith, 2007). Successfully accelerating the reduction of impacts from these fuels, however, has not been found to be easily accomplished with biomass/coal stove programs implemented to date and may require moving to clean fuels (Bruce *et al.*, 2013). The climate benefits from improving household biomass fuel combustion come in part from potential reduction of net warming by reducing emissions of aerosols (including black carbon), but more confidently from reduction of CH_4 and other CAPs that are produced by incomplete combustion, as well as reductions in net CO_2 emissions if interventions are applied in areas relying on non-renewably harvested wood fuel (WG1, Section 8.5.3).

11.9.1.3. Primary Co-Pollutants

Outdoor exposure to PM, especially to particles with diameters less than 2.5 µm ($PM_{2.5}$), contributes significantly to ill-health including cardio- and cerebrovascular disease, adult chronic and child acute respiratory illnesses, lung cancer, and possibly other diseases. The Comparative Risk Assessment (CRA) for outdoor air pollution done as part of the Global Burden of Disease (GBD) 2010 Project found approximately 3.2 million premature deaths globally from ambient particle pollution or about 3% of the global burden of disease (Lim *et al.*, 2012). Importantly, reductions in ambient PM concentrations have also been shown to decrease morbidity and premature mortality (Boldo *et al.*, 2010). A significant portion of ambient particle pollution derives from fuel combustion, perhaps 80% globally (GEA, 2012).

Because of higher exposures, an additional set of diseases has also been associated with combustion products in households burning biomass and/or coal for cooking and heating. Thus, in addition to the diseases noted above, cataracts, low birth weight, and stillbirth have been associated strongly with exposures to incomplete combustion products, such as PM and CO. CO has impacts on unborn children in utero through exposures to their pregnant mothers (World Health Organization Regional Office for Europe, 2010). There is also growing evidence of exacerbation of tuberculosis (Pokhrel *et al.*, 2010) in adults and cognitive effects in children (Dix-Cooper *et al.*, 2012). The CRA of the GBD-2010 found 3.5 million premature deaths annually from household air pollution derived from cooking fuels or 4.4% of the global burden of disease (Lim *et al.*, 2012). Importantly, there are also studies showing health benefits of household interventions, for child pneumonia (Smith *et al.*, 2011) blood pressure (Baumgartner *et al.*, 2011; McCracken *et al.*, 2007) , lung cancer (Lan *et al.*, 2002) , and chronic obstructive pulmonary disease (Chapman *et al.*, 2005). Another half a million premature deaths are attributed to household cookfuel's contribution to outdoor air pollution, making a total of about 4 million in 2010 or 4.9% of the global burden of disease (Lim *et al.*, 2012).

Black carbon (BC), a primary product of incomplete combustion, is both a strong CAP and health-damaging (Bond *et al.*, 2013; IPCC, 2007; Ramanathan and Carmichael, 2008). A systematic review, meta-analysis, and the largest cohort study to date of the health effects of BC found that there were probably stronger effects on mortality from exposure to BC than for undifferentiated fine particles ($PM_{2.5}$) (Smith *et al.*, 2009). Reviews have concludes that abatement of particle emissions including BC represents an opportunity to achieve both climate mitigation and health benefits (Shindell *et al.*, 2012; UNEP, 2011). WG1 (Box TS-6), however, concluded that the net impact of BC emissions reductions overall is not certain as to sign, i.e., whether net warming or cooling. Nevertheless, there would be climate (and health) benefits in circumstances where BC is emitted without many other cooling aerosols, as with diesel and kerosene combustion (Lam *et al.*, 2012).

Other examples of climate forcing, health-damaging co-pollutants of CO_2 from fuel use are carbon monoxide, non-methane hydrocarbons, and sulfur and nitrogen oxides. Each co-pollutant poses risks as well as being climate altering in different ways. See WGI for more on climate potential and WHO reviews of health impacts (World Health Organization Regional Office for Europe, 2010; World Health Organization, 2006).

11.9.1.4. Secondary Co-Pollutants

In addition to being a strong GHG, methane (CH_4) is also a significant precursor to regional anthropogenic tropospheric ozone production, which itself is both a GHG and damaging to health, crops, and ecosystems (WG1 TS.5.4.8). Thus, reductions in CH_4 could lead to reductions in ambient tropospheric ozone concentrations, which in turn could result in reductions in population morbidity and premature mortality and climate forcing.

One study found that a reduction of global anthropogenic CH_4 emissions by 20% beginning in 2010 could decrease the average daily maximum 8-h surface ozone by 1 ppb by volume, globally; sufficient to prevent 30,000 premature all-cause mortalities globally in 2030, and 370,000 between 2010 and 2030 (West, Fiore et al. 2012). CH_4 emissions are generally accepted as the primary anthropogenic source of tropospheric ozone concentrations above other human-caused emissions of ozone precursors (West *et al.*, 2007) and thus, the indirect health co-benefits of CH_4 reductions are epidemiologically significant. On the other hand, work done for the GBD-2010 estimated 150,000 premature deaths from all ozone exposures globally in 2010, indicating a more conservative interpretation of the evidence for mortality from ozone (Lim *et al.*, 2012).

In an analysis of ozone trends from 1998-2008 in the United States, Lefohn et al. (2010) found that 1-hour and 8-hour ambient ozone averages have either decreased or failed to increase due to successful regulations of ozone precursors, predominantly NO_x and CH_4. This is consistent with the US EPA (2010) conclusion that in the US, for the period 1980-2008, emissions of nitrogen oxides and volatile organic compounds fell by 40% and 47%, respectively (Lefohn *et al.*, 2010; US EPA, 2010). These results point to the effectiveness of reducing ambient ozone concentrations through regulatory tools that reduce the emissions of ozone precursors, some of which, like CH_4, are GHGs.

Not every CAP emitted from fuel combustion is warming. The most prominent example is sulfur dioxide emitted from fossil fuel combustion, which changes to particle sulfate in the atmosphere. Although health damaging, sulfate particles have a cooling effect on global radiative forcing. Thus, reduction of sulfur emissions, which is important for health protection, does not qualify as a co-benefit activity since it actually acts to unmask more of the warming effect of other CAP emissions (Smith *et al.*, 2009).

11.9.1.5. Case Studies of Co-Benefits of Air Pollution Reductions

A recent UNEP- and WMO-led study of black carbon and tropospheric ozone found that, if all of 400 proposed BC and CH_4 mitigation measures were implemented on a global scale, the estimated benefits to health would come predominately from reducing $PM_{2.5}$ (0.7 – 4.6 million avoided premature deaths; 5.3 – 37.4 million avoided years of life lost) compared to tropospheric ozone (0.04 – 0.52 million avoided premature deaths; 0.35 – 4.7 million avoided years of life lost) based on 2030 population figures (UNEP, 2011). About 98% of the avoided deaths would come from reducing $PM_{2.5}$, with 80% of the estimated health benefits occurring in Asia (Anenberg *et al.*, 2012). Another study of the reduction of PM and ozone exposures due to CAPs emissions controls and including climate change feedback showed potential reductions of 1.3 million premature deaths by 2050 with avoided costs of premature mortality many times those of the estimated cost of abatement (West *et al.*, 2013).

A study of the benefits of a hypothetical 10-year program to introduce advanced combustion cookstoves in India found that in addition to reducing premature mortality by about 2 million and DALYs by 55 million over that period, there would be reduction of 0.5-1.0 billion tons CO_2-eq (Wilkinson *et al.*, 2009). Another study of India found a potential to reduce 570 thousand premature deaths a year, one-third of national BC emissions, and 4% of all national greenhouse emissions by hypothetical substitution of clean household fuel technologies (Venkataraman *et al.*, 2010).

In their estimation of effects of hypothetical physical and behavioral modifications in UK housing, Wilkinson and colleagues (Wilkinson *et al.*, 2009) found that the magnitude and direction of implications for health depended heavily on the details of the intervention. However, the interventions were found to be generally positive for health. In a strategy of housing modification that included insulation, ventilation control, and fuel switching, along with behavioral changes, it was estimated that 850 fewer DALYs, and a savings of 0.6 megatonnes of CO_2 per million population in one year could be achieved. These calculations were made by comparing the health of the 2010 population with and without the specified physical and behavioral modifications (Wilkinson *et al.*, 2009).

Markandya *et al.* (2009) assessed the changes in emissions of $PM_{2.5}$ and subsequent effects on population health that could result from climate change mitigation measures aimed to reduce GHG emissions by 50% by 2050 (compared with 1990 emissions) from the electricity generation sector in the EU, China, and India In all three regions, changes in modes of production of electricity to reduce CO_2 emissions were found to reduce $PM_{2.5}$ and associated mortality. The greatest effect was found in India and the smallest in the EU. The analysis also found that if the health benefits were valued similarly to the approach used by the EU for air pollution, they offset the cost of GHG emission reductions, especially in the Indian context where emissions are high but costs of implementing the measures are low (Markandya *et al.*, 2009).

11.9.2. Access to Reproductive Health Services

Population growth influences the consumption of resources and emissions of CAPs (Cohen, 2010). Although population growth rates and total population size do not alone determine emissions, population size is an important factor. One study showed that CO_2 emissions could be lower by 30% by 2100 if access to contraception was provided to those women expressing a need for it (O'Neill *et al.*, 2010). Providing the unmet need for these services in areas such as the Sahel region of Africa that has both high fertility and high vulnerability to climate change can potentially significantly reduce human suffering as climate change proceeds (Potts and Henderson, 2012). This is important not only in poor countries, however, but also some rich ones like the US, where there is unmet need for reproductive health services as well as high CO_2 emissions per capita (Cohen, 2010). Also, because of income rise in developing countries and concurrent reduction of greenhouse emissions in developed countries, a convergence in emissions per capita is expected in most scenarios by 2100 (WG1 TS5.2). Slowing population growth through lowering fertility, as might be achieved by increasing access to family planning, has been associated with improved maternal and child health – the co-benefit - in two main ways: increased birth spacing and reducing births by very young and old mothers.

11.9.2.1. Birth and Pregnancy Intervals

Current evidence supports, with medium confidence, that short birth intervals (defined as birth intervals ≤24 months and inter-pregnancy intervals <6 months) are associated with increased risks of uterine rupture and bleeding (placental abruption and placenta previa) (Bujold *et al.*, 2002; Conde-Agudelo *et al.*, 2007).

There is also a correlation between short birth interval and elevated risk of low-birth-weight (Zhu, 2005). Zhu (2005) found, in a review of three studies performed in the United States that the smallest risk of low birth weight was found with inter-pregnancy spacing between 18-23 months. Another review of five cohort studies found that a birth interval shorter than 18 months was significantly associated with decreased low birth weight, preterm birth, and infant mortality after controlling for confounding factors (Kozuki *et al.*, 2013).

Although an ecological analysis, a review across 17 countries shows a strikingly coherent picture of the relationship between birth spacing and reductions in child, infant and neonatal mortality (Figure 11-S3) with risk of child undernutrition and mortality both increasing with shorter birth intervals (Rutstein, 2005). One study estimated that shifting birth spacing from current patterns in the world to a minimum of 24 months would reduce by 20% (~2 million) the current excess child mortality in the world (Gribble *et al.*, 2009; Rutstein, 2005).

11.9.2.2. Maternal Age at Birth

Risk of death during delivery is highest in very young and very old mothers, and these are also the age groups that most often want to control their fertility (Engelman, 2010). Women who begin child bearing under the age of 20 years are at an increased risk of developing pregnancy complications such as cephalopelvic disproportion, obstructed labor, preterm delivery, toxemia, bleeding, and maternal death (Tsui *et al.*, 2007). Additionally, children born to women under the age of 20 are at increased risk of fetal growth retardation and low birth weight, both of which can lead to long term physical and mental developmental problems (Tsui *et al.*, 2007). Childbearing at later ages (>35 years) is associated with increased risk of miscarriage and other adverse health outcomes (Cleary-Goldman *et al.*, 2005; Ujah *et al.*, 2005).

Providing access to family planning saves women's lives by reducing the total number of births and, in particular, through the reduction of births in high-risk groups (Prata, 2009) while simultaneously reducing total fertility and subsequent CAP emissions. Studies have found that when women have access to family planning, it is the highest risk age groups (youngest and oldest women) who reduce their fertility the most. In other words, family planning has a differential impact on maternal mortality reduction through reducing births in the highest risk groups (Diamond-Smith and Potts, 2011).

11.10. Key Uncertainties and Knowledge Gaps

There is evidence that poverty alleviation, public health interventions such as provision of water and sanitation, and early warning and response systems for disasters and epidemics will help to protect health from climate risks. The key uncertainty is the extent to which society will strengthen these services, including taking into account the risks posed by climate change. With a strong response, climate change health effects are expected to be relatively small in the next few decades, but otherwise climate-attributable cases of disease and injury will steadily increase.

Since AR4, national governments, through the World Health Assembly, have specifically called for increased research on (i) the scale and nature of health risks from climate change; (ii) effectiveness of interventions to protect health; (iii) health implications of adaptation and mitigation decisions taken in other sectors, (iv) improvement in decision support systems and surveillance, and (v) estimation of resource requirements. A recent scoping review identified quantitative peer-reviewed studies across all of these areas, with the exception of studies on the effectiveness or cost-effectiveness of targeted adaptation measures (Hosking and Campbell-Lendrum, 2012). There are also comparatively few studies of vulnerability in low and middle income populations, or of more complex disease pathways, such as the effect of more extreme weather on water and sanitation provision and diarrhea rates, on zoonotic diseases, or mental health. Studies of health co-benefits of climate change mitigation policies also remain rare compared to the size of the potential health gains. Potential negative side effects also need to be addressed, for example those arising from biofuel policies that compete with food production.

Relevant research for health protection in the near term is therefore likely to come from cross-disciplinary studies, including public health decision makers, in the following areas; improved vulnerability and adaptation assessments that focus on particularly vulnerable populations and encompass complex causal pathways; quantitative estimation of the effectiveness of health adaptation measures; surveillance, monitoring, and observational systems that link climate, health and economic impact data and provide a basis for early warning systems as well as development of future scenarios; assessment of the health co-benefits of alternative climate mitigation policies.

In the longer term, research will need to make the best use of traditional epidemiologic methods, while also taking into account the specific characteristics of climate change. These include the long-term and uncertain nature of the exposure and effects on multiple physical and biotic systems, with the potential for diverse and widespread effects, including high-impact events. There are low-probability, but plausible, scenarios for extreme climate regimes before the end of the century. Although difficult, it is important to develop robust methods to investigate the health implications of conditions that may apply in 2100, as decisions today about mitigation will determine their likelihood. Given the increase globally in life expectancies, many babies born this decade will be alive at the end of the century, and will be personally affected by the climate that is in place in 2100.

Frequently Asked Questions

FAQ 11.1: How does climate change affect human health? *[to remain at the end of the chapter]*
Climate change affects health in three ways; 1) Directly, such as the mortality and morbidity (including "heat exhaustion") due to extreme heat events, floods, and other extreme weather events in which climate change may play a role; 2) Indirect impacts from environmental and ecosystem changes, such as shifts in patterns of disease-carrying mosquitoes and ticks, or increases in waterborne diseases due to warmer conditions and increased precipitation and runoff; and 3) indirect impacts mediated through societal systems, such as undernutrition and

mental illness from altered agricultural production and food insecurity, stress and undernutrition and violent conflict caused by population displacement, economic losses due to widespread "heat exhaustion" impacts on the workforce, or other environmental stressors, and damage to health care systems by extreme weather events.

FAQ 11.2: Will climate change have benefits for health? *[to remain at the end of the chapter]*
Yes. For example some populations in temperate areas may be at less risk from extreme cold, and may benefit from greater agricultural productivity, at least for moderate degrees of climate change. Some areas currently prone to flooding may become less so. However, the overall impact for nearly all populations and for the world as a whole is expected to be more negative than positive, increasingly so as climate change progresses. In addition, the latitude range in the world that may benefit from less cold (e.g. the far north of the Northern Hemisphere) has fewer inhabitants compared with the equatorial latitudes where the burden will be greatest.

FAQ 11.3: Who is most affected by climate change? *[to remain at the end of the chapter]*
While the direct health effects of extreme weather events receive great attention, climate change mainly harms human health by exacerbating existing disease burdens and negative impacts on daily life among those with the weakest health protection systems, and with least capacity to adapt. Thus, most assessments indicate that poor and disenfranchised groups will bear the most risk and, globally, the greatest burden will fall on poor countries, particularly on poor children, who are most affected today by such climate-related diseases as malaria, undernutrition, and diarrhea. However, the diverse and global effects of climate change mean that higher income populations may also be affected by extreme events, emerging risks, and the spread of impacts from more vulnerable populations.

FAQ 11.4: What is the most important adaptation strategy to reduce the health impacts of climate change?
[to remain at the end of the chapter]
In the immediate future, accelerating public health and medical interventions to reduce the present burden of disease, particularly diseases in poor countries related to climatic conditions, is the single most important step that can be taken to reduce the health impacts of climate change. Priority interventions include improved management of the environmental determinants of health (such as provision of water and sanitation), infectious disease surveillance, and strengthening the resilience of health systems to extreme weather events. Alleviation of poverty is also a necessary condition for successful adaptation.

There are limits to health adaptation, however. For example, the higher-end projections of warming indicate that before the end of the 21st Century, parts of the world would experience temperatures that exceed physiological limits during periods of the year, making it impossible to work or carry out other physical activity outside.

FAQ 11.5: What are health "co-benefits" of climate change mitigation measures?
[to remain at the end of the chapter]
Many mitigation measures that reduce emissions of climate-altering pollutants (CAPs) have important direct health benefits in addition to reducing the risk of climate change. This relationship is called "co-benefits." For example, increasing combustion efficiency in households cooking with biomass or coal could have climate benefits by reducing CAPs and at the same time bring major health benefits among poor populations. Energy efficiency and reducing reliance on coal for electricity generation not only reduces emissions of greenhouse gases, but also reduces emissions of fine particles which cause many premature deaths worldwide as well as reducing other health impacts from the coal fuel cycle. Programs that encourage "active transport" (walking and cycling) in place of travel by motor vehicle reduce both CAP emissions and offer direct health benefits. A major share of greenhouse gas emissions from the food and agriculture sector arises from cows, goats and sheep – ruminants that create the greenhouse gas methane as part of their digestive process. Reducing consumption of meat and dairy products from these animals may reduce ischemic heart disease (assuming replacement with plant-based polyunsaturates) and some types of cancer. Programs to provide access to reproductive health services for all women will not only lead to slower population growth and its associated energy demands, but also will reduce the numbers of child and maternal deaths.

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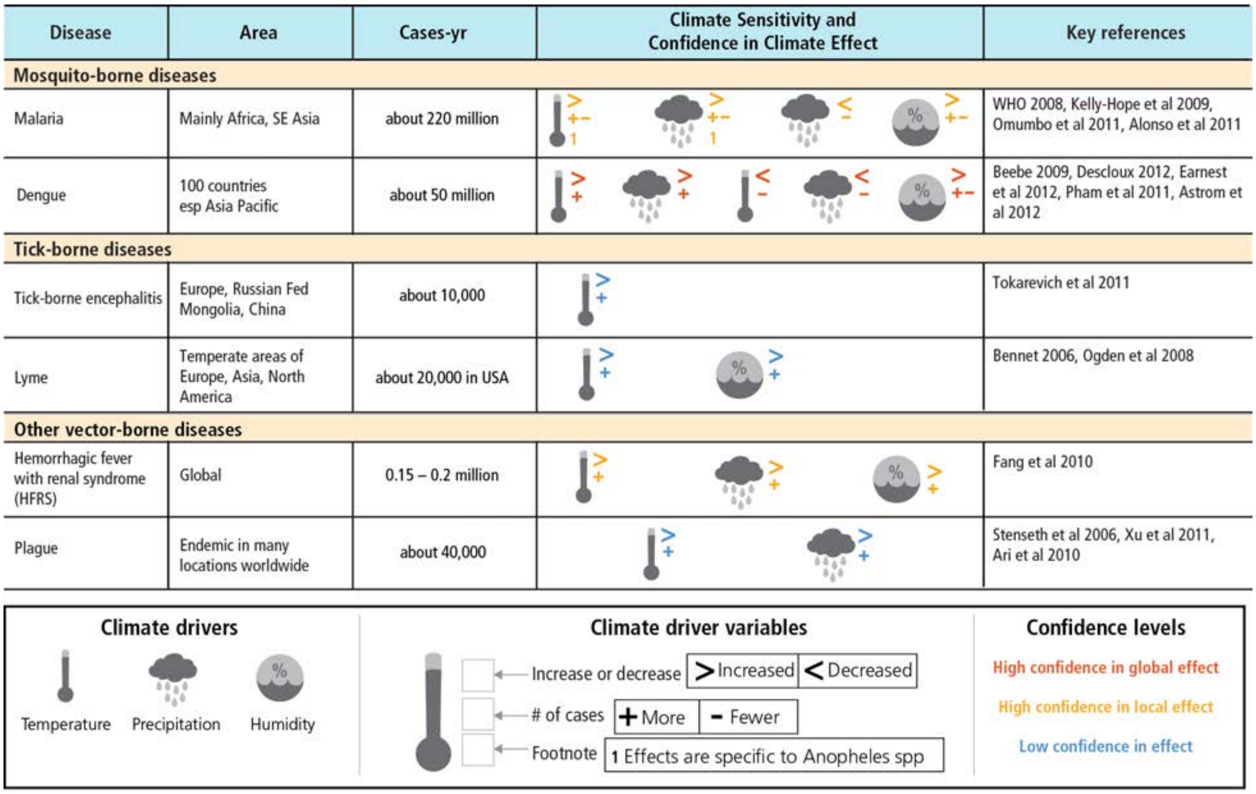
Table 11-1: The association between different climatic drivers and the global prevalence and geographic distribution of selected vector-borne diseases observed over the period 2008-2012. Among the vector borne diseases shown here, only dengue fever was associated with climate variables at both the global and local levels (*high confidence*), while malaria and hemorrhagic fever with renal syndrome showed a positive association at the local level (*high confidence*).



Disease	Area	Cases-yr	Climate Sensitivity and Confidence in Climate Effect	Key references
Mosquito-borne diseases				
Malaria	Mainly Africa, SE Asia	about 220 million	Temperature > +− 1; Precipitation > +− 1; Precipitation < −; Humidity > +−	WHO 2008, Kelly-Hope et al 2009, Omumbo et al 2011, Alonso et al 2011
Dengue	100 countries esp Asia Pacific	about 50 million	Temperature > +; Precipitation > +; Temperature < −; Precipitation < −; Humidity > +−	Beebe 2009, Descloux 2012, Earnest et al 2012, Pham et al 2011, Astrom et al 2012
Tick-borne diseases				
Tick-borne encephalitis	Europe, Russian Fed Mongolia, China	about 10,000	Temperature > +	Tokarevich et al 2011
Lyme	Temperate areas of Europe, Asia, North America	about 20,000 in USA	Temperature > +; Humidity > +	Bennet 2006, Ogden et al 2008
Other vector-borne diseases				
Hemorrhagic fever with renal syndrome (HFRS)	Global	0.15 – 0.2 million	Temperature > +; Precipitation > +; Humidity > +	Fang et al 2010
Plague	Endemic in many locations worldwide	about 40,000	Temperature > +; Precipitation > +	Stenseth et al 2006, Xu et al 2011, Ari et al 2010

Table 11-2: Number of under-nourished children less than 5 years of age (in millions) in 2000 and 2050, using the NCAR (National Center for Atmospheric Research) climate model (and the A2 scenario from AR4). Results assume no effect of heat on farmers' productivity, and no CO_2 fertilization benefits. Adapted from Nelson *et al.* (2009).

Scenario	**South Asia**	**East Asia/ Pacific**	**Europe and Central Asia**	**Latin America and Caribbean**	**Middle East/ North Africa**	**Sub-Saharan Africa**	**All Developing Countries**
2000	75.6	23.8	4.1	7.7	3.5	32.7	147.9
2050							
No climate change	52.3	10.1	2.7	5.0	1.1	41.7	113.3
Climate change	59.1	14.5	3.7	6.4	2.1	52.2	138.5

Table 11-3: Examples of recent (post AR4) research studies on co-benefits of climate change mitigation and public health policies. For recent estimates of the global and regional burden of disease from the various risk factors involved, see Lim *et al.* (2012).

Co-benefit category	**Benefits for health**	**Benefits for climate**	**References in chronological order**
Reduction of co-pollutants from household solid fuel combustion [see also WGIII-7, WGIII-8, WGIII-9, WGIII-10]	Potentially reduce exposures that are associated with disease, chronic and acute respiratory illnesses, lung cancer, low birth weight and stillbirths, and possibly tuberculosis	Reduces CAP emissions associated with household solid fuel use including CO2, CO, black carbon, and CH4	Bell *et al.*, 2008 Smith *et al.*, 2008 Wilkinson *et al.*, 2009 Lefohn *et al.*, 2010 Venkataraman *et al.*, 2010 World Health Organization Regional Office for Europe, 2010 Po *et al.*, 2011 Anenberg *et al.*, 2012
Reduction of GHGs and associated co-pollutants from industrial sources, such as power plants and landfills by more efficient generation or substitution of low carbon alternatives [27.3.7.2]	Reductions health-damaging co-pollutant emissions would decrease exposures to outdoor air pollution and could reduce risks of cardiovascular disease, chronic and acute respiratory illnesses, lung cancer, and preterm birth.	Reductions in emissions of CO2, black carbon, CO, CH4,and other CAPs	Bell *et al.*, 2008 Apsimon *et al.*, 2009 Jacobson, 2009 Puppim de Oliveira *et al.*, 2009 Smith *et al.*, 2009 Tollefsen *et al.*, 2009 Dennekamp *et al.*, 2010 Jacobson, 2010 Nemet, *et al.*, 2010 Rive and Aunan, 2010 Shonkoff *et al.*, 2011 Shindell *et al.*, 2012 West *et al.*, 2012 West *et al.*, 2013
Energy efficiency. Actual energy reduction may sometimes be less than anticipated because part of the efficiency benefit is taken as more service	Reductions in fuel demand potentially can reduce emissions of CAPs associated with fuel combustion and subsequent exposures to pollutants that are known to be health damaging.	Reductions in emission of CAPs due to decreases in fuel consumption	Markandya *et al.*, 2009 Wilkinson *et al.*, 2009

Increases in active travel and reductions in pollution due to modifications to the built environment, including better access to public transport and higher density of urban settlements [See also 24.4, 24.5, 24.6, 24.7, 26.8,]	Increased physical activity; reduced obesity; reduced non communicable disease burden, health service costs averted; improved mental health; reduced exposure to air pollution; increased local access to essential services, including food stores; enhanced safety.	Reductions of CAP emissions associated with vehicle transport; Replacing existing vehicles with lower emission vehicles could reduce air pollution	Babey *et al.*, 2007 Reed and Ainsworth, 2007 Kaczynski and Henderson, 2008 Casagrande *et al.*, 2009 Jarrett *et al.*, 2009 Rundle *et al.*, 2009 Woodcock *et al.*, 2009 Durand *et al.*, 2011 Grabow *et al.*, 2011 McCormack and Shiell, 2011 Jensen *et al.*, 2013 Woodcock *et al.*, 2013
Healthy low GHG emission diets which can have beneficial effects on a range of health outcomes [See also Table 11.3]	Reduced dietary saturated fat in some populations (particularly from ruminants) and replacement by plant sources associated with decreased risk of (ischemic) heart disease, stroke, colorectal cancer (processed meat consumption) Increased fruit and vegetable consumption can reduce risk of chronic diseases. Reduced CH_4 emissions due to a decreased demand for ruminant meat products would reduce the tropospheric ozone.	Reductions in CO2 and CH4 emissions from energy-intensive livestock systems	McMichael *et al.*, 2007 Friel *et al.*, 2009 Sinha *et al.*, 2009 Smith and Balakrishnan, 2009 Jakszyn *et al.*, 2011 Hooper *et al.*, 2012 Pan *et al.*, 2012 Xu *et al.*, 2012
Greater access to reproductive health services	Lower child and maternal mortality from increased birth intervals and shifts in maternal age.	Potentially slower growth of energy consumption and related CAP emissions; less impact on land use change, etc.	Tsui *et al.* 2007 Gribble *et al.*, 2009 Prata, 2009 O'Neill *et al.*, 2010 Diamond-Smith and Potts, 2011 Potts and Henderson, 2012 Kozuki *et. al.*, 2013
Increases in urban green space [Table 25-5]	Reduced temperatures and heat island effects; reduced noise; enhanced safety; psychological benefits; better self-perceived health status.	Reduces atmospheric CO2 via carbon sequestration in plant tissue and soil	Mitchell and Popham, 2007 Babey *et al.*, 2008 Maas *et al.*, 2009 van den Berg *et al.*, 2010 van Dillen *et al.*, 2011
Carbon sequestration forest plantations, REDD and carbon offset sales [see Chpt 13, 15.3.4, see also 20.4.1, 26.8.4.3]	Poverty alleviation and livelihood/job generation through sale of CDM and voluntary market credits. Ameliorate declines in production or competitiveness in rural communities.	Reduces emissions of CAPs and promotes carbon sequestration through REDD	Holmes, 2010 Ezzine-de-Blas *et al.*, 2011

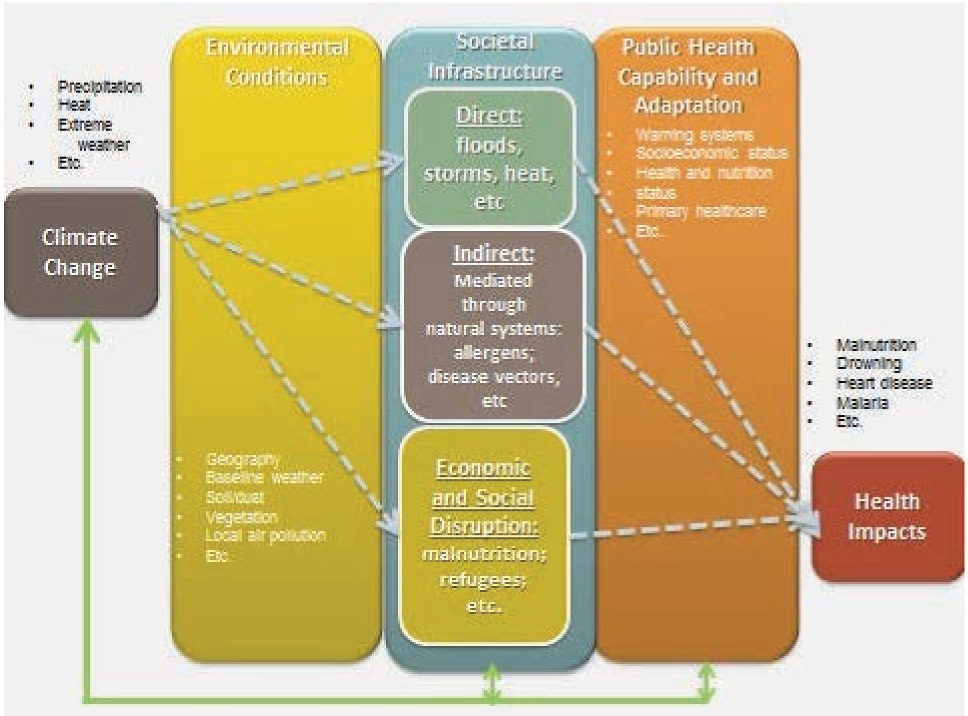


Figure 11-1: Conceptual diagram showing three primary exposure pathways by which climate change affects health: directly through weather variables such as heat and storms; indirectly through natural systems such as disease vectors; and pathways heavily mediated through human systems such as undernutrition. The yellow box indicates the moderating influences of local environmental conditions on how climate change exposure pathways are manifest in a particular population. The orange box indicates that the extent to which the three categories of exposure translate to actual health burden is moderated by such factors as background public health and socioeconomic conditions, and adaptation measures. The green arrows at the bottom indicate that there may be feedback mechanisms, positive or negative, between societal infrastructure, public health, and adaptation measures and climate change itself. As discussed later in the chapter, for example, some measures to improve health also reduce emissions of climate-altering pollutants, thus reducing the extent and/or pace of climate change as well as improving local health. Credit: E. Garcia, UC Berkeley.
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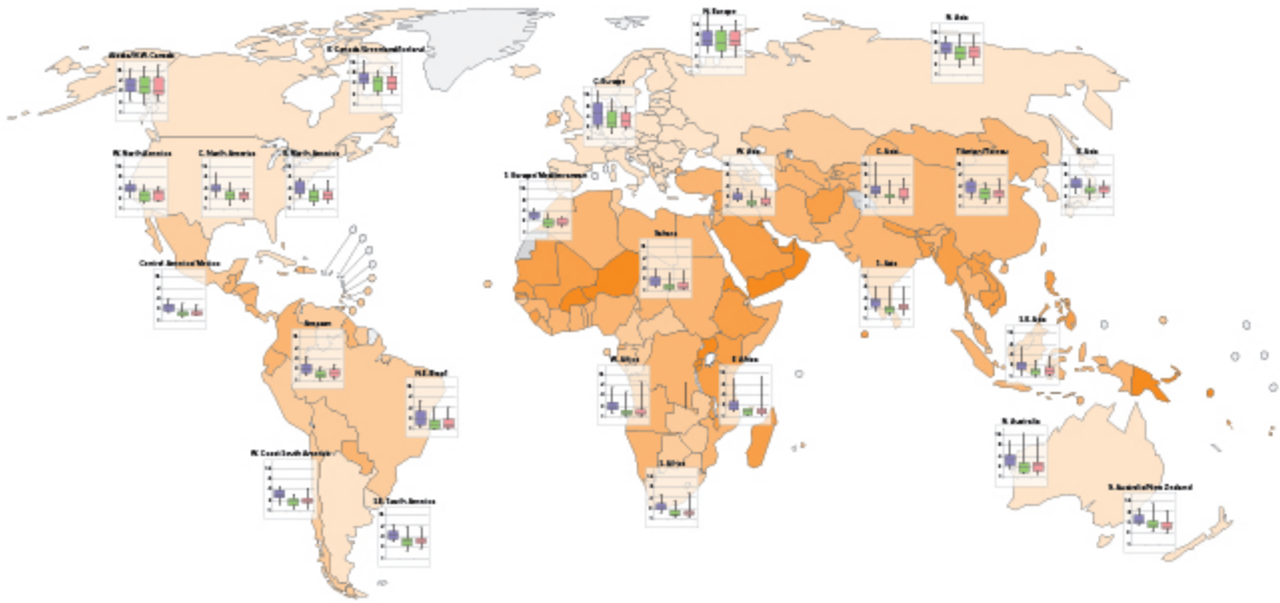

Figure 11-2: Increasingly frequent heat extremes will combine with rapidly growing numbers of older people living in cities – who are particularly vulnerable to extreme heat. Countries are shaded according to the expected proportional increase in urban populations aged over 65 by the year 2050. Bar graphs show how frequently the maximum daily temperature that would have occurred only once in 20 years in the late 20th century is expected to occur in the mid-21st century, with lower numbers indicating more frequent events. Results are shown for 3 different "SRES" scenarios (Blue = B1; Green = A1B, Red = A2), as described in the IPCC Special Report on Emissions Scenarios, and based on 12 global climate models participating in the third phase of the Coupled Model Intercomparison Project (CMIP3). Coloured boxes show the range in which 50% of the model projections are contained, and whiskers show the maximum and minimum projections from all models. Source: World Health Organization and World Meteorological Organization, 2012.
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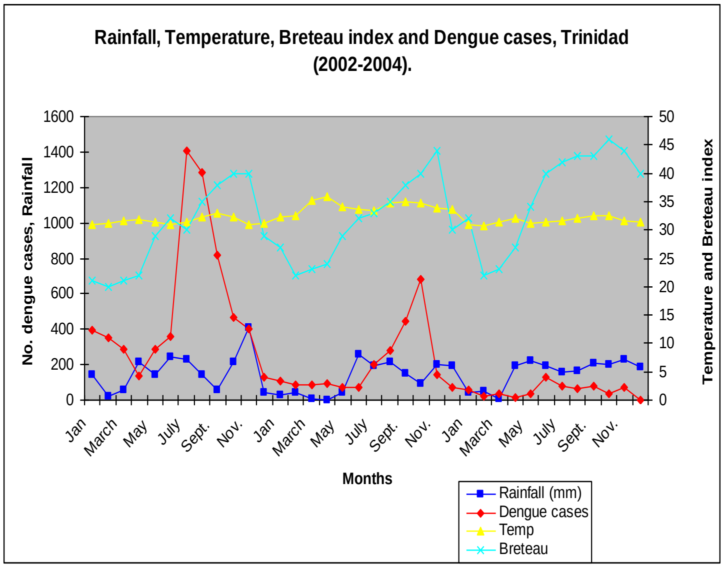

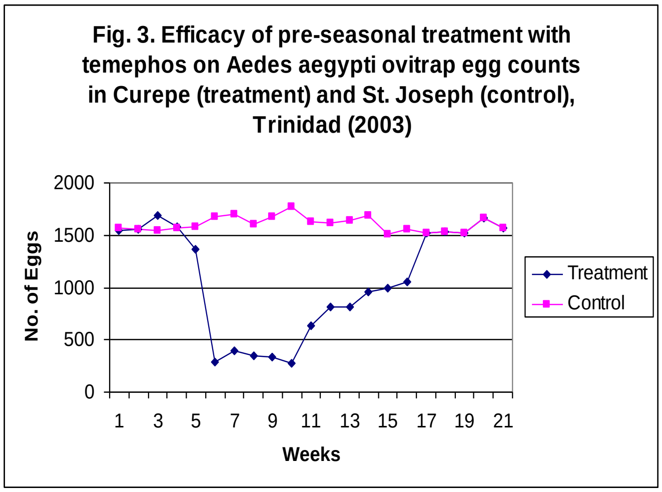

Figure 11-3: a) Rainfall, temperature, Breteau index (number of water containers with *Ae. aegypti* larvae per 100 houses), and dengue fever cases, Trinidad (2002-2004). Rainfall was found to be significantly correlated with an increase in the *Ae. aegypti* population and dengue fever incidence, with a clearly defined "dengue season" between June and November over two years of the study. Source: (Chadee *et al.*, 2007). b) Efficacy of pre-seasonal treatment with temephos on *Ae. aegypti* ovitrap egg counts in Curepe (treatment) and St. Joseph (control), Trinidad (2003). Evidence of the efficacy of the pre-seasonal larval control through focal treatment of *Ae. aegypti* population is provided. Treatment at the onset of the rainy season can effectively prevent the rapid increase in *Ae. aegypti* populations and therefore suppress the onset of dengue transmission. Source: Chadee, 2009.
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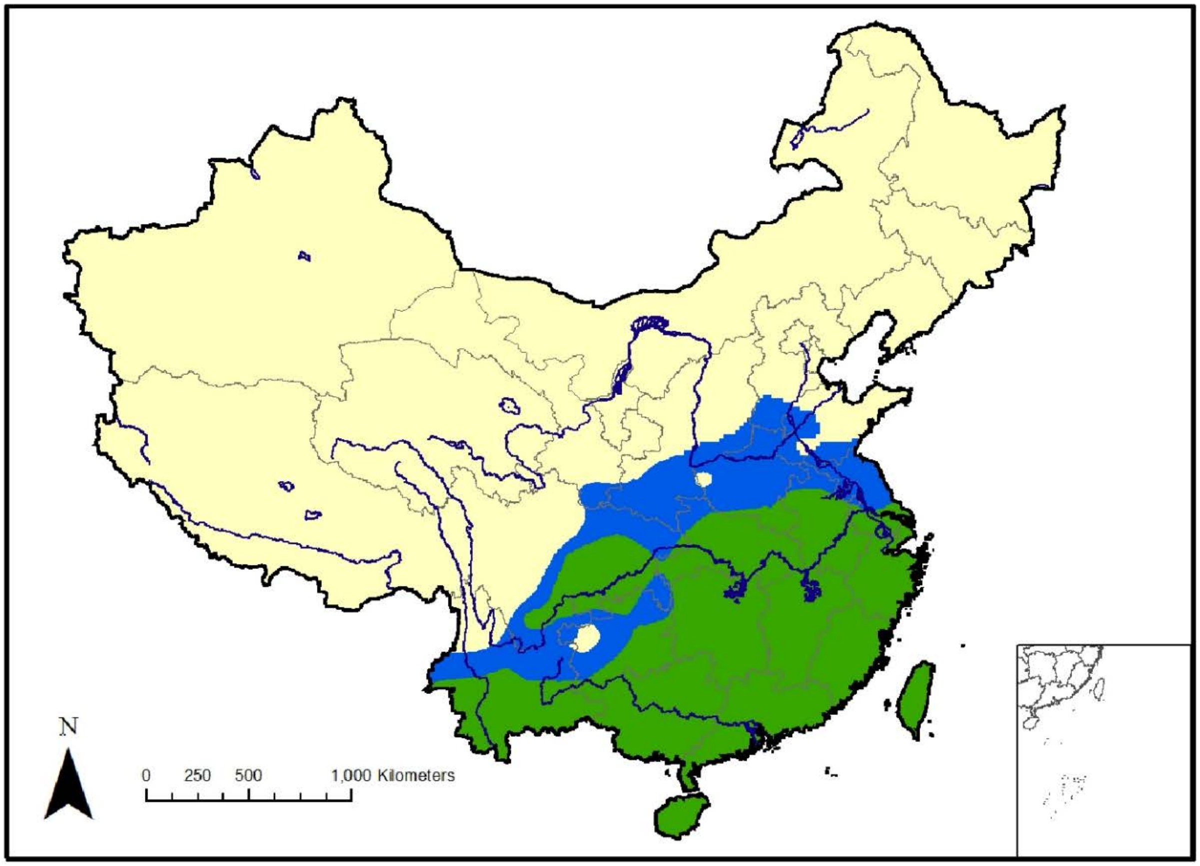

Figure 11-4: Effect of rising temperatures on the area in which transmission of *Schistosomiasis japonica* may occur. Green area denotes the range of schistosomiasis in China in 2000. The blue area shows the additional area suitable for disease transmission in 2050. Based on a biology-driven model including parasite (*Schistosoma japonicum*) and snail intermediate host (*Oncomelania hupensis*) and assuming average temperatures in China in mid-winter (January) increase by 1.6°C in 2050, compared with 2000. Adapted from Zhou *et al.*, 2008.
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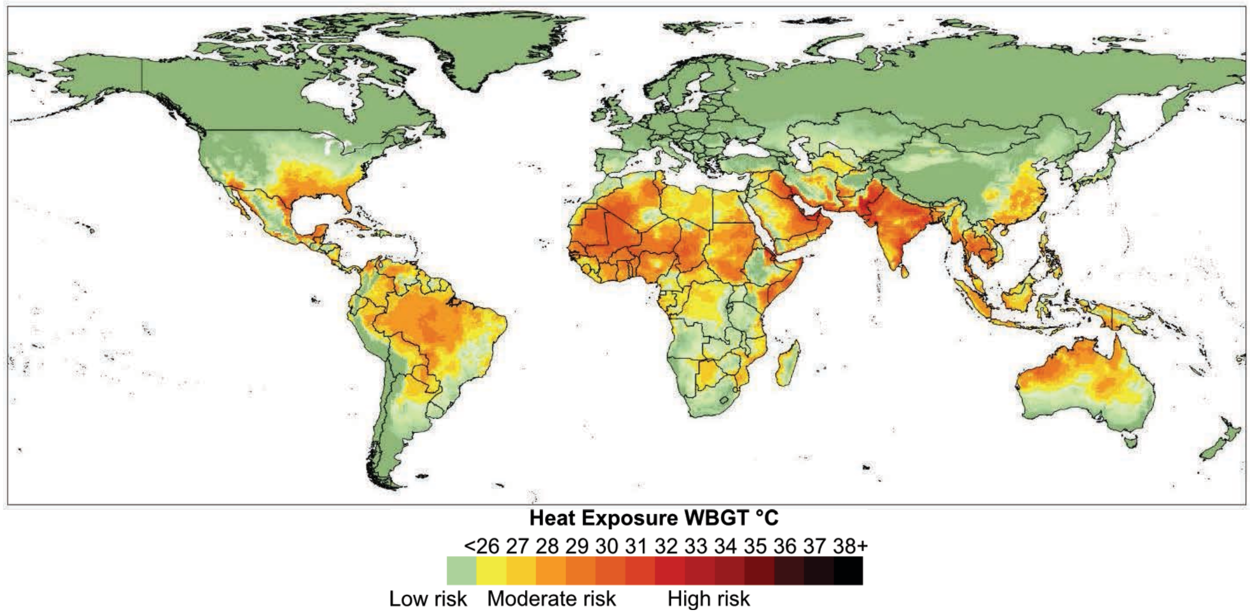

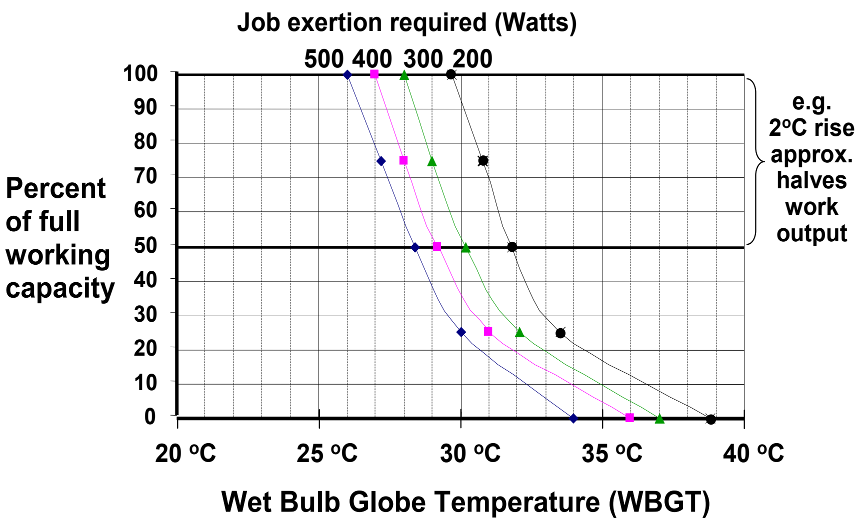

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Figure 11-5: The 1980-2009 average of the hottest months globally, measured in web bulb globe temperature (WBGT), which combines temperature, humidity, and other factors into a single index of the impact on work capacity and threat of heat exhaustion. The insert shows the International Standard Organization standard (1989) for heat stress in the workplace that leads to recommendations for increased rest time per hour to avoid heat exhaustion at different work levels. This is based on studies of healthy young workers and includes a margin of safety. Note that some parts of the world already exceed the level for safe work activity during the hottest month. In general, with climate change, for every 1°C that Tmax goes up, the WBGT goes up by about 0.9°C, leading to more parts of the world being restricted for more of the year, with consequent impacts on productivity, heat exhaustion, and need for air conditioning to protect health. Source: Lemke and Kjellstrom, 2012.
[Illustration to be redrawn to conform to IPCC publication specifications.]

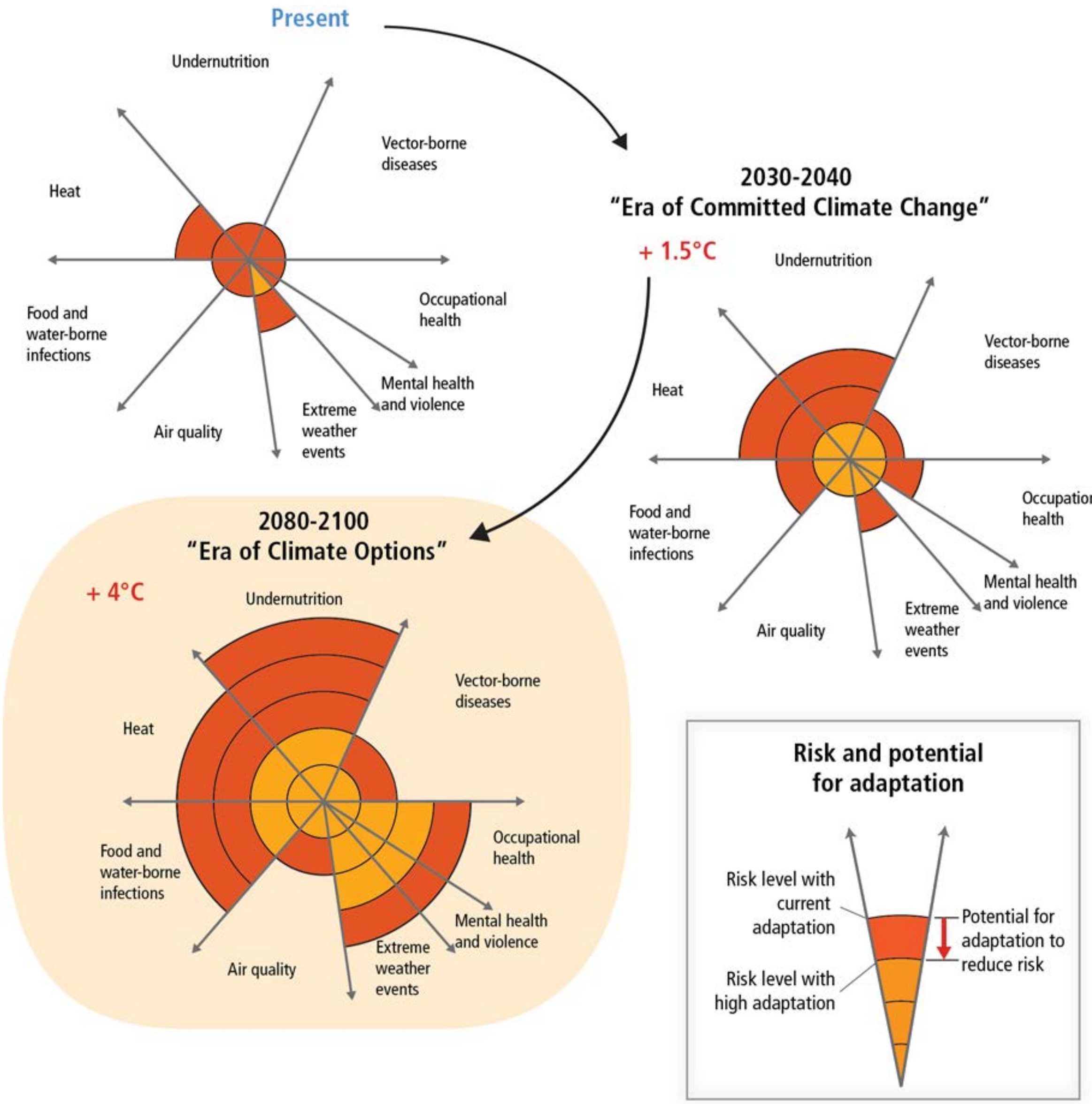

Figure 11-6: Conceptual presentation of the health impacts from climate change and the potential for impact reduction through adaptation. Impacts are identified in eight health-related sectors based on assessment of the literature and expert judgments by authors of Chapter 11.The width of the slices indicates in a qualitative way the relative importance in terms of burden of ill-health globally at present and should not be considered completely independent. Impact levels are presented for the near-term era of committed climate change (2030-2040), in which projected levels of global mean temperature increases do not diverge substantially across emissions scenarios. For some sectors, e.g., vector-borne diseases, heat/cold stress, and agricultural production and undernutrition, there may be benefits to health in some areas, but the net impact is expected to be negative. Estimated impacts are also presented for the longer-term era of climate options (2080-2100), for global mean temperature increase of 4°C above preindustrial levels, which could potentially be avoided by vigorous mitigation efforts taken soon. For each timeframe, impact levels are estimated for the current state of adaptation and for a hypothetical highly adapted state, indicated by different colors.

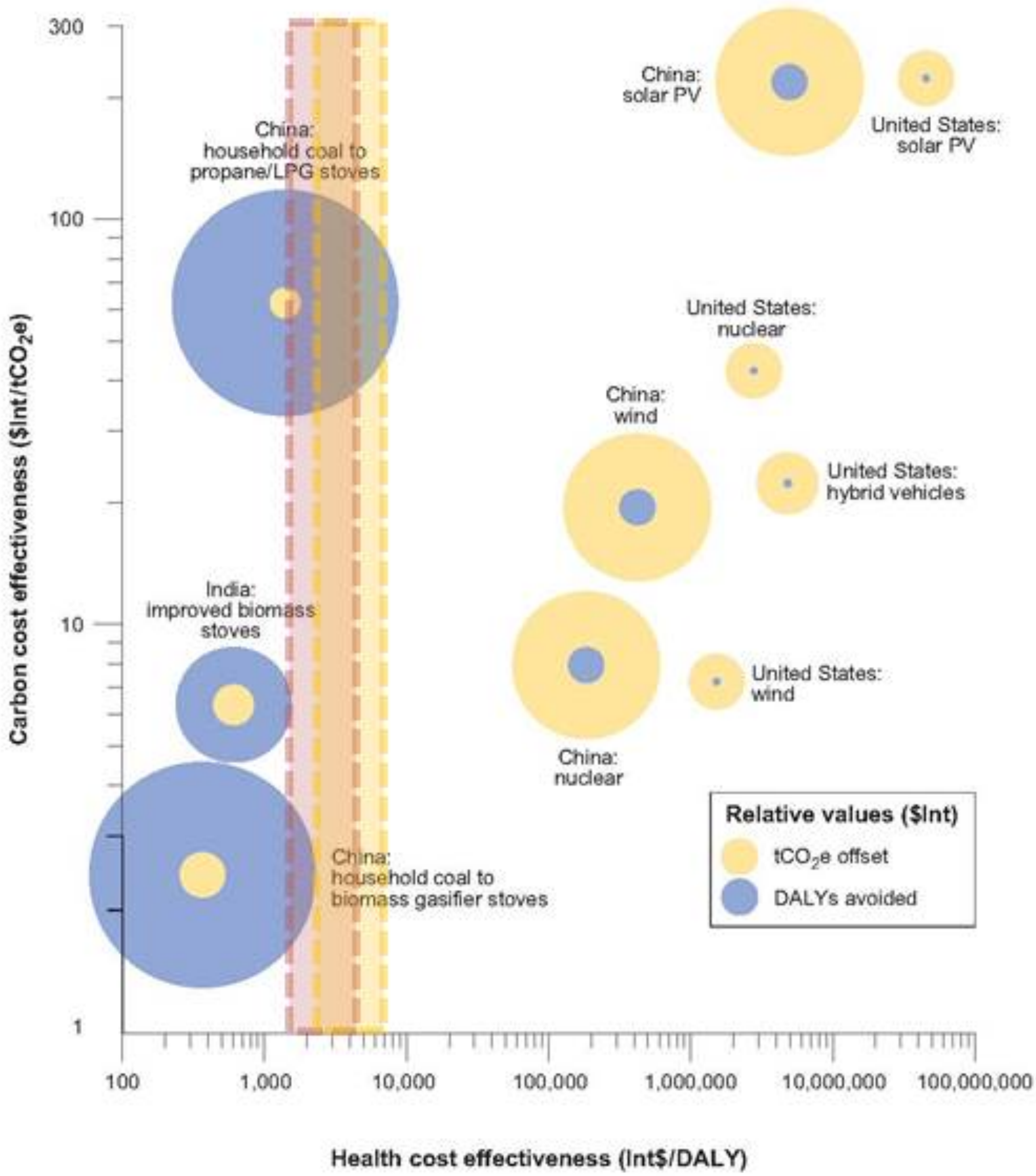

Figure 11-7: Illustrative co-benefits comparison of the health and climate cost-effectiveness of selected household, transport, and power sector interventions (Smith and Haigler, 2008). Area of each circle denotes the total social benefit in international dollars from the combined value of carbon offsets (valued at 10$/t$CO_2$e) and averted DALYs [$7450/DALY, which is representative of valuing each DALY at the average world GDP (PPP) per capita in 2000]. The vertical bar shows the range of the cut offs for cost-effective and very cost-effective health interventions in India and China using the WHO CHOICE criteria (World Health Organization, 2003). This figure evaluates only a small subset of all co-benefits opportunities and thus should not be considered either current or complete. It does illustrate, however, the kind of comparisons that can help distinguish and prioritize options. Note that even with the log-log scaling, there are big differences among them. For other figures comparing the climate and health benefits of co-benefits actions including those in food supply and urban design, see Haines *et al*. (Haines *et al.*, 2009). See the original reference for details of the calculations in this figure (Smith and Haigler, 2008).
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Chapter 12. Human Security

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Chapter Boxes

Frequently Asked Questions

Executive Summary

Human security will be progressively threatened as the climate changes (*high agreement, robust evidence)*. Human insecurity almost never has single causes, but instead emerges from the interaction of multiple factors [12.1.2; 12.2]. Climate change is an important factor in threats to human security through a) undermining livelihoods [12.2], b) compromising culture and identity [12.3], c) increasing migration that people would rather have avoided [12.4], and d) challenging the ability of states to provide the conditions necessary for human security [12.6].

Climate change will compromise the cultural values that are important for community and individual well-being *(high agreement, medium evidence*). The effect of climate change on culture will vary across societies and over time, depending on cultural resilience and the mechanisms for maintaining and transferring knowledge. Changing weather and climatic conditions threaten cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion and sense of place. Loss of land and displacement, for example on small islands and coastal communities, has well documented negative cultural and well-being impacts [12.3.1, 12.3.3, 12.4.2].

Indigenous, local and traditional forms of knowledge are a major resource for adapting to climate change (*high agreement, robust evidence*). Natural resource dependent communities, including indigenous peoples, have a long history of adapting to highly variable and changing social and ecological conditions. But the salience of indigenous, local and traditional knowledge will be challenged by climate change impacts. Such forms of knowledge are often neglected in policy and research, and their mutual recognition and integration with scientific knowledge will increase the effectiveness of adaptation [12.3.3, 12.3.4].

Climate change will have significant impacts on forms of migration that compromise human security (*high agreement, medium evidence*). Some migration flows are sensitive to changes in resource availability and ecosystem services. Major extreme weather events have in the past led to significant population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. Many vulnerable groups do not have the resources to be able to migrate to avoid the impacts of floods, storms and droughts. Models, scenarios and observations suggest that coastal inundation and loss of permafrost can lead to migration and resettlement [12.4.2]. Migrants themselves may be vulnerable to climate change impacts in destination areas, particularly in urban centres in developing countries [12.4.1.2].

Mobility is a widely used strategy to maintain livelihoods in response to social and environmental changes (*high agreement, medium evidence*). Migration and mobility are adaptation strategies in all regions of the world that experience climate variability. Specific populations that lack the ability to move also face higher exposure to weather-related extremes, particularly in rural and urban areas in low and middle-income countries. Expanding opportunities for mobility can reduce vulnerability to climate change and enhance human security [12.4.1, 12.4.2]. There is insufficient evidence to judge the effectiveness of resettlement as an adaptation to climate change.

Some of the factors that increase the risk of violent conflict within states are sensitive to climate change (*medium agreement, medium evidence*). The evidence on the effect of climate change and variability on violence is contested [12.5.1]. Although there is little agreement about direct causality, low *per capita* incomes, economic contraction, and inconsistent state institutions are associated with the incidence of violence [12.5.1]. These factors can be sensitive to climate change and variability. Poorly designed adaptation and mitigation strategies can increase the risk of violent conflict [12.5.2].

People living in places affected by violent conflict are particularly vulnerable to climate change (*high agreement, medium evidence*). Evidence shows that large-scale violent conflict harms infrastructure, institutions, natural capital, social capital and livelihood opportunities. Since these assets facilitate adaptation to climate change, there are strong grounds to infer that conflict strongly influences vulnerability to climate change impacts [12.5.3].

Climate change will lead to new challenges to states and will increasingly shape both conditions of security and national security policies (*medium agreement, medium evidence*). Physical aspects of climate change, such as sea level rise, extreme events and hydrologic disruptions, pose major challenges to vital transport, water, and energy infrastructure [12.6]. Some states are experiencing major challenges to their territorial integrity, including, small-island states and other states highly vulnerable to sea level rise [12.6.2]. Some transboundary impacts of climate change, such as changes in sea ice, shared water resources, and the migration of fish stocks, have the potential to increase rivalry among states. The presence of robust institutions can manage many of these rivalries such that human security is not severely eroded [12.5.1, 12.6.2].

12.1. Definition and Scope of Human Security

There are many definitions of human security, which vary according to discipline. This Chapter defines human security, in the context of climate change, as a condition that exists when the vital core of human lives is protected, and when people have the freedom and capacity to live with dignity. In this assessment, the vital core of human lives includes the universal and culturally specific, material and non-material elements necessary for people to act on behalf of their interests. Many phenomena influence human security, notably the operation of markets, the state, and civil society. Poverty, discrimination of many kinds, and extreme natural and technological disasters undermine human security.

The concept of human security has been informed and debated by many disciplines and multiple lines of evidence, by studies that use diverse methods (Paris 2001; Alkire, 2003; Owen 2004; Gasper 2005; Hoogensen and Stuvøy 2006; Mahoney and Pinedo 2007; Brauch *et al.*, 2009; Inglehart and Norris 2012). The concept was developed in parallel by UN institutions, and by scholars and advocates in every region of the world (UNDP 1994; Commission on Human Security, 2003; Najam 2003;Kaldor 2007; Poku and Sandkjaer 2009; Rojas 2009; Chourou, 2009; Sabur 2009; Othman 2009; Wun Gaeo 2009; Black and Swatuk 2009).

This Chapter assesses the risks climate change poses to individuals and communities, including threats to livelihoods, culture, and political stability. Chapters in Working Group II (WGIIAR4) in the Fourth Assessment Report (AR4) identified the risk climate change poses to livelihoods, cultures, and indigenous peoples globally (Chapters 5, 7, 9 10, 16, and 17) and that migration and violent conflicts increase vulnerability to climate change (Chapter 19), as well as highlighting that migration plays a role in adaptation. But this Chapter is the first systematic assessment across the dimensions of human security.

Research since publication of the AR4 has addressed the linkages between climate change and human security through concerted international research programmes and initiatives (Matthew *et al.*, 2010; Afifi and Jäger, 2010; O'Brien *et al.*, 2010; Oswald-Spring, 2012; Scheffran *et al.*, 2012a; Gleditsch, 2012; Sygna *et al.*, 2013). Specific dimensions of human security, such as food security, public health and well-being, livelihoods, and regional perspectives are examined systematically in Chapters 11, 13 and 19, and in Chapters 22-29 of this report, and this Chapter cross-refers to those assessments.

The assessment in this Chapter is based on structured reviews of scientific literature. These were carried out firstly using searches of scientific databases of relevant studies published from 2000 until 2013, with searches targeted at the core dimensions of culture, indigenous peoples, traditional knowledge, migration, conflict, and transboundary resources. These searches were supplemented by open searches to capture book and other non-journal literature. The comprehensive review in this Chapter reflects the dominant findings from the scientific literature that the impacts of climate change on livelihoods, cultures, migration, and conflict are negative, but that some dimensions of human security are less sensitive to climate change and driven by economic and social forces.

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Box 12-1. Relationship between Human Rights and Human Security in the Context of Climate Change

This Chapter focuses on human security, but does not explicitly frame the issue as one of rights. The argument is made in political and legal scholarship that human rights to life, health, shelter and food are fundamentally breached by the impacts of climate change. Climate change puts both human security and human rights at risk (Slade, 2007; Humphreys, 2010; Caney, 2010). But framing the issue of rights specifies minimum standards that apply universally, and such rights are often not realized in national and international law and practice or neglect the harm or rights of non-human species (Humphreys, 2010; Bell, 2013). Human security by contrast is inclusive of political, sociocultural, and economic rights, rather than legal rights (CHS, 2003), which are instrumental to its achievement (Bell, 2013).

Research on climate change risks to human rights examines legal issues in policy, litigation, and compensation (Posner, 2007). Many legal commentators argue that claims to human rights may ultimately not offer greater explanation of the harm to individuals or realise political traction in climate policy (Carlane and Depledge, 2007; Adelman, 2010; Bodansky, 2010). Several cases have tested these rights, especially of women, children, indigenous peoples, and other minorities (Oswald-Spring, 2008; Knox, 2009; Bodansky, 2010).

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This Chapter assesses research on how climate change may exacerbate specific threats to human security, and how factors such as lack of mobility or the presence of conflict restrict the ability to adapt to climate change. Research on the specific interaction of human security and climate change focuses on how cultural, demographic, economic, and political forces interact with direct and indirect climate change impacts, affecting individuals and communities (Krause and Jütersonke, 2005; Hoogensen and Stuvøy, 2006; O'Brien, 2006; Betancourt *et al.*, 2010; Sygna *et al*, 2013). The analysis concerns drivers of vulnerability across multiple scales and sectors, including, gender relations, culture, political institutions and markets. Each of these areas has its distinct disciplinary focus, methods, and levels of evidence as discussed in Box 12-2.

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Box 12-2. The Nature of Evidence about Climate Change and Human Security

Understanding the effects of climate change on human security requires evidence about social and environmental processes across multiple scales and sectors. This process-based analysis is informed by a wide array of theories, methods, and evidence used in different academic disciplines, and so is not contiguous. For example, this Chapter assesses anthropological research where culture influences responses to climate change or may be shaped by climate change; alongside political and economic studies which use data sets to test for correlations between climatic factors and violent conflicts; and historical observations using documentary and archaeological methods. These diverse sources strengthen the robustness of the conclusions for this assessment when they converge on similar findings (Van de Noort, 2011; Nielsen and Reenberg, 2012).

This Chapter reviews empirical studies from the social and physical sciences using both quantitative and qualitative data. Some studies examine the interactions between environmental changes and social outcomes. Few explicitly address climate change and human security links, but provide evidence of climate change impacts on human security (Ford *et al.*, 2010). Individual case studies often make causal claims in given contexts, but their results may not be generalized. Where results from multiple comparative case studies agree, generalization is sometimes possible. This Chapter also assesses quantitative studies about large social units with correlations among different factors. Correlations alone do not explain causality, although they are important in testing theories.

Given the many and complex links between climate change and human security, uncertainties in the research on the biophysical dimensions of climate change, and the nature of the social science, highly confident statements about the influence of climate change on human security are not possible (Scheffran et al., 2012a). Yet there is good evidence about many of the discrete links in the chains of causality between climate change and human insecurity. In this Chapter the standardized IPCC language of uncertainty is applied to those linkages where appropriate.

Many climate change risks to human security warrant further investigation. There is a need for more comprehensive evidence, collected across multiple locations, and over long durations, to build and test theories about relationships between climate change and livelihoods, culture, migration, and conflict. Meeting this need requires analysis of the sensitivity of diverse livelihood systems to climate change; and the effects of cultural, economic, and political changes on the vulnerability and adaptability of livelihoods. Questions surrounding the cultural dimensions of climate require much more research using multiple methods to enable more general conclusions to be drawn, in particular about the effects of culture on climate change mitigation and adaptation. The sensitivity of human mobility to climate also requires new investigation, including, importantly, systematic long-term monitoring of population changes. The effects of migration on the vulnerability and adaptation of migrants, sending, and destination communities also warrants more research, to permit scope for targeted policy interventions to reduce vulnerability. Finally, with respect to advancing knowledge of climate change and violence, extensive as well as case-based research is necessary to build theories of causality, including examination of cases where climate changes and variability were managed peacefully, in addition to cases where conflict emerged. Explanations of processes that reduce violence despite climate variability and change are necessary for responses that help sustain and improve peace in a future where the climate is changing.

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Human security and insecurity are universal issues. In every country there are individuals and groups who are insecure (Mahoney and Pinedo, 2007; Pietsch and McAllister, 2010). Much research suggests that while the impacts of climate change on human security will be experienced most in developing countries, human security is at risk for vulnerable populations everywhere (Naess *et al.*, 2006; Leichenko and O'Brien, 2008; Berrang-Ford *et al.*, 2011).

The Chapter also evaluates research on the interaction between the state and human security, suggesting that increased human insecurity may coincide with a decline in the capacity of states to conduct effective adaptation efforts, thus creating circumstances in which there is greater potential for violent conflict, especially in the absence of means to resolve conflicts effectively. The analysis extends to assess how states protect the human security of their citizens. In other words, this Chapter examines the security of the state because it directly impinges on human security by affecting the ability of states to protect their citizens.

The framing of climate change as a security issue has been controversial. Some authors suggest that discourses on climate change and national security tend to downplay human security dimensions, and skew mitigation and adaptation responses towards state interests rather than those of the most vulnerable human populations (Floyd 2008; Barnett 2007, 2009; Brauch, 2009; Dalby 2009; Trombetta 2009; Verhoeven 2009; Oels, 2013). Nevertheless, some countries associate climate change risks with conventional security risks and many countries are concerned about the risks climate change poses to relations between states (see Sections 5 and 6). This Chapter therefore adopts a comprehensive approach to human security, which is widely supported in the literature (Barnett, 2001; Brauch *et al.*, 2008, 2009, and 2011; Matthew *et al.*, 2010; O'Brien *et al.* 2010; Oswald-Spring, 2012).

12.2. Economic and Livelihood Dimensions of Human Security at Risk from Climate Change

12.2.1. Climate Change Impacts on Material Aspects of Livelihood Security

The direct and material aspects of livelihood security include access to food, housing, clean water employment and the avoidance of direct risks to health. Chapters 7, 11, and 13 assess the evidence of the mechanisms that link climate change with these phenomena. They find that climate change poses significant risks in all these areas and all conclude that material aspects of life and livelihood, such as food, water and shelter are closely coupled to weather and climate but also to multiple factors in the economy and society (Battisti and Naylor, 2009; Bohle, 2009; Hertel et a*l*., 2010; Schlenker and Lobell, 2010; Deligiannis, 2012; Chapter 13.1.4). Hence, while attributing changes climate directly to human security is difficult, some major risks are well documented. This Chapter builds on that knowledge base to assess the interaction of those risks with cultural dimensions of change, and the risks of migration and conflict. It is well established that direct risks of climate change to life and livelihoods are highly differentiated by socio-demographic factors, such as by age, wealth and gender. Box CC-GC, for example, highlights how specific populations of men and women are vulnerable to weather extremes.

Table 12-1 summarizes studies that exemplify how climate variability and change affect the material aspect of human security through deprivation of immediate basic needs and erosion of livelihood assets and human capabilities. There are well-established links from climate variability and change to the stability of agriculture and food security; water stress and scarcity; as well as destruction of property (Carter *et al.*, 2007; Leary *et al.*, 2008; Peras *et al.*, 2008; Paavola, 2008; Tang *et al.*, 2009). Projections using various socio-economic and climate change scenarios indicates an increase in economic and health risks, including loss of lives in all regions (Hall *et al.*, 2003; Kainuma et al., 2004; Tang *et al*., 2009) as well as a range of psychological stresses accompanying extreme climate events and decreased access to ecosystem resources (e.g. Doherty and Clayton, 2011). The cross chapter box on Heat Stress (Box CC-HS), for example, documents the evidence on the impacts of heat stress on both labour productivity and on health outcomes. Modeled and observational analysis of human exposure to climate-related natural disasters finds significant risk of large human losses, particularly in countries with significant populations in poverty (Peduzzi et al., 2009; Busby et al., 2013). Table 12.1, and the analysis in cognate chapters (Chapters 7.3; 11.3, 13.2.2) shows that risks are significant and well understood though there is uncertainty about how dimensions of basic needs livelihoods and the integrity of place and economic assets will unfold under scenarios of climate change. Those cognate Chapters confirm that elements of nutrition, economic stability, and threats to shelter and human health interact with each other and all represent significant challenges for adaptation. Following from this body of evidence, a number of studies conclude that adverse impacts of climate change on health and on human capital will lead to the erosion of human capability (UNDP, 2007; Costello *et al.*, 2009).

[INSERT TABLE 12-1 HERE
Table 12-1: Illustrative examples of impacts of climate variability and change on immediate basic needs and longer term capabilities and assets from observational studies and from projections.]

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Box 12-3. Food Prices, Food Insecurity, and Links to Climate

Food prices and food-price shocks have significant impacts on human security. They do so through reduced access to and production of food that affects both consumers and food producers (e.g. Chapter 7.4.3, Chapter 13.2.1 and 13.2.2; Barrett, 2010). It is well established that food security is determined by a range of interacting factors including poverty, water availability, food policy agreements and regulations and the demand for productive land for alternative uses (Barrett, 2010; 2013). It is also established that many of these factors are themselves sensitive to climate variability and climate change. Specific observed food prices have, however, multiple causes and complex dynamics between markets, non-food demand for agricultural land, and the impact of adverse weather and droughts on the major agricultural producing regions (Piesse and Thirtle, 2009).

Spikes in food prices have particularly acute impacts on food insecurity at the domestic level, even in the absence of climate stresses. There was, for example, high regional variation in self-reported food insecurity following the global 2008 price spike: the reported food insecurity was especially serious insecurity across Africa and Latin American countries (Heady, 2013). The 2010-11 food price spike has been estimated to have pushed 44 million people below the basic needs poverty line across 28 countries (Ivanic et al., 2012). Food availability can also be affected by domestic production of food, particularly for those countries where there are restrictions on food imports (Berazneva and Lee, 2013; Barrett, 2013). There are therefore multiple pathways by which consumers including agricultural wage labourers in low-income countries are affected (Mendelsohn et al., 2007; Ahmed et al., 2009; Hertel and Rosch, 2010; Cohen and Garrett, 2010; Ruel at al., 2010). Declines in agricultural productivity linked to climate variability and losses in maize production, for example, have been shown in Zambia to reduce real urban incomes and to influence urban poverty for a portion of the population (Thurlow *et al.*, 2012).

Food prices and food availability also affect socio-political stability and in the case of the 2008-09 and 2010-11 food price spikes have been associated with food riots (Johnstone and Lazo, 2011; Berazneva and Lee, 2013; Barrett, 2013). High food prices affect food access and food availability, but such insecurity is highly conditional on the responses of markets and governments and hence is variable. Berazneva and Lee (2013) show that 14 countries in Africa experienced food riots in 2008 and that they are characterized by higher levels of poverty, restricted food access and availability, more urbanized, and have more oppressive regimes and stronger civil societies than those countries which did not experience riots. The linkages between food riots are therefore dependent on responses of multiple private and state actors and it is generally concluded that it is difficult to attribute causality (Barrett, 2013).

Food prices, food access and food availability are critical elements of human security. There is robust evidence that food security affects basic-needs elements of human security and, in some circumstances, is associated with political stability and climate stresses. But there are complex pathways between climate, food production and human security and hence this area requires further concentrated research as an area of concern.

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12.2.2. Adaptation Actions and Livelihood Dimensions of Human Security

Adaptation strategies seek to reduce vulnerability and thereby advance human security. But they also run the risk of exacerbating elements of insecurity (e.g. Deligiannis, 2012; see also Section 12.2.2). Evaluations of development interventions, for example, provide robust evidence on how livelihoods can be secured and enhanced through adaptation in the context of external shocks and shorter-term climates stresses (e.g. Ellis, 2000; Dercon, 2004). But an emerging literature documents how some adaptation interventions can create new risks, are inefficient, or fail to recognize wider goals of system resilience (e.g. Eriksen et al., 2011; Adger et al., 2011; see also Chapter 13.3.2 and Chapter 20.3.2).

Adaptation interventions and strategies have been documented that reduce risks to human security, but vary in their effectiveness. Strategies that have been documented as promoting well-being include 1) diversification of income-generating activities in agricultural and fishing systems (Tolossa, 2008; Coulthard, 2008; Paavola, 2008; Galvin, 2009; Badjeck *et al.*, 2010; West and Hovelsrud, 2010); 2) migration as a risk management strategy, for example, among pastoralists and farmers in rain-fed areas (Galvin, 2009) and amongst fishing communities (Perry and Sumaila, 2007; Badjeck et al., 2009); 3) the development of insurance systems, particularly amongst vulnerable groups (Badjeck *et al.*, 2010; Linneroth-Bayer and Vari, 2008); and 4) the education of women (Boyle et al., 2006, Rammohan and Johar, 2009).

Some adaptation strategies may, however, undermine human security, particularly where strategies are implemented without taking cognizance of complex livelihood arrangements. In some cases, adaptations may entrench vulnerabilities and also have the potential to enforce inequalities (Barnett and O'Neill, 2010).
For example in parts of the Middle East and North Africa, the Andes and the Caribbean, amongst other areas, skewed water policy allocation in some cases that favour the affluent may heighten overall livelihood vulnerabilities to climate stress (Chapter 13.2.1.1).

12.3. Cultural Dimensions of Human Security

12.3.1. How Culture Interacts with Climate Impacts and Adaptation

Culture is a contested and highly fluid term that is defined in this Chapter as material and non-material symbols that express collective meaning. In all societies culture is expressed in knowledge, worldviews, beliefs, norms, values and social relationships (Crate, 2008; 2011; Heyd, 2008; Roncoli et al., 2009; Strauss, 2009; O'Brien and Wolf, 2010; Tingley et al., 2010; Rudiak-Gould, 2012; Sudmeier-Rieux *et al.*, 2012). In this definition culture shapes the relationship of society to environments and is a significant determinant of responses to environmental and other risks and challenges (Siurua and Swift, 2002; Pearce *et al.*, 2009; Nielsen and Reenberg, 2010; Petheram et al., 2010; Buikstra et al., 2010; Paul and Routray, 2011).

There has been significant new research from psychology, anthropology, sociology and human geography in the period since AR4 on the lived experience of weather extremes and observed climate change, driven in part by observed warming trends in regions. This body of knowledge from across social science disciplines argues that climate change is embedded in and acts upon culture in myriad ways. For example, all consumption patterns are culturally embedded and therefore culture influences greenhouse gas emissions. The phenomenon of climate change itself is perceived differently depending on the culture in which it is viewed, with scientific expression representing only one possibility (Norgaard, 2011). Similarly, there are widely different cultural expressions of weather, risk and the need for adaptation to such hazards (Hulme, 2008; Adger *et al.*, 2013). Therefore, since climate change has consequences for people this emerging body of knowledge shows with *high confidence* that climate change has significant cultural implications (Crate, 2011; Strauss, 2012).

Anthropological analysis of culture focuses on identity, community and economic activities. There is a growing body of research on how climate and other environmental change affects livelihood activities such as pastoralism, herding, farming, fishing and hunting and gathering in places where there is significant observed change. Research has documented how rural livelihoods and, therefore, cultural practices have been affected by changes in climate and associated impacts on natural capital. Many anthropological studies suggest that further significant changes in the natural resource base upon which many cultures depend would directly affect the cultural core, worldviews, cosmologies and mythological symbols of indigenous cultures (Crate, 2008; Gregory and Trousdale, 2009; Jacka, 2009). While changing socio-economic and environmental conditions may constrain existing community coping mechanisms (Rattenbury *et al.*, 2009; West and Hovelsrud, 2010; Quinn *et al.*, 2011), other studies focus on how cultures adapt to significant societal and environmental changes. Many successful examples of the persistence of cultures despite significant upheaval exist throughout history (Nuttall, 2009; Cameron, 2012; Strauss, 2012).

Culture also interacts with adaptation though the way that cultural, local and individual perceptions affect narratives of risk, resilience and adaptive capacity. A body of research across disciplines argues that incorporation of cultural understanding of environment, risk and social practices increases the explanatory power of models of risk (Ifejika Speranza et al., 2008; Jacka, 2009; Adger et *al.*, 2011). The way in which resource-dependent communities articulate and perceive climate change is often based on how English language terms are translated and understood in the local language (Rudiak-Gould, 2012). Furthermore, information is interpreted through personal lifestories life stories and culture (Kuruppu and Liverman, 2011). Local perceptions of what kind of knowledge is trustworthy may in fact lead to questioning of scientific findings (Ingram *et al.*, 2002; Burns *et al.*, 2010; Roncoli *et al.*, 2011). Table 12-2 illustrates different dimensions in which climate change is interpreted and against which human security is affected.

Culturally embedded perceptions of climate change may either facilitate or hinder adaptation with implications for human security (Zamani *et al.*, 2006; Burningham *et al.*, 2008; West and Hovelsrud, 2010; Rudiak-Gould, 2012; Gómez-Baggethun *et al*., 2012; Nursey-Bray *et al*., 2012). Scientific information on weather variability and change is framed through cultural practices that can both enable (Dannevig *et* al., 2012) and constrain (Roncoli, 2006) adaptation. There are a number of anthropological studies that document how some cognitive frames do not perceive a changing climate and hence the concept of climate change itself does not have cultural resonance, whether or not the parameters of climate have been observed (Rudiak-Gould, 2012; Kuruppu and Liverman, 2011; Sánchez-Cortés and Chavero, 2011; Lipset, 2011; Hovelsrud *et al*., 2013). Most of these studies conclude that climate policies do not have legitimacy and salience when they do not consider how individual behaviour and collective norms are embedded in culture (Stadel, 2008; Jacka, 2009).

[INSERT TABLE 12-2 HERE
Table 12-2: Cultural dimensions of climate science, policy, impacts, and extreme events in the context of climate change.]

There is a significant body of research that analyses community and collective action for adaptation and generally finds positive outcomes. Many studies conclude that community-led action is effective for reducing risks and building capacity for adaptation (Davidson *et al.*, 2003; Catto and Parewick, 2008; Harries and Penning-Rowsell, 2011; Gero *et al.*, 2011; Fazey *et al.*, 2010; Furgal and Seguin, 2006; Sudmeier-Riuex *et al.*, 2012; Anik and Khan, 2012; Adler, *et al*., 2012). Specifically, this literature finds that community participation in risk and vulnerability assessments produces more sustainable solutions (Ardalan *et al.*, 2010; Gero *et al.*, 2011) and that co-management of resources and learning increase adaptive capacity (Fazey *et al.*, 2010; Armitage *et al.*, 2011; Dumaru, 2010; Ford *et al*., 2007). Much of this literature recognises, however, the structural barriers to community-led action and limited participation that can hinder effective community adaptation to climate change (Singleton, 2000; Davidson *et al.*, 2003; King, 2008; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Onta and Resurrection, 2011). Further studies highlight barriers to widespread community responses that result from colonial history (Marino, 2012) and from political and economic globalization (Keskitalo, 2009; O'Brien *et al*., 2004).

12.3.2. Indigenous Peoples

There are around 400 million indigenous people worldwide (see Glossary for an inclusive definition), living under a wide range of social, economic and political conditions and locations (Nakashima *et al.*, 2012). Indigenous peoples represent the world's largest reserve of cultural diversity and the majority of languages (Sutherland, 2003). Climate change poses challenges for many indigenous peoples, including to post-colonial power relations, cultural practices, their knowledge systems and adaptive strategies. For example, the extensive literature on the Arctic shows that changing ice conditions pose risks in terms of access to food and increasingly dangerous travel conditions (Ford *et al.*, 2008; Ford *et al.*, 2009; Hovelsrud *et al*., 2011; Chapter 28.4.1). Accordingly, there is a strong research tradition on the impacts of climate change in regions with substantial indigenous populations that focuses on indigenous peoples and their attachment to place. Most studies focus on local, traditional, and rural settings (Cameron, 2012) and hence have been argued to create a knowledge gap regarding new urban indigenous populations. Indigenous peoples are often portrayed in the literature as victims of climate change (Salick and Ross, 2009) and as vulnerable to its consequences (ACIA, 2005). However, traditional knowledge is increasingly being combined with scientific understanding to facilitate a better understanding of the dynamic conditions of indigenous peoples (Huntington 2011; Section 12.3.4).

There is a *high agreement* that, historically, indigenous peoples have had a high capacity to adapt to variable environmental conditions. This literature also suggests indigenous peoples also have less capacity to cope with rapidly changing socio-economic conditions and globalization (Tyler *et al.*, 2007; Crate and Nuttall, 2009). Documented challenges for indigenous cultures to adapt to colonization and globalization may reflect resilience and the determination of indigenous peoples to maintain cultures and identities. Furthermore, historical legacies affect the way that indigenous populations adapt to modern challenges: anthropological research has documented clear linkages between historical colonization and the way the way indigenous peoples respond to current climatic changes (Salick and Ross 2009; Cameron 2012; Howitt et al 2012; Marino, 2012).

Most of the literature in this area emphasizes the significant challenge of maintaining cultures, livelihoods and traditional food sources under the impacts climate change (Crate and Nuttall, 2009; Rybråten and Hovelsrud, 2010; Lynn *et al*., 2013). Examples from the literature show that traditional practices are already under pressure from multiple sources, reducing the ability of such practices to effectively respond to climate variability (Green *et al.*, 2010). Empirical evidence suggests that the efficacy of traditional practices can be eroded when governments relocate communities (Hitchcock, 2009; McNeeley, 2012; Maldonado *et al*., 2013); if policy and disaster relief creates dependencies (Wenzel, 2009; Fernández-Giménez *et al.*, 2012); in circumstances of inadequate entitlements, rights and inequality (Shah and Sajitha, 2009; Green *et al.*, 2010; Lynn *et al*., 2013); and when there are constraints to the transmission of language and knowledge between generations (Forbes, 2007). Some studies show that current indigenous adaptation strategies may not be sufficient to manage the projected climate changes (Wittrock *et al.*, 2011).

Assessments of the cultural implications of climate change for human security illustrate similarities across indigenous peoples. Indigenous peoples have a right to maintain their livelihoods and their connections to homeland and place (Howitt *et al.,* 2012) and it is suggested that the consequences of climate change are challenging this right (Box 12-1; Crate and Nuttall, 2009). Some raise the question whether the western judicial system can uphold indigenous rights in the face of climate change (Williams, 2012) and that there is a need for justice that facilitates adaptation (Whyte, 2013). Additionally, there are uneven societal consequences related to climate change impacts (for example, use of sea ice - Ford *et al.*, 2008)), which adds complexity to adaptation in indigenous societies. Heterogeneity within indigenous groups and differentiated exposure to risk has been found in other contexts, for example, in pastoralist groups of the Sahel (Barrett *et al.*, 2001).

Much research on indigenous peoples concludes that lack of involvement in formal, government decision-making over resources decreases resilience: the literature recommends further focus on indigenous perceptions of risk and traditional knowledge of change, hazards and coping strategies and collective responses (Ellemor, 2005; Brown, 2009; Finucane, 2009; Turner and Clifton 2009; Sánchez-Cortés and Chavero, 2011; Maldonado *et al.*, 2013). While providing economic opportunities, tourism development and industrial activities are particular areas of risk for indigenous peoples when they are not involved in decision-making (Petheram *et al.*, 2010). Lack of formal participation in international negotiations may pose risks for indigenous peoples because their perspectives are not heard (Schroeder, 2010). However, there are examples of successful indigenous lobbying and advocacy, as in the case of managing persistent organic pollutants and heavy metals in the Arctic (Selin and Selin, 2008).

12.3.3. Local and Traditional Forms of Knowledge

There is *high agreement* among researchers that involvement of local people and their local, traditional, or indigenous forms of knowledge in decision-making is critical for ensuring human security (Ellemor, 2005; Kesavan and Swaminathan, 2006; Burningham *et al.*, 2008; Mercer et al., 2009; Pearce et al., 2009; Anik and Khan, 2012). Such forms of knowledge include categories such as traditional ecological knowledge, indigenous science and ethnoscience (Nakashima and Roué, 2002). Collectively they are defined as ‘a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations’ (Berkes 2012: 7). In addition to reasserting culture, identity and traditional values, such forms of knowledge are experiential, dynamic and highly context dependent, developed through interactions with other forms of knowledge (Ford *et al.*, 2006; Orlove *et al.*, 2010; Sánchez-Cortés and Chavero, 2011; Eira *et al.*, 2013).

The conclusion of much anthropological studies in this area is that there is *robust evidence* that mutual integration and co-production of local and traditional and scientific knowledge increase adaptive capacity and reduce vulnerability (Kofinas, 2002; Oberthür *et al.*, 2004; Tyler *et al.*, 2007; Anderson *et al.*, 2007; Vogel *et al.*, 2007; West *et al*., 2008; Armitage *et al*., 2011; Frazier *et al.*, 2010; Marfai *et al.*, 2008; Flint *et al*., 2011; Ravera *et al.*, 2011; Nakashima *et al.*, 2012; Eira *et al*., 2013). Local and traditional knowledge about historical changes, events and adaptation strategies are valuable for evaluating contemporary responses to environmental and social change and policy (Angassa and Oba, 2008; Desta and Coppock, 2004; Eira *et al.*, 2013; Ford *et al.*, 2008; Lefale, 2010; Osbahr *et al.*, 2010; Orlove *et* al., 2000; Fernández-Giménez, *et al.*, 2012). Traditional knowledge contributes to mitigating the impact of natural disasters (Rautela, 2005), maintaining domestic biodiversity (Emperaire and Peroni, 2007) and developing sustainable adaptation and mitigation strategies (Nyong *et al.*, 2007; Adler *et al*., 2012). A study of Borana indigenous pastoralists, for example, documented how loss of technical and organizational practices contributed to progressive land degradation, erosion of social structures and poverty (Homann *et al.*, 2008). Local and traditional knowledge is also applied in folk forecasting of weather and has been shown to be mutually reinforcing with scientific forecasts of weather at different timescale (Orlove *et al*., 2000; Nyong *et al.*, 2007; Tyler *et al.*, 2007; Gearheard *et al*., 2010; Hovelsrud and Smit, 2010;).

Despite recognition in studies of the value of local and traditional knowledge, such knowledge is most often not included in adaptation planning (Tàbara *et al.*, 2003; King *et al.*, 2007; Ifejika Speranza *et al.*, 2008; Huntington, 2011). There are many challenges in managing, utilizing, acknowledging and incorporating local and traditional knowledge (Huntington, 2011). Such knowledge is often generated and collected through participatory approaches, an approach that may not be sufficient because of the cultural and social dynamics of power and interpretation (Roncoli *et al.*, 2011). Local and traditional knowledge itself may have its limits. Some studies suggest that local or traditional knowledge may not be sufficient to provide the proper response to unexpected or infrequent risks or events (Nunn, 2000; Burningham *et al.*, 2008; Kuhlicke, 2010).

There is also concern, documented in many anthropological studies, that indigenous and traditional knowledge is itself under threat. If local or traditional knowledge is perceived to be less reliable because of changing environmental conditions (Ingram *et al.*, 2002; Ford *et al.*, 2006) or because of extreme or new events that are beyond the current local knowledge and cultural repertoire (Valdivia *et al.*, 2010; Hovelsrud *et al.*, 2010a), then community vulnerability and the vulnerability of local or traditional knowledge itself, may increase (Kalanda-Joshua *et al.*, 2011). New conditions may require new knowledge to facilitate and maintain flexibility and improving livelihoods (see also Homann *et al.*, 2008). Kesavan and Swaminathan (2006) documented how societal and environmental conditions have changed to the point at which local knowledge is supplemented with new technologies and new knowledge in coastal communities in India. A study in the Himalayas found that erosion of traditional knowledge occurs through government regulations of traditional building materials and practices (Rautela, 2005). The social cohesion embedded in such practices is weakened because of a move towards concrete construction which changes the reliance on and usefulness of traditional knowledge about wood as a building material (Rautela, 2005).

12.4. Migration and Mobility Dimensions of Human Security

12.4.1. Impacts of Climate Change on Displacement, Migration, and Mobility

12.4.1.1. Nature of Evidence on Climate Change and Migration

This Section details how some existing migration systems may be significantly disrupted by impacts of climate change in a number of important dimensions. This finding comes from a very significant new body of observational and theoretical research in the past five years, as the migration and mobility dimensions of the impacts of climate change and the central role of mobility in adaptation has become apparent (Afifi and Jäger, 2010; Piguet *et al*., 2011; Foresight, 2011; Serrano-Oswald *et al*., 2013). As with other elements of human security, the dynamics of interaction of mobility with climate change are multi-faceted and direct causation is difficult to establish.

The major findings of this emerging science demonstrate the multiple drivers of migration; show the role of displacement of populations from extreme weather events; and highlight the governance challenges of displaced peoples and the challenges of migration for urban sustainability (Foresight, 2011; Seto, 2011; Black *et al.*, 2011a, 2011c; White, 2011a; Parnell and Walawege, 2011; Geddes *et al.*, 2012). Studies have derived these findings through multiple methods and lines of evidence including statistical inference to explain observed migration patterns using climate or related impacts as independent variables; sample surveys of migrant motivations and behavior; modeling techniques; and historical analogies (McLeman and Hunter, 2010; Piguet, 2010; Warner, 2011; Warner and Afifi, 2013; Oswald-Spring, 2013).

Migration in this Chapter is defined in terms of temporal and spatial characteristics: it is a permanent or semi-permanent move by a person of at least one year that involves crossing an administrative, but not necessarily a national, border (Brown and Bean, 2005). Permanent migration as well as temporary and seasonal migration, are prevalent in every part of the world, driven by economic and other imperatives. The most significant contemporary overall trend in migration continues to be major movements of people from rural to urban settlements. The proportion of the global population that is urban has risen from 10 percent in 1900 to over 50 percent in 2009 and is projected to reach 59 percent by 2030 (Grimm *et al*., 2008). Around 80 percent of all migration is presently within countries (UNDP 2009). Existing global migration trends mapped onto ecological zones by de Sherbinin *et al.*

(2012) show that the past four decades have seen out-migration from mountain regions and from drylands. Net migration to coastal zones is estimated as having been over 70 million people in the 1990-2000 census period.

12.4.1.2. Potential Pathways from Climate Change to Migration

Extreme weather events provide the most direct pathway from climate change and migration. It is widely established that extreme weather events displace populations in the short term because of their loss of place of residence or economic disruption. Only a proportion of displacement leads to more permanent migration (Foresight, 2011; Hallegatte, 2012). Much of the literature, such as reviewed in the IPCC SREX report, concludes that an increasing incidence and changing intensity of extreme weather events due to climate change, will lead directly to the risk of increased levels of displacement.

The evidence on displacement as a result of weather-related events suggests that most displaced people attempt to return to their original residence and rebuild as soon as practical. The Pakistan floods of 2010 for example caused primarily localised displacement for large numbers of people across a wide area (Gaurav *et al.*, 2011), rather than longer-distance migration. Structural economic causes of social vulnerability may determine whether temporary displacement turns into permanent migration. In New Orleans, after Hurricane Katrina, for example, economically disadvantaged populations were displaced in the immediate aftermath and most (?) have not returned (Myers *et al.*, 2008; Mutter, 2010). Fussell *et al.* (2010) found that 14 months after the event, African American residents returned more slowly, because they had suffered greater housing damage. Studies conclude that displacement affected human security through affecting housing, economic and health outcomes and that these have perpetuated the initial impact into a chronic syndrome of insecurity (Adams et al., 2009; Hori and Shafer, 2010). Furthermore, there are well-documented gender differences in displacement from extreme events, especially when women lose their social networks or their social capital, and women are often affected by adverse mental health outcomes in situations of displacement (Tunstall *et al.*, 2006; Oswald-Spring, 2008; Hunter and David, 2011).

Therefore, extreme weather events are not necessarily associated with displacement and can also be associated with immobility or in-migration. Changing economic structures can shape the ability of affected populations to cope with extreme weather without being displaced. While the poorest households in Honduras were hardest hit by Hurricane Mitch in 1990 (Glantz and Jamison, 2000; McLeman and Hunter 2010; McSweeney and Coomes, 2011), they were found to be less vulnerable to storms a decade later due to changes in land tenure and better early warning systems (Villagrán, 2011, 2011a). Paul (2005) found that there was little displacement in Bangladesh following floods and that residents perceived an influx of migrants due to the reconstruction.

It is well established in demography that while migration is a common strategy to deal with livelihood risk, movement is costly and disruptive and hence may only be used as an adaptation of last resort (McLeman, 2009). Hurlimann and Dolnicar (2011) showed for eight Australian settlements experiencing long term drought that relocation and migration was perceived to be the least desirable adaptation. Marshall *et al.* (2012) similarly showed that place attachment dominated decision-making and reluctance to undertake relocation of farming communities. Haug (2002) showed that pastoralists displaced due to drought in Sudan in the 1990s attempted to return to their previous settlements after the drought, notwithstanding conflict and other factors. McLeman and Hunter (2010) reviewed historical cases of displacement migration and concluded that non-migration or rapid return significantly outweighs permanent migration following hurricane impacts in the Caribbean, Dust Bowl migration in the 1930s USA, or dry season migration in the West African Sahel.

A further strand of evidence shows social differentiation in access to the resources necessary to migrate influences migration outcomes (Renaud *et al*., 2011; Black *et al.*, 2013). Vulnerability is inversely correlated with mobility, leading to those being most exposed and vulnerable to the impacts of climate change having the least capability to migrate (Figure 12-1). Therefore, climate change risks can be significant when they reduce and constrain opportunities to move (Black *et al.*, 2013). Alternatively, the most vulnerable households are able to use migration to cope with environmental stress, but their migration is an emergency response that creates conditions of debt and increased vulnerability, rather than reducing them (Warner and Afifi, 2013). Table 12-3 summarises studies on the migration outcomes of weather extremes and long-term environmental change. It shows that some events lead to increased displacement of populations; while others lead to reduce mobility. Table 12-3 also demonstrates that, in many circumstances, members of a population will display differentiated migration outcomes on the basis of ethnicity, wealth or gender (Elliot and Pais, 2006; Gray and Mueller, 2012; Upton, 2012).

[INSERT FIGURE 12-1 HERE
Figure 12-1: Relationship between vulnerability to environmental change and mobility showing that populations most exposed and vulnerable to the impacts of climate change may have least ability to migrate. Source: Adapted from Black *et al.*, 2013.]

There is some evidence that climate changes, through impacts on productivity, can lead to reductions in migration flows. Studies in Table 12-3 highlight that some longer distance migration is reduced by drought in pastoral systems (Findley, 1994; van der Geest, 2011; Sánchez *et al.*, 2012). Drought was also found to reduce migration in other systems. Henry *et al.* (2004) confirmed in a multi-year study of Burkina Faso that the movement to other rural areas increased in dry years, but long distance or international migration was limited to years of high agricultural productivity. Pioneer migration to urban centres, long distance migration and international migration require significant human and financial capital and hence is restricted to wealthier populations or to time periods where the household has sufficient resources. However, in some contexts drought can lead to increased migration – often short term and short distance migration. Kniveton *et al.* (2011, 2012) modeled migration movements from the 1980s in Burkina Faso and project that future scenarios of decreased rainfall would increase rates of out-migration from rural areas.

[INSERT TABLE 12-3 HERE
Table 12-3: Empirical evidence on observed or projected mobility outcomes (migration, immobility, or displacement) associated with weather-related extremes or impacts of longer-term climate change.]

Whether or not negative environmental change influences the decision to migrate; migrant populations may be exposed to more hazardous climatic conditions in their new destinations (Black *et al.*, 2011a). There is some evidence that new migrants are more at risk in destination areas such as cities. Low-income migrants, as well as being socially excluded, cluster in high-density areas that are often highly exposed to flooding and landslides, with these risks increasing with climate change (Chatterjee, 2010; Fox and Beall, 2012; McMichael *et al.*, 2012). Migrants in Buenos Aires, Lagos, Mumbai and Dakar (Chatterjee, 2010; World Bank, 2010; Mehrotra *et al.*, 2011) more often live in hazardous locations than long-term residents. In Dakar, 40 percent of new migrants in the decade till 2008 resided in areas with high flood risk. Wang *et al.* (2012) found that migrants had less knowledge about typhoon risks in Shanghai. Tompkins *et al.* (2009) showed that new migrants in the Cayman Islands are most vulnerable to tropical cyclones as they are least likely to prepare for cyclones, live in locations with high exposure to cyclone impacts, and interact mostly with expatriates without previous cyclone experience. There is no established evidence that rapid urbanization itself is a source of conflict: Buhaug and Urdal (2013) test hypotheses on social disorder and population growth in 55 cities in Africa and find that rapid growth of city populations does not drive urban unrest.

12.4.1.3. Migration Trends and Long-Term Climate Change

Long-term environmental change, sea-level rise, coastal erosion, and loss of agricultural productivity (Table 12-3) will have a significant impact on migration flows (Lilleor and Van den Broeck, 2011). The evidence in this area comes from simulation studies of future migration flows and permanent displacement. Barbieri *et al.* (2010) estimated emigration rates in Brazil from affected rural areas and found that de-population occurs with relatively modest rates of warming. In their scenarios the biggest increase in migration comes from productive agricultural areas that support a large labour force. Mendelsohn *et al.* (2007) concluded that in dryland Brazil urban migration is *very likely* due to agricultural income loss.

Longer term environmental change caused by climate change also amplifies existing trends such as rural to urban migration, though results diverge on the importance of climate change and resource scarcity in driving such trends. Modelling studies with future projections on Mexico-US migration rates (Feng *et al.*, 2009), and on Brazilian internal migration (Barbieri *et al.*, 2011) show that projections of drying increase emigration in established migration routes and de-population of rural areas (Oswald-Spring *et al.*, 2013). Barrios *et al.* (2006) showed that observed rainfall declines in areas of sub-Saharan Africa explain part of the differences in urbanization rates across countries, with periods of rainfall decline increasing urbanization in sub-Saharan Africa, but the urbanization is also explained by simultaneous economic liberalization and policy change.

Sea level changes have been projected to lead to permanent displacements as coastal areas become uninhabitable. Curtis and Schneider (2011), for example, project 12 million people to be displaced by sea-level rise by 2030 in four major coastal areas in the US. Nicholls *et al.* (2011) estimate permanent displacements based on potential sea-level changes till 2100 (see Chapter 5.5.7). A 0.5m sea-level change implies a *likely* land loss of 0.877 million km^2 by 2100, displacing 72 million people, with no adaptation investment; with a 2.0 m sea- level change, 1.789 million km^2 would be lost, displacing 187 million people, or 2.4 percent of global population, mostly in Asia. If governments undertook adaptation investments in all coasts (e.g. building protective dikes), then the study suggests very low levels of people displaced under the 0.5 m scenario and a population of less than half a million displacement under the 2.0 m sea level rise scenario. Hallegatte *et al.* (2011) and Seto (2011) show that such protection measures are *very likely* as the cost of not investing in protecting urban land and infrastructure is much greater, especially for major urban centres.

Even in areas under threat from long-term climate change and sea-level rise, observations show that populations at risk do not always choose to migrate. For example, a series of studies have sought to explain population stability in low-lying island nations. Mortreux and Barnett (2009) found that migration from Tuvalu was not driven by perceptions of climate change and that, despite forecasts that the island could become uninhabitable, residents have remained for reasons of culture and identity. Shen and Gemenne (2011) concur that both Tuvalu residents and migrants from Tuvalu did not cite climate change as a reason for the migration that occurs. Similarly, in the Peruvian Andes, Adams and Adger (2013) found that cultural ecosystem services and place attachment shape decisions not to migrate and hence populations persist despite difficult environmental conditions. However, these studies also find that environmental risks directly affect perceptions of well-being, cultural integrity and economic opportunities. They conclude that the impacts of climate change may be a more significant driver of migration in the future.

12.4.2. Migration as an Adaptation to Climate Change Impacts

Migration is a widely used adaptation strategy that reduces risks in highly vulnerable places, as demonstrated by a wide range of studies. Research drawing on experience of migration policy concludes that a greater emphasis on mobility within adaptation policies would be effective when undertaken in a sensitive manner (Bardsley and Hugo, 2010; Barnett and Webber, 2010; Warner, 2010; Gemenne, 2011). This emerging literature shows that migration can be promoted to successfully reduce risk, not least through remittance flows between sending and destination areas (Fox and Beall, 2012; Martin, 2012; Deshingker, 2012). The prospect of migration as an effective adaptation is recognized through its inclusion in the Cancun Accord of the UN Framework Convention on Climate Change (Warner, 2012).

With observed climate changes and projected changes in resource productivity and risks, various governments are engaged in planning to move settlements as part of adaptation strategies (de Sherbinin *et al.*, 2011; Biermann, 2012). Scientific literature on these policies most often portrays resettlement as a failure of adaptation and a policy of last resort (Barnett and Webber, 2010; Fernando *et al.*, 2010; Hugo, 2011). Most practice to date, learning from other resettlement programmes, demonstrates negative social outcomes for those resettled, often analysed as breaches in individual human rights (Bronen, 2011; Johnson, 2012; Arnall, 2013). There are some documented examples of settlements that are already planning for their own relocation, such as five indigenous communities in Alaska that have experienced increased erosion, loss of sea ice cover, and flooding over the past decades (Bronen, 2010). These settlements have undertaken planning for relocation and have received government funding for these processes. Bronen (2010) and Bronen and Chapin (2013) conclude that while the relocations are feasible, there are significant perceptions of cultural loss and related studies report psychological stress and community dislocation (Cunsolo-Wilcox *et al.*, 2012, 2013). The studies argue that legitimacy and success depend on incorporating cultural and psychological factors in the planning processes (Bronen and Chapin, 2013). There is significant resistance to relocation, even where such options are well planned and have robust justifications, as demonstrated by Marino (2012) for relocation in Alaska.

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Box 12-4. Evidence on the Existence of Environmental Migrants and International Policy for their Protection

There is widespread agreement in the scientific and legal literature that the use of the term climate refugee is scientifically and legally problematic (Taccoli, 2009; Piguet, 2010; Black *et al.*, 2011a; Gemenne, 2011; Jakobeit and Methmann 2012; Bettini, 2013; Piguet, 2013). McAdam calls the concept 'erroneous as a matter of law and conceptually inaccurate' (McAdam, 2011, p. 102). The reasons are threefold. First, most migration and climate studies point to the environment as triggers and not causes for migration decisions. Second, some studies focus on the negative geo-political implications of changing the Geneva Convention on refugees to include environmental migrants as well as the lack of global instruments to handle internal displaced peoples or international migrants (Martin, 2009; Cournil, 2011). Third, many small island countries are reluctant themselves to have their international migrants designated as being victims of climate change (McNamara and Gibson, 2009; Farbotko, 2010; Barnett and O'Neill, 2011; Farbotko and Lazrus, 2012).

The arguments put forward for a specific legal instrument to deal with migrants who have been displaced as a direct result of climate change impacts include issues of rights, given such migration is imposed and involuntary (Bates, 2002; Bell, 2004); and the particular status of small island nations where displacement could affect sovereignty (Williams, 2008; Owens, 2008; Biermann and Boas, 2009). For international displacement and migration, there is a growing literature on practical adaptation and action: the existence of governance mechanisms to improve handling of currently displaced people, and the optimal design of such mechanisms in the future (e.g. Bryavan and Rajan, 2006; Williams, 2008; Biermann and Boas, 2009, Docherty and Giannini, 2009; Martin, 2009; McAdam, 2011). This literature focuses on strategies for adaptation, mitigation and resilience building, and concludes that significant adaptation may be required to protect and to empower internally or international migrants triggered by climate change.

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12.5. Climate change and Armed Conflict

12.5.1. Climate Change as a Cause of Conflict

In the past decade there has been a marked increase in research investigating the relationship between climate change and violent and armed conflict. This section assesses of the full spectrum of research using diverse methods and data that seeks to understand the relationship between climate change and armed conflict. Chapter 19 provides a more detailed assessment of those studies that seek to quantify the influence of climate factors on violence of all kinds, including personal violence. Chapter 19 defines the influence of climate facts on violence to be an emergent risk and a new focus of research. In this Chapter, armed conflicts are defined as those conflicts that involve more than 25 battle-related deaths in a year. This can include: interstate conflicts, intrastate conflicts that involve governments, non-state conflicts in which governments are not directly involved, and one-sided conflicts involving organised violence against civilians (Themnér and Wallensteen, 2012).

There is a specific research field that explores the relationship between large-scale disruptions in climate and the collapse of past empires. Relationships are explored using statistical analysis and data derived from archaeological and other historical records. For example, the timing of the collapse of the Khmer empire in the Mekong basin in the early 15th century corresponds to an unusually severe prolonged drought (Buckley *et al.*, 2010). DeMenocal (2001) summarizes evidence that suggests that major changes in weather patterns coincided with the collapse of several previously powerful civilizations, including the Anasazi, the Akkadian, Classic Maya, Mochica, and Tiwanaku empires. Other historical reference points of the interaction of climate with society emerge from analysis of the little

Ice Age. Some studies show that the Little Ice Age in the mid 17th century was associated with more cases of political upheaval and warfare than in any other period (Parker 2008, Zhang *et al.*, 2011), including in Europe (Tol and Wagner 2010), China (Brook 2010), and the Ottoman empire (White 2011b). These studies all show that climate change can exacerbate major political changes given certain social conditions, including a predominance of subsistence producers, conflict over territory, and autocratic systems of government with limited power in peripheral regions. The precise causal pathways that link these changes in climate to changes in civilizations are not well understood due to data limitations. Therefore, it should be noted that these findings from historical antecedents are not directly transferrable to the contemporary globalized world. The literature urges caution in concluding that mean future changes in climate will lead to large-scale political collapse (Butzer 2012).

Most of the research on the connections between climate change and armed conflict focuses on the connections between climate variability and intrastate conflicts in the modern era. For the most, part this research examines rainfall or temperature variability as proxies for the kinds of longer-term chances that might occur due to climate change. Several studies examine the relationship between short-term warming and armed conflict (Burke *et al*., 2009; Buhaug 2010; Koubi *et al*., 2012; Theisen *et al.*, 2012; O'Loughlin *et al.*, 2012). Some of these find a weak relationship, some find no relationship, and collectively the research does not conclude that there is a strong positive relationship between warming and armed conflict (Theisen *et al.,* 2013).

The large majority of studies focuses on Africa and use satellite-enhanced rainfall data collected since 1980. A global study by Hsiang *et al.* (2011) considers changes in climate over multiple years, and finds that since 1950 and in countries that are affected by ENSO the risk of war within countries rises during an ENSO period. This study is supported by some studies that find associations between deviations in rainfall and civil war (Miguel *et al*., 2004; Hendrix and Glaser 2007; Hendrix and Salehyan 2012; Raleigh and Kniveton 2012), but contradicted by others that find no significant association between droughts and floods and civil war (Buhaug 2010; Buhaug and Theisen 2012; Koubi *et al.* 2012; Theisen *et al*. 2012; Slettebak 2012). There is high agreement that in the specific circumstances where other risk factors are extremely low (such as where *per capita* incomes are high, and states are effective and consistent), the impact of changes in climate on armed conflict is negligible (Bernauer *et al.,* 2012; Koubi *et al*., 2012; Scheffran *et al.,* 2012a; Theisen *et al.,* 2013).

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Box 12-5. Climate and the Multiple Causes of Conflict in Darfur

Climate variability or climate change are popularly reported to be significant causes of the mass killing in the Darfur region that began in 2003 (see Mazo, 2009). Five detailed studies dispute the identification of the Darfur conflict as being primarily caused by climate change (Kevane and Gray, 2008; Brown, 2010; Hagen and Kaiser, 2011; Sunga, 2011; Verhoeven, 2011). They find that the violence in Darfur has multiple causes, notably:

- The legacy of past violence, which established groups that had a history of violent action and a supply of weapons;
- Manipulation of ethnic divisions by elites in Khartoum;
- Weakening of traditional conflict resolution mechanisms through government policies and as a consequence of famines;
- Systematic exclusion of local groups from political processes, including of the Fur, Masalit and Zaghawa ethnic groups;
- Limited economic development and inadequate provision of public services and social protection, stemming from governance and policy failures, political instability, and misuse of official development assistance.

All studies of this conflict agree that it is not possible to isolate any of these specific causes as being most influential (Kevane and Gray, 2008; Hagen and Kaiser, 2011; Sunga, 2011; Verhoeven, 2011). Most authors identify government practices as being far more influential drivers than climate variability, noting also that similar changes in climate did not stimulate conflicts of the same magnitude in neighboring regions, and that in the past people in Darfur were able to cope with climate variability in ways that avoided large scale violence.

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A growing body of research examines the connections between climate variability and non-state conflicts. There is some agreement that either increased rainfall and decreased rainfall in resource-dependent economies enhances the risk of localized violent conflict, particularly in pastoral societies in Africa (Benjaminsen and Ba, 2009; Benjaminsen *et al.*, 2009; Adano et al., 2012; Butler and Gates, 2012; Fjelde and von Uexkull, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012). In all such cases, the presence of institutions that are able to peacefully manage conflict are highlighted as the critical factors in mediating such risks (Gausset, 2005; Hidalgo *et al.*, 2010; Adano *et al.*, 2012; Benjaminsen *et al.*, 2012, Butler and Gates, 2012, O'Loughlin *et al.*, 2012, Theisen, 2012).

In response to the challenges of finding direct associations between changes in climate and violence, some research has examined the effects of changes in climate on factors that are known to increase the risk of civil war (Bergholt and Lujala, 2012, Koubi *et al.*, 2012). Civil war has been studied extensively using quantitative and qualitative techniques, and there is high agreement about factors that increase the risk of civil war, namely: a recent history of civil violence, low levels of *per capita* income, low rates of economic growth, economic shocks, inconsistent political institutions, and the existence of conflict in neighboring countries (Miguel *et al*.,2004, Weede, 2004; Hegre and Sambanis, 2006; Dixon, 2009; Blattman and Miguel, 2010; Brückner and Ciccone, 2010). Nevertheless, almost all studies note the need for convincing theories that explain these associations.

Many of the factors that increase the risk of civil war and other armed conflicts are sensitive to climate change. For example, Chapter 10 shows that climate change will slow rates of economic growth and impede efforts to grow *per capita* incomes in some low income countries, particularly in Africa where the risk of conflict is highest (Mendelsohn *et al.*, 2000, Mendelsohn *et al.*, 2006, Stern, 2007, Eboli *et al*., 2010). Extreme events, which may become more intense due to climate change, can also produce economic shocks (Bergholt and Lujala, 2012; Hallegatte, 2012; Adam, 2013), although the direct association between disasters and armed conflict is contested (Pelling and Dill, 2010; Bergholt and Lujala, 2012; Slettebak, 2012). Studies have inferred that climate change can undermine the consistency of institutions that provide public goods (Barnett and Adger, 2007; Scheffran *et al*., 2012b) and hence weaken states and increase conflict risks. However, there is some evidence that under certain circumstances, disasters can provide critical opportunities to build peace in conflict settings and to improve governance institutions (Kingsbury, 2007; Olson and Gawronski, 2010; Bruckner and Ciccone, 2011).

In summary, there is justifiable common concern that climate change or changes in climate variability increases the risk of armed conflict in certain circumstances (Bernauer *et al.*, 2012; Gleditsch, 2012; Scheffran *et al.*, 2012; Hsiang *et al*., 2013), even if the strength of the effect is uncertain. This concern is justified given robust knowledge of the factors that increase the risk of civil wars, and medium evidence that some of these factors are sensitive to climate change. There is also general agreement in the literature that there is a need for theories and data that explain the processes that lead from changes in climate to violence; for example on how formal and informal institutions that help avoid violent outcomes (Barnett and Adger, 2007; Scheffran and Battaglini, 2011; Buhaug and Theisen, 2012, Gleditsch, 2012; Murtinho and Hayes, 2012). Confident statements about the effects of future changes in climate on armed conflict are not possible given the absence of generally supported theories and evidence about causality (see Box 12-5).

12.5.2. Conflict and Insecurity Associated with Climate Policy Responses

Research is beginning to show that climate change mitigation and adaptation actions can increase the risk of armed conflict, as well as compound vulnerabilities in certain populations (Bumpus and Liverman, 2008; Adger and Barnett, 2009; Webersik, 2010; Fairhead *et al.*, 2012; Marino and Ribot, 2012; Steinbruner *et al*., 2012). This is based on robust evidence that violent political struggles occur over the distribution of benefits from natural resources (Peluso and Watts, 2001). Hence, in circumstances where property rights and conflict management institutions are ineffective or illegitimate, efforts to mitigate or adapt to climate change that change the distribution of access to resources have the potential to create and aggravate conflict.

Actions taken in response to climate change can aggravate existing significant inequalities or grievances over resources (Marino and Ribot, 2012), limit access to land and other resources required to maintain livelihoods, or otherwise undermine critical aspects of human security (Bumpus and Liverman, 2008, Fairhead *et al.*, 2012). Maladaptation or greenhouse gas mitigation efforts at odds with local priorities and property rights may increase the risk of conflict in populations, particularly where institutions governing access to property are weak, or favour one group over another (Barnett and O'Neill, 2010; Butler and Gates, 2012, McEvoy and Wilder, 2012). Research on the rapid expansion of biofuels production includes studies connecting land grabbing, land dispossession, and social conflict (Molony and Smith, 2010; Borras *et al.*, 2010; Dauverge and Neville, 2010; Vermeulen and Cotula, 2010). One study has identified possible links between increased biofuels production, food price spikes, and social instability such as riots (Johnstone and Mazo, 2011).

The provision of financial resources in payment for ecosystem services projects, such as are associated with Reduced Emissions from Deforestation and Forest Degradation (REDD), has the potential to stimulate conflict over resources and property rights (Melick, 2010). For example, efforts to ensure 'REDD readiness' in Tanzania (Beymer-Farris and Bassett, 2012; 2013; Burgess *et al*., 2013) and the Congo basin (Brown *et al.*, 2011) have been contested, and placed communities in conflict with conservationists and governments. Eriksen and Lind (2009) similarly find that climate change adaptation interventions in Kenya have aggravated surrounding conflicts.

Climate change mitigation will increase demand for deployment of less carbon-intensive forms of energy, including hydropower some of which have historically resulted in social conflict and human insecurity (for example because of forced resettlement), and this is a basis for concern about increased violence and insecurity in the future (Conca, 2005; McDonald-Wilmsen *et al*., 2010; Sherbinin *et al.*, 2011). Other research points to an increased use of nuclear power increasing the threat of nuclear proliferation or incidents of nuclear terrorism (Socolow and Glaser, 2009, Steinbruner *et al*., 2012). Climate policy responses also have the potential to reduce conflict in various ways, as explained further in Section 12.5.4.

12.5.3. Violent Conflict and Vulnerability to Climate Change

Many of the capacities required to adapt to climate change are threatened by ongoing or recent armed conflict (Barnett, 2006, Brklacich *et al.*, 2010). There is a strong body of evidence from development studies and political science that violent conflict undermines human security and the capacity of individuals, communities and states to cope with changes (Stewart and Fitzgerald, 2001; Blattman and Miguel, 2010). These observations suggest, with *high confidence,* that where violent conflict emerges and persists the capacity to adapt to climate change is reduced for affected populations. This is illustrated in Figure 12-2 shows that post-conflict societies have low adaptive capacity, where human development acts as a proxy for its status (Barnett, 2006; Lind and Eriksen, 2006; Eriksen and Lind, 2009; Adger, 2010).

[INSERT FIGURE 12-2 HERE
Figure 12-2: Conflict and post-conflict societies exhibit low levels of governance and human development. Data based on UNDP Human Development Index and World Bank index on Governance effectiveness. Source: Adapted from Adger, 2010.]

Armed conflict disrupts markets and destroys infrastructure, limits education and the development of human capital, causes death and injury to workers, and decreases the ability of individuals, communities and the state to secure credit (Stewart *et al.*, 2001; Goodhand, 2003; Blattman and Miguel, 2010). Conflict thus creates poverty and constrains livelihoods: that in turn increases vulnerability to the impacts of climate change (Nigel, 2009; Deng, 2010a, Hilson and van Bockstael, 2011). Thus, violent conflict is a major cause of hunger and famines (de Waal, 1993, Messer and Cohen, 2011, Rowhani *et al.*, 2011). Armed conflict interrupts the ability of resource dependent individuals and communities to access natural resources (Pike, 2004; Detraz, 2009; Kolmannskog, 2010; Raleigh, 2011), and in so doing limits their capacity to adapt to climate change. The denial of strategic space as a tactic in armed conflict (through for example, deliberate destruction of crops and spreading of landmines in conflict affected regions) can reduce the capacity of individuals and communities to access natural capital and hence cope with climate variability (Berhe, 2007; Unruh, 2011).

A parallel body of research documents spiraling negative feedbacks where armed conflict reduces access to ecosystem goods and services, that can lead to inefficient use of natural resources and hence to further environmental degradation. Chronic political instability in Zimbabwe, is, for example, implicated in high levels of illegal bush meat hunting (Lindsey *et al.,* 2011). Conflict, and the displacement of large populations, can also alter the abundance and distribution of biodiversity and can result in significant deforestation (Chase and Griffin, 2011; Lindsell *et al.*, 2011; Stevens *et al.*, 2011).

The capacity for collective action is a critical determinant of the capacity to adapt to climate impacts, and this too can be undermined by violent conflict, depending on the nature of violence and the strategies households adapt in response (Deng, 2008, 2010b). When conflict exacerbates existing horizontal inequalities between ethnic or religious groups, foments distrust in local or government institutions, or isolates individuals and households, the social capital that is important for adapting to climate change is also degraded (Bogale and Korf, 2007). Conflict-related displacement also disrupts social networks and makes it difficult to achieve elements of secure livelihoods, such as marriage, access to land, or access to communal social safety nets (Kolmannskog, 2010; Raleigh, 2011). In situations of violent conflict, efforts to address climate change that provide financial or resource flows that can be captured by local elites or illegitimate institutions, may compound divisions and exacerbate grievances (Brown *et al.,* 2011; Verhoeven, 2011).

Armed conflict can decrease the capacity of governments to function effectively, which in turn impedes adaptation (Tignino, 2011; Feitelson *et al.,* 2012). For example, research has shown that chronic political conflict has reduced the ability of governance institutions at many scales to effectively manage water resources in the Gaza Strip (Shomar, 2011), parts of the Balkans (Skoulikidis, 2009), and the Middle East (Zeitoun *et al*., 2012). Instability has affected planning process around urban land use in Palestine (Raddad *et a*l., 2010) and in regions of Iraq (Hassan, 2010). Armed conflict may also undermine the ability of states to prevent and respond to natural disasters and humanitarian crisis (Keen, 2008). A lack of trust in government commitment or capacity to respond, the presence of police or military forces that lack legitimacy, or recent conflict between government and local forces, hampers the ability of these institutions to provide effective relief (Wisner, 2001).

12.5.4. Peace-Building Activities in Promoting Adaptation

In situations where conflict is resources based, it is widely established that resource management has significant potential to contribute to conflict management by channeling competing interests over resources into non-violent resolutions (Conca and Dabelko, 2002; Conca and Wallace, 2009; Lujala and Rustad, 2011; Jensen and Lonergan, 2013). This research on environmental peacebuilding and peacemaking considers that natural resource management, and by extension climate change adaptation, can help build peace to avoid conflicts, and broker peace in conflict situations (Tanzler *et al*., 2010).

Research on bilateral and multilateral interactions between two or more states from 1948 to 2008 shows strong evidence of significant formal cooperation among river basin riparian states, and no cases of water causing two states to engage in war (Wolf *et al.,* 2003; Wolf, 2007; De Stefano *et al.,* 2010). Transboundary water cooperation, particularly joint management, flood control, and technical cooperation, can form a basis for longer-term cooperation on a range of contentious issues. Efforts at basin-wide institutional development to lower conflict potential focuses on moving from the assertion of conflicting rights to water; to addressing the multiple values of water; and ultimately to sharing benefits across national boundaries (Sadoff and Grey, 2002).

There is an emerging body of evidence about the effectiveness of efforts to enhance cooperation and lower conflict around natural resources (Lujala and Rustad, 2011; Jensen and Lonergan, 2013). Some transboundary conservation areas, referred to as 'peace parks', are designed to reduce conflict and enhance cooperation across borders. The evidence of the effectiveness of peace parks is limited and ambiguous, with some studies documenting political, economic and conservation cooperation (Ali and Marton-LaFevre, 2007), but others document conflict generation between local communities, elites, and states (Duffy, 2002).

12.6. State Integrity and Geopolitical Rivalry

Climate change will affect the integrity of states through impacts on critical infrastructure, threats to territorial integrity, and geopolitical rivalry (Gilman *et al.*, 2011). These infrastructure and geopolitical impacts directly affect state capacities to provide a range of ecological, economic, social, and political services that fundamentally contribute to human security (Barnett, 2003; Busby, 2008; Barnett *et al*., 2010; Webersik, 2010).

12.6.1. Critical Infrastructure and State Capacity

Climate change and extreme events are projected to damage a range of critical infrastructure, with water and sanitation, energy, and transportation infrastructure being particularly vulnerable (Chapter 8.2.4; Rozenzweig *et al.*, 2011; UN Habitat, 2011). Climate change is expected to exacerbate water supply problems in some urban areas that in turn pose multiple risks to cities. For example the high temperature and low rainfall events that can cause a decline in the supply of water to cool power plants are those that simultaneously increase energy demand for cooling, threatening to disrupt power supply and information and communications technology. In areas where there may be flooding or increased snow and ice storms, critical infrastructure may be damaged (see Chapter 8.2.3). Areas that are vulnerable to flooding, landslides or forest fires will have greater risk of such infrastructure damage (Revi, 2005; Awuor *et al*., 2008; Adelekan, 2010; Keywood *et al*, 2013).

Climate change impacts on critical infrastructure will reduce the ability of some states to provide social and public services (see Chapter 8.2.4.6). For example, power outages stemming from water shortages or storms can in turn lead to reductions in service delivery from hospitals, police forces and emergency responders. Damage to roads, rails, airports, bridges and related transport infrastructure can similarly reduce the ability of governments to provide for citizen needs. The impact of thawing permafrost on infrastructure will affect the viability of settlements in high latitudes (Chapter 28.2.4.2; Chapter 28.3.4.3; Larsen *et al*., 2008; Marino, 2012; Dersken *et al*., 2012). In countries that are poor or that depend heavily on climate-sensitive activities such as agriculture, climate impacts are expected to lead to significant declines in income and in turn government revenues. Mideksa (2010) estimates that climate change impacts will reduce Ethiopia’s GDP by nearly ten percent.

12.6.2. Geopolitical Issues

Analysis of the actions of states and security institutions show that many states view current and anticipated climate changes as contributing to geopolitical concerns (Dabelko, 2009; Smith, 2011). The ability of states to share resources and provide human security is challenged by climate change impacts. Climate change impacts can create contested claims to territory on land and at sea and, in extreme cases, can threaten the territorial integrity or viability of states (Barnett and Campbell, 2010; Houghton *et al*., 2010; Yamamoto and Esteban, 2010).

For small island states and countries with significant areas of soft low-lying coasts (Hanson *et al*., 2011), sea-level rise and extreme events threaten to erode and subsume significant land areas and associated infrastructure and settlements, in the absence of significant adaptation (Chapter 5.4.3.2; Nicholls *et al*., 2011). For countries made up entirely of low-lying atolls, sea-level rise, ocean acidification, and increases in episodes of extreme sea-surface temperatures, compromise human security for existing or larger numbers of people (Barnett and Campbell, 2010, Fisher, 2011). With projected high levels of sea-level rise beyond the end of this century, the physical integrity of low-lying islands is under threat (Chapter 29.3, Barnett and Adger, 2003; Houghton *et al*., 2010). The opening of resources, such as the social, economic, and political dimensions of loss of sea ice in the Arctic (Chapter 28.2.5), represents an example of climate change impacts being geopolitically significant to states, even in the absence of direct conflict (Box 12-6). Expected sea level rise and resulting coastline changes may affect the location of Exclusive Economic Zones and contribute to conflicts over natural resources or boundary locations (Houghton *et al*., 2010).

Productive ocean fisheries are already directly affected by climate change, altering the range of important commercial fish stocks (MacNeil *et al*., 2010). Fishing, as an economic activity, is adapted to highly variable environmental and management conditions; however, the movement of fish stocks (See Chapter 6.3.2) (Berkes *et al*., 2006) has been suggested to increase transboundary rivalry (MacNeil *et al*., 2010). For example, northward shifts of mackerel, herring and capelin stocks are creating economic and geopolitical tension (Sumaila *et al*., 2011).

_____ START BOX 12-6 HERE _____

Box 12-6. Evidence on Security and Geopolitical Dimensions of Climate Change Impacts in the Arctic

Impacts of climate change on the Arctic region exemplify the multiple interactions of human security with geopolitical risks. System-wide changes in the Arctic region affect multiple countries and a global commons resource given Arctic roles in regulating the global climate and ocean systems (Carmack *et al*., 2012; Duarte *et al*., 2012). Anticipated changes will contribute to greater geopolitical considerations and human insecurity in the Arctic region. They include: food insecurity affecting specific cultures and knowledge systems (outlined in Section 3); energy security implications through opening of sub-sea oil and gas reserves; increased shipping; increased pollution; search and rescue challenges and increased military presence in the region.

The Arctic has been warming at about twice the global rate since 1980, resulting in unprecedented loss in sea ice. The Arctic Ocean is projected to experience major reductions in sea ice, and under some projections would be ice-free by the end of the century (Chapter 28.1; WG1 SPM E5 medium confidence). These changes have implications for land based infrastructure, shipping, resource extraction, coastal communities, and transport (Holland *et al*., 2006; Larsen *et al*., 2008; Stephenson *et al*., 2011; Chapter 28.3.4). There is medium evidence that changes will create or revive terrestrial and maritime boundary disputes among Arctic countries (Borgerson, 2008; Ebinger and Zambetakis, 2009; Lusthaus, 2010). There is little evidence the changing Arctic will become a site for violent conflict between states (Young, 2009; Berkman, 2010; Brosnan *et al*., 2011). At present, political institutions are providing forums for managing resource competition, new transportation practices, and boundary disputes but anticipated increased stresses will test these institutions in the future (Ebinger and Zambetakis, 2009).

_____ END BOX 12-6 HERE _____

The impacts of climate-induced water variability on transboundary water basins constitute a cluster of geopolitical concerns. The high levels of international interdependence on transboundary rivers such as the Nile, Limpopo, Amu Darya, Syr Darya, Mekong, Ganges, Brahmaputra, Tigris, Euphrates, and Indus connect the conditions of the rivers with national development trajectories. Climate change is expected to disrupt the dynamics of runoff (*high agreement, robust evidence*, see Chapter 3.4.5). Warming, for example, will bring forward the snow melt season in all but the coldest regions, altering seasonal water flows (See Chapter 3.4.5). Such projects have led to concerns over transboundary tensions, particularly where challenges stemming from rising consumption and growing populations are already present (Swain, 2012; National Research Council, 2012).

Research on transboundary conflict and cooperation prioritizes rate of change rather than absolute scarcity in connection with the risk of conflict over water, particularly between states (De Stefano *et al*., 2012). This focus stems from higher perceived risk of conflict when institutions at local, state, and regional levels have less time to adapt to scarcity or variability by dealing with disputes through diplomatic and other non-violent mechanisms (Wolf *et al*., 2003; Wolf, 2007; De Stefano *et al*., 2010; De Stefano *et al*., 2012). Sudden changes in flow that heighten risk and challenge institutional responses include declines in seasonal snow or glacial melt. Transboundary basin institutions and international legal mechanisms have demonstrated an ability to manage conflict effectively (Sadoff and Grey, 2002; Wolf, 2007; Dellapenna and Gupta 2009; Brochmann and Hensel, 2009; Goulden *et al*., 2010; Dinar *et al.*, 2011; Tir and Stinnett, 2012; Bernauer and Siegfried, 2012; Feitelson *et al.*, 2012; Gartzke, 2012). Other research emphasizes that these transboundary water institutions receive limited financial and political investment, involve unequal or inequitable cooperation between powerful and less powerful countries, and are present in only a limited number of transboundary basins (Conca *et al*., 2006; Zeitoun and Warner, 2006; Zeitoun and Mirumachi, 2008).

Geoengineering that involves deliberate large-scale manipulation of the environment aimed at reducing negative climate change impacts (Chapter 20.3), remains an unproven strategy to address climate change. The high levels of uncertainty and high likelihood of differential geographic impacts of geoengineering are anticipated sources of tension or conflict between states (Robock, 2008; Preston, 2013; Dalby, 2013). These include regional effects of solar radiation management on reduced precipitation in specific areas in Asia or in the Sahel (Ricke *et al*., 2011; Haywood *et al*., 2013) with negative food production implications. The ability of states to deploy geoengineering unilaterally under limited international legal mechanisms creates the potential for conflict. Examples of security institutions attempting weather modification present the prospect of military involvement in deploying or interdicting geoengineering efforts (Fleming, 2010). The prospect for the securitization of geoengineering responses is contested: geoengineering technologies could be used for hostile purposes but the significance of this possibility is contested (Keith, 2000; Robock, 2008; Corner and Pidgeon, 2010; Brzoska, 2012).

12.7. Synthesis

This Chapter shows that climate change and climate variability pose risks to various dimensions of human security, which arise through diverse causal processes, and which will be manifest at different scales. There is *high agreement* in the literature for this conclusion that comes from multiple lines of evidence. There are, however, multiple and competing perspectives on the nature and causes of insecurity arising from climate change (Barnett, 2010). For example, farmers in the Sahel are concerned about the risks weather extremes pose to their livelihoods (Mertz *et al*., 2009), whereas people in Tuvalu report that the cultural impacts of migration are a primary concern rather than climate change directly (Mortreux and Barnett, 2009). Organisations whose mandates include aspects of human security prioritise some risks of climate change over others. For example the International Organization for Migration is concerned with the implications of climate change for migration, and the United States National Intelligence Council is focused on the risk that climate change will increase political instability and geopolitical rivalry. In this respect the framing of climate change as an issue of human security enables conversations across the boundaries of diverse policy communities (Gasper, 2010).

The risks that climate change poses to human security, arise through multiple and interacting processes. Those processes also operate across diverse spatial and temporal scales. High levels of complexity mean that no conceptual model or theory captures the full extent of the interactions between all of climate change, livelihoods, culture, migration, and violent conflict. However, as this Chapter has shown, there are feedbacks between the key elements of livelihoods, culture, migration, and violent conflict. Figure 12-3 depicts interactions between the primary elements discussed in this Chapter. Deterioration in livelihoods, influenced in certain cases by climate change and climate variability, is a human security issue in its own right. But such stress to livelihoods also gives rise to migration, which may be unavoidable and undesirable. Such movements, in turn, imply changes in important cultural expressions and practices, and, in the absence of institutions to manage the settlement and integration of migrants in destination areas, can increase the risk of violent conflict. This conflict can in turn undermine livelihoods, impel migration, and weaken valued cultural expressions and practices. The evidence in the Sections above shows that some interventions and policies enhance human security, while others inadvertently can exacerbate insecurity (depicted in red and blue arrows in Figure 12-3).

[INSERT FIGURE 12-3 HERE
Figure 12-3: Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies indicated by difference between initial conditions (solid black) and outcome of intervention (white circles). Some interventions (blue arrows) show net increase human security while others (red arrows) lead to net decrease in human security.]

Each dimension of human security examined in this Chapter demonstrates the potential for adaptation to minimize risks to human security. Again there is high agreement on this finding, reflected in Table 12-4, with multiple lines of evidence from food security, to migration, to conflict resolution. This Chapter suggests that often institutions anticipate and react to these risks to human security (Barnett *et al*., 2010; Ribot, 2011; Artur and Hilhorst, 2012). These institutional responses can significantly dampen or amplify the way changes in climate change and extreme events give rise to human insecurity. Table 12-4 summarises a number of example risks to human security, with the final column demonstrating that these risks can be ameliorated through adaptation for many of those examples. In general, higher levels of climate change impacts become less amenable to adaptation.

[INSERT TABLE 12-4 HERE
Table 12-4: Examples of important risks from climate change for elements of human security and the potential for risk reduction through mitigation and adaptation. These risks are identified based on this Chapter assessment and expert judgments of the authors, with supporting evaluation of evidence and agreement in the relevant chapter sections. Each risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by symbols. As the assessment considers potential impacts on diverse and incompatible elements and systems, risk levels should not be used to evaluate relative risk between the rows.]

Adaptation and mitigation strategies and interventions can also affect human insecurity in positive and negative directions. There is evidence that adaptation and mitigation strategies that are imposed on communities are more likely to impact negatively on human security than those that are consistent with their capabilities and values (*medium agreement, limited evidence*) (Ensor and Berger, 2009; Barnett and O'Neill, 2011, Marino, 2012, Mercer *et al*., 2012). Adaptation strategies that seek to reduce exposure to climate change, through the development of large infrastructure or the resettlement of communities against their will, carry risks of disrupted livelihoods, displaced populations, deterioration of valued cultural expressions and practices, and in some cases violent conflict (Table 12-4). Similarly, mitigation policies that entail changes in property regimes that are not consistent with resource ownership and use can impact negatively on human security. There is strong evidence to demonstrate that mitigation activities that align with local interests and institutions can have significant co-benefits for human security, especially through human health (Klein et al., 2005; Ayers and Huq, 2009; Laukkonen *et al.*, 2009; Haines *et al.*, 2009; Moser 2012; West *et al.*, 2013).

In summary, climate change is one of many risks to the vital core of material well-being and culturally specific elements of human security that vary depending on location and circumstance. For regions where human insecurity is prevalent, these additional factors include poverty, discrimination, and inadequate provision of public services and public health, and opportunities for education. Investments in institutional responses to facilitate adaptation can dampen many of the potential adverse effects of climate change on human security (see Figure 12-3). Conversely, inappropriate climate policy responses may accelerate and amplify human insecurity including conflict.

There is much uncertainty about the future impacts of climate change on human security, as defined in this Chapter around the vital core of well-being and non-material elements. On the basis of current evidence about the observed impacts of climate change on environmental conditions, climate change will be an increasingly important driver of human insecurity in the future (see Figure 12-3).

At very high levels of projected warming, all aspects of human security discussed in this Chapter will be adversely affected (for example in high latitude regions - Box 12-6). At high levels of warming, the rate of changes in environmental conditions in most places will be without any precedent in human history (New *et al.*, 2011). Hence analysis concerning human security in those circumstances of very high impacts (as depicted in Table 12-4) is uncertain. Much of the current literature on human security and climate change is informed by contemporary relationships and observation and hence is limited in analyzing the human security implications of rapid or severe climate change.

Frequently Asked Questions

FAQ 12.1: What are the principal threats to human security from climate change?
[to be placed in Section 12.1.2]
Climate change threatens human security because it undermines livelihoods, compromises culture and individual identity, increases migration that people would rather have avoided, and because it can undermine the ability of states to provide the conditions necessary for human security. Changes in climate may influence some or all of the factors at the same time. Situations of acute insecurity, such as famine, conflict, and sociopolitical instability, almost always emerge from the interaction of multiple factors. For many populations that are already socially marginalized, resource dependent, and have limited capital assets, human security will be progressively undermined as the climate changes.

FAQ 12.2: Can lay knowledge of environmental risks help adaptation to climate change?
[to be placed in Section 12.3.4]
Lay knowledge about the environment and climate is deeply rooted in history, and encompasses important aspects of human life. This characteristic is particularly pertinent in cultures with an intimate relationship between people and the environment. For many indigenous and rural communities, for example, livelihood activities such as herding, hunting, fishing or farming are directly connected to and dependent on climate and weather conditions. These communities thus have critical knowledge about dealing with environment changes and associated societal conditions. In regions around the world, such knowledge is commonly used in adapting to environmental conditions and is directly relevant to adaptation to climate change.

FAQ 12.3: How many people could be displaced as a result of climate change? *[to be placed in Section 12.4.1.3]*
Displacement is the movement of people from their place of residence, and can occur when extreme weather events, such as flood and drought, make areas temporarily uninhabitable. Major extreme weather events have in the past led to significant population displacement, and changes in the incidence of extreme events will amplify the challenges and risks of such displacement. Many vulnerable groups do not have the resources to be able to migrate from areas exposed to the risks from extreme events. There are no robust global estimates of future displacement, but there is significant evidence that planning and increased mobility can reduce the human security costs of displacement from extreme weather events. Climate changes in rural areas could amplify migration to urban centres. However, environmental conditions and altered ecosystem services are few among the many reasons why people migrate. So while climate change impacts will play a role in these decisions in the future, given the complex motivations for all migration decisions, it is difficult to categorize any individual as a climate migrant [12.4].

FAQ 12.4: What role does migration play in adaptation to climate change, particularly in vulnerable regions?
[to be placed in Section 12.4.2]
Moving from one place to another is a fundamental way humans respond to challenging conditions. Migration patterns everywhere are primarily driven by economic factors: the dominant migration system in the world has been movement from rural to urban areas within countries as people seek more favorable work and living conditions.

FAQ 12.5: Will climate change cause war between countries? *[to be placed in Section 12.5.1]*
Climate change has the potential to increase rivalry between countries over shared resources. For example, there is concern about rivalry over changing access to the resources in the Arctic and in transboundary river basins. Climate changes represent a challenge to the effectiveness of the diverse institutions that manage relations over these resources. However, there is high scientific agreement that this increased rivalry is unlikely to lead directly to warfare between states. The evidence to date shows that the nature of resources such as transboundary water and a range of conflict resolution institutions have been able to avert rivalries in ways that avoid violent conflict.

Cross-Chapter Boxes

Box CC-GC. Gender and Climate Change

[Jon Barnett (Australia), Marta G. Rivera Ferre (Spain), Petra Tschakert (U.S.A.), Katharine Vincent (South Africa), Alistair Woodward (New Zealand)]

Gender, along with socio-demographic factors of age, wealth and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger *et al.*, 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer *et al.*, 2007; Nightingale, 2009; Buechler, 2009; Nelson and Stathers, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resureccion, 2011; Omolo, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labour markets, making women in particular less able to cope with and adapt to climate change impacts (Rijkers and Costa, 2012; Djoudi and Brockhaus, 2011; Paavola, 2008). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whilst both men and women experience increases in productive roles, only women experience increased reproductive roles (Resureccion, 2011; 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income, and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity since food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota *et al.*, 2011).

AR4 assessed a body of literature that focused on women's relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger *et al.*, 2007). Additional literature published since that time adds nuances by showing how socially-constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*) [11.3.3, Table 12-3]. Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981-2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007) [Box 13-1]. Reasons for gendered differences in mortality include various socially- and culturally-determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house, even during floods and in risk-prone areas (Bradshaw, 2010). While the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality [Box 13-1]. In Hai Lang district, Vietnam, for example, more men died than women due to their involvement in search and rescue and protection of fields during flooding (Campbell *et al.*, 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the U.S. and Australia (Jenkins and Phillips, 2008; Anastario *et al.*, 2009; Alston, 2011; Whittenbury, 2013; Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and Sao Paulo (Bell *et al.*, 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Figueiredo and Perkins, 2012; Arora-Jonsson, 2011; Vincent *et al.*, 2010). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women since cash generation is seen as a male activity in rural areas (Gladwin *et al.*, 2001;13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor which women cannot necessarily afford to provide (Baiphethi *et al.*, 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Below *et al.*, 2012; Goulden *et al.*, 2009; Vincent *et al.*, 2010) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert, 2013; Bee *et al.*, 2013; Tschakert and Machado, 2012; see also 22.4.3 and Table 22-5).

Box CC-GC References

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Box CC-HS. Heat Stress and Heat Waves

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Heat waves are periods of abnormally and uncomfortably hot weather during which the risk of heat stress on people and ecosystems is high. The number and intensity of hot days have increased markedly in the last three decades (Coumou et al., 2013) (*high confidence*). According to WG I, it is *likely* that the occurrence of heat waves has more than doubled in some locations due to human influence and it is *virtually certain* that there will be more frequent hot extremes over most land areas in the latter half of the 21st century. Coumou et al. (2013) predicted that, under a medium warming scenario, the number of monthly heat records will be over 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +10C or more, the habitability of large parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and they may act as triggers for tipping points (Hughes et al., 2013). Consequently, heat waves play an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society [Ch 10, 11, 12, 13]

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012). In LICs and MICs, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health [Ch 11]

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro *et al.*, 2011; Rahmstorf and Coumou, 2011; Nitschke et al., 2011; Diboulo et al., 2012; Hansen et al., 2012). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, Jan C et al., 2008). Increase in ozone concentrations due to high temperatures affects health (Smith et al., 2010), leading to premature mortality, e.g. cardiopulmonary mortality (Smith et al., 2010). High temperatures are also associated with an increase in air-borne allergens acting as a trigger for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems [Ch 4, 5, 6, 30]

Tree mortality is increasing globally (Williams et al., 2012) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult due to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013), Box 4.2.

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (Hoegh-Guldberg et al., 2007), Figure 6-5, (*medium confidence*) [Ch 6.3.1, 6.3.5; 30.4; 30.5; CC-MB]

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*). [Ch 5, 6, 30.4-30.5, CC-CR, CC-MB]

Agriculture [Ch 7]

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2011). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and

suitability for crops (*medium evidence, medium agreement*) (Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the U.S., current economic losses due to heat stress of livestock are estimated at several billion USD annually (St-Pierre et al., 2003).

Box CC-HS References

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Table 12-1: Illustrative examples of impacts of climate variability and change on immediate basic needs and longer term capabilities and assets from observational studies and from projections.

Dimensions of impact	**Illustrative examples of observed impacts due to aggravating climate stresses**	**Illustrative examples of potential changes in livelihoods and capabilities as a consequence of climate variability and climate change**
	Deprivation of basic needs	
Livelihood assets	• Household assets such as livestock sold or lost during drought: documented examples – 1999-2000 drought, Ethiopia and 1999-2004 drought, Afghanistan (Carter *et al.*, 2007; de Weijer 2007). • Riverbank erosion, floods, and groundwater depletion and salinisation associated with changed hydrological regimes, causes loss of agricultural land (Paul and Routray, 2010; Taylor et al., 2013).	• Simulated future climate volatility leads to reduced future production of staple grains and increases in poverty (Ahmed *et al*., 2009). • Changes in the viability of livestock feed crops have an impact on smallholder farmers: maize yields are projected to decline in many regions (Jones and Thornton, 2003; Chapter 7.4). • Projections of land loss, riverbank erosion and groundwater depletion, in combination with environmental change and human interventions, suggest future stress on livelihood assets (Le *et al*., 2007; Taylor et al., 2013).
Water stress and scarcity	• Glaciers lower river flows affect water stress and scarcity, with livelihood and cultural loss (Orlove *et al.*, 2008): glacier recession in the Cordillera Blanca in Peru is altering the hydrological regime with implications for local livelihoods and water availability in the arid coastal zone (Mark *et al.*, 2010).	• Projected stresses to water availability show increased populations without sustainable access to safe drinking water (Hadipuro 2007). • Projected reduction in glacier extent and the associated loss of a hydrological buffer is expected to increase (Vuille, 2008; Chapter 3.4.4).
Loss of property and residence	• Floods destroy shelter and properties and curtail ability to meet basic needs. Example – Fiji flood in 2009 resulted in economic losses of F$24 million affecting at least 15% of farm households (Lal, 2010). • Sea-level rise and increased frequency of extreme events increases risk of loss of lives, homes, and properties and damages infrastructure and transport systems (Adrianto and Matsuda, 2002; Suarez *et al.*, 2005; Philips and Jones 2006; Ashton *et al.*, 2008; Von Storch *et al.*, 2008).	• Changes in flood risk may increase and cause economic damages: in the Netherlands, the total amount of urban area that can potentially be flooded has increased six-fold during the 20th century and may double again during the 21st century (de Moel *et al.*, 2011). In England and Wales, projected changes in flood risk mean economic damages may increase up to 20 times by the 2080s (Hall *et al.*, 2003).
	Erosion of livelihood and human capabilities	
Agriculture and food security	• Interaction of climate change with poverty and other political, social, institutional and environmental factors may adversely affect agriculture production and exacerbate the problem of food insecurity (Downing 2002; Trotman *et al*., 2009; Saldana-Zorrilla 2008). Examples: in Kenya, Oluoko-Odingo 2011; in Southern Africa, Drimie and Gillespie 2010; in Zimbabwe and Zambia (Mubaya *et al*., 2012).	• Studies of African agriculture using diverse climate scenarios indicate increasing temperature and rainfall variation have negative impacts on crops and livestock production and lead to increased poverty, vulnerability and loss of livelihoods. Examples: Ethiopia (Deressa and Hassan 2009); Kenya (Kabubo-Mariara 2009); Burkina Faso, Egypt, Kenya and South Africa (Molua *et al.* 2010); and sub-Saharan Africa (Jones and Thornton 2009). • Potential livelihood insecurity among small-scale rain-fed maize farmers in Mexico is projected due to potential loss of traditional seed sources in periods of climate stress (Bellona *et al.*, 2011).

Human capital	Health: • Food shortage, absence of safe and reliable access to clean water and good sanitary conditions, and destruction of shelters and displacements, all have negative bearing on human health (Costello *et al.*, 2009; Chapter 11.4) Education: • Droughts and floods can intensify the pressure to transfer children to the labour market (Ethiopia and Malawi, UNDP 2007). Indian women born during a drought or flood in the 1970s were 19 percent less likely to ever attend primary school, when compared with women of the same age who were not affected by natural disasters (UNDP 2007).	Health: • Analysis of the economic and climatic impacts of three emission scenarios and three tax scenarios, estimates the impacts on food productivity and malaria infection to be very severe in some Asian countries (Kainuma *et al.*, 2004). Loss of lives: • Studies of the impacts of future floods using a combination of socio-economic and climate change scenarios for developed countries show an increase in mortality. Example: in the Netherlands, sea level rise combined with other factors, potentially increases the number of fatalities four times by 2040 (Maaskant *et al.*, 2009)

Table 12-2: Cultural dimensions of climate science, policy, impacts, and extreme events in the context of climate change.

Core climate change dimensions	**Cultural dimensions**	**Role in human security**	**Sources**
Climate science and policy	Framing of climate change in a dominant language. Global climate change policy implemented at international scales.	How concepts and uncertainties are translated, imported and incorporated facilitate or hinder adaptation: *Facilitate Adaptation*: Available explanatory tools; Successful translation of climate change impacts; Awareness of culture. *Hinder Adaptation*: Lack of trust in science and in policy; Policy not recognizing the connection between nature and culture. Policy and decision-making that is inclusive of cultural perspectives *increases security*.	Ifejika Speranza *et al.*, 2008; Stadel, 2008; Jacka, 2009; Green, *et* al., 2010; Schroeder, 2010; Osbahr *et al.*, 2010; McNeely, 2012; Gero *et al.*, 2011; Sánchez-Cortés and Chavero, 2011; Roncoli et al., 2011; Kuruppu and Liverman, 2011; Rudiak-Gould, 2012.
Impacts of environmental conditions and extreme events and changing natural resource base	Elements of collective understanding such as: Worldviews Coupling of nature-culture Power relations Heterogeneity within groups and communities	*Facilitate Adaptation*: New technologies; Livelihood diversification and flexibility; Perceptions of resilience; Narratives and history about past changes and current conditions; Co-management of resources increases adaptive capacity. *Hinder Adaptation*: Limitations of local knowledge; Lack of awareness and understanding of culture constrains action; Knowledge and cultural repertoire limited for responding to new challenges; Perceptions of resilience; Erosion of cultural core potentially *decreases human security*. Institutional responses and resource management will impact human security either negatively or positively.	Nunn, 2000; Davidson *et al.*, 2003; Desta and Coppock, 2004; Zamani *et al.*, 2006; Ford *et al.*, 2006, 2008; Kuruppu and Liverman, 2011, Rudiak-Gould, 2012; Roncoli *et al.*, 2011; Gearheard *et al.*, 2010; Hovelsrud and Smit, 2010; Nyong *et al.*, 2007; Tyler *et al.*, 2007; Angassa and Oba, 2008; Osbahr *et al.*, 2010; Lefale, 2010; Crate, 2008; Gregory and Trousdale, 2009; Harries and Penning-Rowsell, 2011; Gero *et al.*, 2011; Fazey *et al.*, 2010; Furgal and Seguin, 2006; Sudmeier-Riuex *et al.*, 2012; Anik and Khan, 2012; Kuhlicke, 2010; Valdivia *et al.*, 2010; Kesavan and Swaminathan, 2006; Jacka, 2009; Pearce *et al.*, 2009; Adler, *et al.*, 2012; Gómez-Baggethun *et al.*, 2012; Burningham *et al.*, 2008; West and Hovelsrud, 2010; Nursey-Bray *et al.*, 2012; Armitage *et al.*, 2011; Dumaru, 2010; King, 2008; Nielsen and Reenberg, 2010; Onta and Resurrection, 2011; de Sherbinin *et al.*, 2008; Kalikoski *et al.*, 2010; Hovelsrud *et al.*, 2010a,b; Rybråten and Hovelsrud, 2010; McNeeley, 2012; Marshall 2011; Berkes and Armitage, 2010; Ford and Goldhar, 2012; Eakin *et al.*, 2012.

Scientific observations monitoring, models, projections, scenarios	Local, traditional and indigenous knowledge through observations and experience	*Facilitate Adaptation*: Mutual integration of traditional, local and scientific knowledge; Climate projections with local relevance; Intergenerational knowledge transfers Local knowledge included in climate policy and decision-making *increases human security*. Knowledge not included in adaptation planning *decreases human security*.	Orlove *et al.*, 2000, 2010; Ingram *et al.*, 2002; Tàbara *et al.*, 2003; Alcántara-Ayala et al., 2004; Gearheard *et al*., 2010; Roncoli, 2006; Forbes, 2007; Anderson *et al.*, 2007; Vogel *et al.*, 2007; Nyong *et al.*, 2007; Tyler *et al.*, 2007; Catto and Parewick, 2008; Frazier *et al.*, 2010; Marfai *et al.*, 2008; Mercer *et al.*, 2009; Pearce *et al.*, 2009; Marin, 2010; Mark *et al.*, 2010; Smit et al 2010; Burns *et al.*, 2010; Hovelsrud and Smit, 2010; Kalanda-Joshua et al., 2011; Flint *et al*., 2011; Ravera *et al.*, 2011; Sánchez-Cortés and Chavero, 2011; Huntington, 2011; Eira *et al.*, 2013; Dannevig *et al*., 2012.

Table 12-3: Empirical evidence on observed or projected mobility outcomes (migration, immobility or displacement) associated with weather-related extremes or impacts of longer-term climate change.

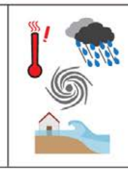
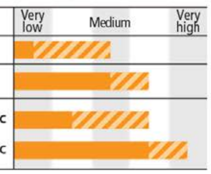
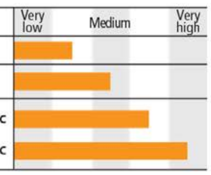
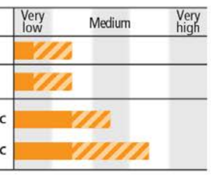
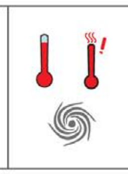
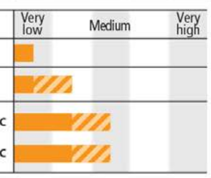
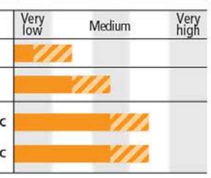
Change in migration trend or flow	**Impact on migration, by type of short term event and long term change**	**Source**
	Drought and land degradation	
Evidence for increased mobility or increased displacement	↑ Ethiopia: Outmigration of household heads due to drought-related famine. Different coping strategies lead to variations in the timing of migration.	Meze-Hausken, 2000;
	↑ Mexico: At the state level, a reduction in crop yields associated with an increase in international migration to the United States.	Feng *et al.*, 2010;
	↑ Western Sahara: Environmental factors influenced decisions to migrate internationally from refugee camps.	Gila *et al.*, 2011;
	↑ Kenya: Households farming high quality soil are less likely to migrate, especially for temporary labour migration; soil degradation therefore causes increased outmigration.	Gray, 2011;
	↑ India: Temporary migration identified as 'the most important' coping strategy in times of drought in rural villages.	Jülich, 2011;
	↑ *Burkina Faso: Simulated scenarios of dry climate increase migration fluxes compared to wet scenarios. Highest international migrant flows are shown with the dry climate scenarios.	Kniveton *et al.*, 2011;
	↑ Canada: Higher population loss was associated with settlements containing areas of poorer quality agricultural soils during droughts of 1930s.	McLeman and Ploeger, 2011;
	↑ Guatemala: Migrants to the expanding agricultural frontier commonly attributed their outmigration to soil degradation.	López-Carr, 2012;
	↑ Sahel: In three case regions, the pressure to migrate had significantly increased since the 1970s, with response to persistent droughts identified as a factor.	Scheffran *et al.*, 2012b; 2012c;
	↑ Burkina Faso: Drier region populations were more likely to engage in rural-rural migration, both temporary and permanent, than people from regions with more rainfall. Rainfall deficits have different impacts depending on the duration and distance of the migration.	Henry *et al.*, 2004;
Evidence for decreased mobility	↓ Mali: Reduced international migration during 1980s drought and an increase in cyclical migration.	Findley, 1994;
	↓ Nepal: Deforestation, population pressure and agricultural decline leads to local mobility, especially among women, but no increases in internal or international migration	Massey *et al.*, 2010; Bohra-Mishra and Massey (2011);
	↓ Uganda: High soil quality marginally increases migration, especially permanent non-labor migration; therefore soil degradation reduces outmigration.	Gray, 2011;
Evidence for socially-differentiated mobility outcomes	⇅ United States: Dustbowl migrants from Oklahoma to California in the 1930s had different social and economic capital endowments to those who stayed within state.	McLeman and Smit, 2006;
	⇅ Ecuador: Influence of natural capital on migration differed between men and women. Access to land facilitates migration in men; women are less likely to migrate from environmentally degraded areas.	Gray, 2010;
	⇅ Ethiopia: Male migration increases with drought. However, marriage related moves by women decrease with drought.	Gray and Mueller, 2012;
	⇅ Burkina Faso: Labour migration became a key off-farm livelihood strategy after droughts in the 1970s for groups dependent on rain-fed agriculture	Nielsen and Reenberg, 2010;
	⇅ Mongolia: Diversity in herders' mobility strategies in response to climate change. For a minority, responses entailed greater overall annual mobility. Other herding households experienced significant reductions in mobility.	Upton, 2012;

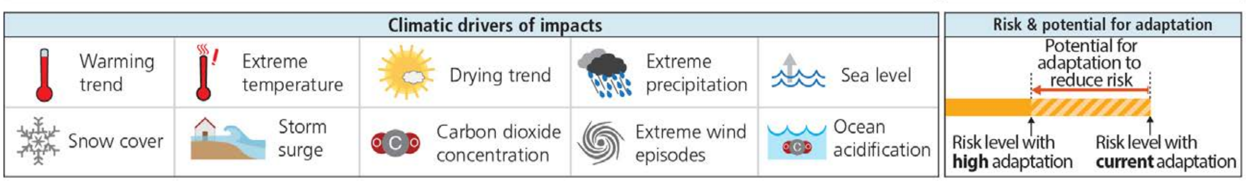
	Flooding	
Evidence for increased mobility or increased displacement	↑ USA: Ten counties and parishes in Louisiana, of the 77 impacted counties, experienced 82% of the total population increase in the year following Hurricane Katrina. ↑ Vietnam: Cumulative impacts of seasonal flooding increases outmigration rates in the Mekong Delta. ↑ Bangladesh: 22% of households affected by tidal-surge floods, and 16% affected by riverbank erosion, moved to urban areas.	Frey and Singer, 2006; Dun, 2011; Penning-Rowsell *et al.*, 2013;
Evidence for decreased mobility or trapped populations	↓ Bangladesh: No out-migration detected after 2004 tornado in Bangladesh as a result of the effective distribution of disaster aid. ↓ Senegal: Over 40 percent of new migrant populations located in high risk flood zones in Dakar.	Paul, 2005; Quoted in Black *et al.*, 2011b;
Evidence for socially-differentiated mobility outcomes	⇅ USA: Emergency evacuation responses and return migration after Hurricane Katrina highly differentiated by income, race, class and ethnicity. ⇅ Bangladesh: Wide variation among groups in attitudes towards, and capabilities for, migration as an adaptation to the impact of cyclone Aila.	Elliott and Pais, 2006; Falk *et al.*, 2006; Landry *et al.*, 2007; Kartiki, 2011;

	Sea level rise	
Evidence for increased mobility or increased displacement	↑ United States: Relative sea level rise caused island depopulation in Maryland. Final abandonment was a result of the population falling below the threshold required to support local services. ↑ Vanuatu: Contemporary example of whole village displacement associated with inundation, both from sea level rise and tectonic movement on Torres Islands. ↑ United States*: The impact of future sea-level rise is projected to extend beyond the inundated counties through migration networks that link inland and coastal areas and their populations. ↑ Papua New Guinea: Population considering resettlement on Bougainville to the main island due to coastal erosion, land loss, saltwater inundation and food insecurity. ↑ United States: Coastal villages in Alaska affected by sea-level rise and coastal erosion to the point where resettlement is the only viable adaptation.	Arenstam Gibbons and Nicholls, 2006; Ballu *et al.*, 2011; Curtis and Schneider, 2011; Oliver-Smith, 2011; Bronen, 2010; Oliver-Smith, 2011; Marino, 2012;
Evidence for decreased mobility or lower migration	↓ Tuvalu: On the island of Funafuti, surveyed residents emphasize place attachment as reasons for not migrating, and do not cite climate change as a reason to migrate.	Mortreux and Barnett, 2009.

Note: * indicates study based on simulations or projections

Table 12-4 Examples of important risks from climate change for elements of human security and the potential for risk reduction through mitigation and adaptation. These risks are identified based on this Chapter assessment and expert judgments of the authors, with supporting evaluation of evidence and agreement in the relevant chapter sections. Each risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by symbols. As the assessment considers potential impacts on diverse and incompatible elements and systems, risk levels should not be used to evaluate relative risk between the rows.

Example risks	Adaptation issues and prospects	Climatic risks	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Displacement associated with extreme events (*high confidence*)	Adaptation to extreme events are well understood, but poorly implemented even under present climate conditions. Displacement and involuntary migration are often temporary. With increasing climate risks, displacement is more likely to involve permanent migration.		12.4.1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Loss of land, cultural and natural heritage disrupting cultural practices embedded in livelihoods and expressed in narratives, world views, identity, community cohesion and sense of place (*high confidence*)	Cultural values and expressions are dynamic and inherently adaptable and hence adaptation is possible to avoid losses of cultural assets and expressions. Nevertheless cultural integrity will be compromised in these circumstances.		12.3.2, 12.3.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Violent conflict arising from deterioration in resource dependent livelihoods such as agriculture and pastoralism (*high confidence*)	There are options for buffering rural incomes against climate shocks, for example through livelihood diversification, income transfers, and social safety net provision. There are early warning mechanisms to promote effective risk reduction. There are well-established strategies for managing violent conflict which are effective, but require significant resources, investment and political will.		12.5.1	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Geopolitical competition over access to Arctic resources that escalates into dangerous tensions and crises (*high confidence*)	There are international organizations and elements of international law that regulate competition and access and provide mechanisms for resolving disputes. There are strong transnational networks which are relevant for joint problem-solving. Hence adaptation action has significant potential to reduce risks associated with geo-political rivalry.		12.6.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
New or exacerbated conflict through land acquisition for climate change mitigation and adaptation (*medium confidence*)	Climate change mitigation (e.g. expansion of biofuel production area) and adaptation action (e.g. set-back of coastal land) can exacerbate conflicts when they are already manifest around land and water availability and scarcity. The extent of insecurity and instability from such mitigation and adaptation activities depends on the displacement of populations and the inclusiveness of the planning processes. Careful planning processes can therefore be used to ameliorate the risk of conflict.		12.5.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	



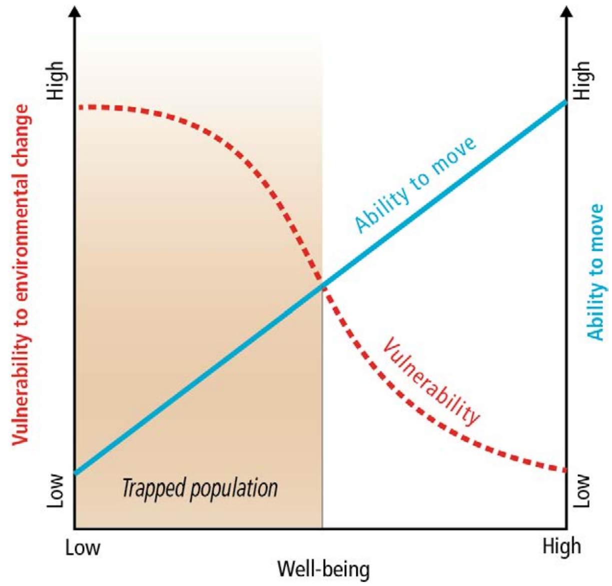


Figure 12-1: Relationship between vulnerability to environmental change and mobility showing that populations most exposed and vulnerable to the impacts of climate change may have least ability to migrate. Source: Adapted from Black *et al.*, 2013.

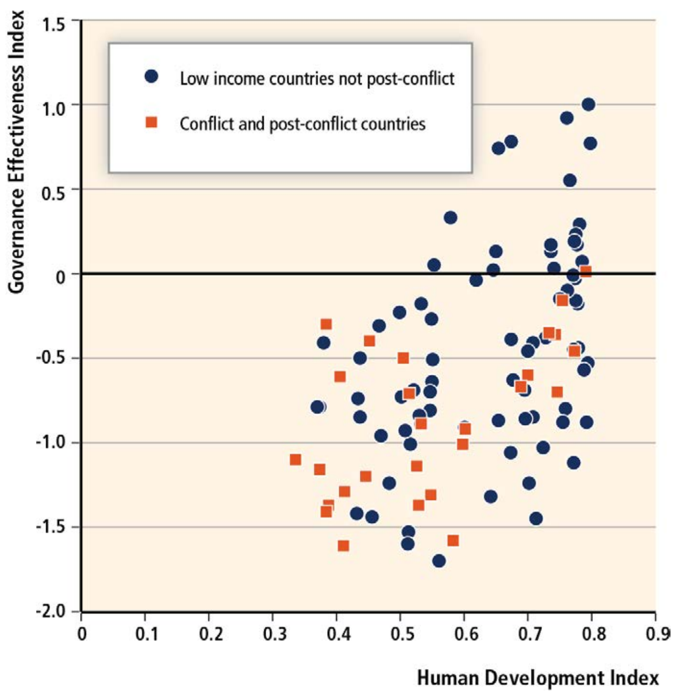


Figure 12-2: Conflict and post-conflict societies exhibit low levels of governance and human development. Data based on UNDP Human Development Index and World Bank index on Governance effectiveness. Source: Adapted from Adger, 2010.

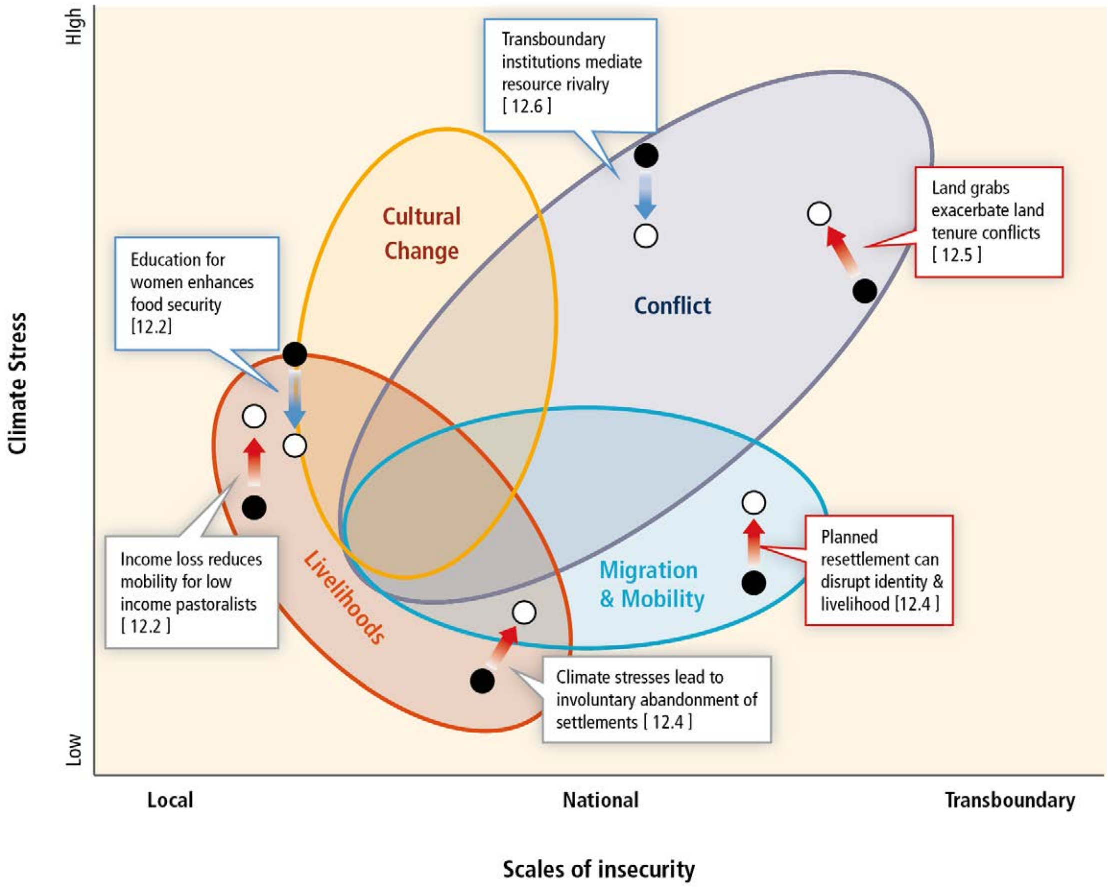


Figure 12-3: Synthesis of evidence on the impacts of climate change on elements of human security and the interactions between livelihoods, conflict, culture, and migration. Interventions and policies indicated by difference between initial conditions (solid black) and outcome of intervention (white circles). Some interventions (blue arrows) show net increase human security while others (red arrows) lead to net decrease in human security.

Chapter 13. Livelihoods and Poverty

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Contents

Executive Summary

This chapter discusses how livelihoods, poverty and the lives of poor people, and inequality interact with climate change, climate variability, and extreme events in multifaceted and cross-scalar ways. It examines how current impacts of climate change, projected impacts up until 2100, and responses to climate change affect livelihoods and poverty. The Fourth Assessment Report stated that socially and economically disadvantaged and marginalized people are disproportionally affected by climate change. However, no comprehensive review of climate change, poverty, and livelihoods has been undertaken to date by the IPCC. This chapter addresses this gap, presenting evidence of the dynamic interactions between these three principal factors. At the same time, the chapter recognizes that climate change is rarely the only factor that affects livelihood trajectories and poverty dynamics; climate change interacts with a multitude of non-climatic factors, which makes detection and attribution challenging.

Observed climate variability, climate change, and extreme events constitute an additional burden to rural and urban people living in poverty. These climate-related hazards act as a threat multiplier, often with negative outcomes for livelihoods (*high confidence, based on medium evidence, high agreement*).

- Climate-related hazards, including subtle shifts and trends to extreme events, affect poor people's lives directly through impacts on livelihoods, such as losses in crop yields, destroyed homes, food insecurity, and loss of sense of place, and indirectly through increased food prices (*robust evidence, high agreement*). [13.2.1, 13.3]
- Changing climate trends lead to shifts in rural livelihoods with mixed outcomes, such as from crop-based to hybrid livestock-based livelihoods or to wage labor in urban employment. Climate change is one stressor that shapes dynamic and differential livelihood trajectories (*robust evidence, high agreement*). [13.1.4, 13.2.1.2]
- Urban and rural transient poor who face multiple deprivations slide into chronic poverty as a result of extreme events, or a series of events, when unable to rebuild their eroded assets. Poverty traps also arise from food price increase, restricted mobility, and discrimination (*limited evidence, high agreement*). [13.2.1.3, 13.2.1.4]
- Many events that affect poor people are weather-related and remain unrecognized by standard climate observations in many low-income countries, due to short time series and geographically sparse, aggregated, or partial data, inhibiting detection and attribution. Such events include short periods of extreme temperature, minor changes in the distribution of rainfall, and strong wind events (*robust evidence, high agreement*). [13.2.1]

Observed evidence suggests that climate change and climate variability worsen existing poverty, exacerbate inequalities, and trigger both new vulnerabilities and some opportunities for individuals and communities. Poor people are poor for different reasons and thus are not all equally affected, and not all vulnerable people are poor. Climate change interacts with non-climatic stressors and entrenched structural inequalities to shape vulnerabilities (*very high confidence, based on robust evidence, high agreement*).

- Socially and geographically disadvantaged people exposed to persistent inequalities at the intersection of various dimensions of discrimination based on gender, age, race, class, caste, indigeneity, and (dis)ability are particularly negatively affected by climate change and climate-related hazards. Context-specific conditions of marginalization shape multidimensional vulnerability and differential impacts. [13.1.2.3, 13.1.3., 13.2.1.5]
- Existing gender inequalities are increased or heightened by climate-related hazards. Gendered impacts result from customary and new roles in society, often entailing higher workloads, occupational hazards indoors and outdoors, psychological and emotional distress, and mortality in climate-related disasters. [13.2.1.5]
- There is little evidence that shows positive impacts of climate change on poor people, except isolated cases of social asset accumulation, agricultural diversification, disaster preparedness, and collective action. The more affluent often take advantage of shocks and crises, given their flexible assets and power status. [13.1.4, 13.2.1.4]

Climate change will create new poor between now and 2100, in low-, medium, and high-income countries (LICs, MICs, and HICs), and jeopardize sustainable development. The majority of severe impacts are projected for urban areas and some rural regions in sub-Saharan Africa and Southeast Asia (*medium confidence, based on medium evidence, medium agreement*).

- Future impacts of climate change, extending from the near-term to the long-term, mostly expecting 2C scenarios, will slow down economic growth and poverty reduction, further erode food security, and trigger new poverty traps, the latter particularly in urban areas and emerging hotspots of hunger. [13. 2.2.2, 13.2.2.4, 13.4]
- Climate change will exacerbate multidimensional poverty in LICs and lower MICs, including high mountain states, countries at risk from sea level rise, and countries with indigenous peoples. Climate change will also create new poverty pockets in upper MICs and HICs where inequality is on the rise. [13.2.2]
- Wage-labor dependent poor households that are net buyers of food will be particularly affected due to food price increases, in urban and rural areas, especially in regions with high food insecurity and high inequality (particularly in Africa), although the agricultural self-employed could benefit [13.2.2.3, 13.2.2.4]

Current policy responses for climate change mitigation or adaptation will result in mixed, and in some cases even detrimental, outcomes for poor and marginalized people, despite numerous potential synergies between climate policies and poverty reduction (*medium confidence, based on limited evidence, high agreement*).

- Mitigation policies with social co-benefits expected in their design, such as CDM and REDD+, have had limited or no effect in terms of poverty alleviation and sustainable development. [13.3.1.1, 13.3.1.2]
- Mitigation efforts focused on land acquisition for biofuel production show preliminary negative impacts on the lives of poor people, such as dispossession of farmland and forests, in many LICs and MICs, particularly for indigenous peoples and (women) smallholders. [13.3.1.4]
- Insurance schemes, social protection programs, and disaster risk reduction may enhance long-term livelihood resilience among poor and marginalized people, if policies address multidimensional poverty. [13.3.2.2, 13.4.1]
- Climate-resilient development pathways will have only marginal effects on poverty reduction, unless structural inequalities are addressed and needs for equity among poor and non-poor people are met. [13.4.2]

13.1. Scope, Delineations, and Definitions: Livelihoods, Poverty, and Inequality

Understanding the impacts of climate change on livelihoods and poverty requires examining the complexities of poverty and the lives of poor and non-poor people, as well as the multifaceted and cross-scalar intersections of poverty and livelihoods with climate change. This chapter is devoted to exploring poverty in relation to climate change, a novelty in the IPCC. It uses a livelihood lens to assess the interactions between climate change and multiple dimensions of poverty. We use the term “the poor,” not to homogenize, but to describe people living in poverty, people facing multiple deprivations, and the socially and economically disadvantaged, as part of a conceptualization broader than income-based measures of poverty, acknowledging gradients of prosperity and poverty. This livelihood lens also reveals how inequalities perpetuate poverty to shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. The chapter first presents the concepts of livelihoods, poverty, and inequality, and their relationships to each other and to climate change. Second, it describes observed impacts of weather events and climate on livelihoods and rural and urban poor people as well as projected impacts up to 2100. We use “weather events and climate” as an umbrella term for climate change, climate variability, and extreme events, and also highlight subtle shifts in precipitation and localized weather events. Third, this chapter discusses impacts of climate change mitigation and adaptation responses on livelihoods and poverty. Finally, it outlines implications for poverty alleviation efforts and climate-resilient development pathways.

Livelihoods and Poverty is a new chapter in the AR5. Although the AR4 WGII contributions mentioned poverty, as one of several non-climatic factors contributing to vulnerability, as a serious obstacle to effective adaptation, and in the context of endemic poverty in Africa (Technical Summary, Chapters 7, 8, 18, 20), no systematic assessment was undertaken. Livelihoods were more frequently addressed in the AR4 and in the SREX, predominantly with reference to livelihood strategies and opportunities, diversification, resource-dependent communities, and sustainability. Yet, a comprehensive livelihood lens for assessing impacts was lacking. This chapter addresses these gaps. It assesses how climate change intersects with other stressors to shape livelihood choices and trajectories, to affect the spatial and temporal dimensions of poverty dynamics, and to reduce or exacerbate inequalities given differential vulnerabilities.

13.1.1. Livelihoods

Livelihoods (see also Glossary) are understood as the ensemble or opportunity set of capabilities, assets, and activities that are required to make a living (Chambers and Conway, 1992; Ellis *et al.*, 2003). They depend on access to natural, human, physical, financial, social, and cultural capital (assets); the social relations people draw upon to combine, transform, and expand their assets; and the ways people deploy and enhance their capabilities to act and make lives meaningful (Scoones, 1998; Bebbington, 1999). Livelihoods are dynamic and people adapt and change their livelihoods with internal and external stressors. Ultimately, successful livelihoods transform assets into income, dignity, and agency, to improve living conditions, a prerequisite for poverty alleviation (Sen, 1981).

Livelihoods are universal. Poor and rich people both pursue livelihoods to make a living. However, as shown in this chapter, the adverse impacts of weather events and climate increasingly threaten and erode basic needs, capabilities, and rights, particularly among poor and disenfranchised people, in turn reshaping their livelihoods (UNDP, 2007; Leary *et al.*, 2008; Adger, 2010; Quinn *et al.*, 2011). Some livelihoods are directly climate-sensitive, such as rain-fed smallholder agriculture, seasonal employment in agriculture (e.g. tea, coffee, sugar), fishing, pastoralism, and tourism. Climate change also affects households dependent on informal livelihoods or wage labor in poor urban settlements, directly through unsafe settlement structures or indirectly through rises in food prices or migration.

13.1.1.1. Dynamic Livelihoods and Trajectories

A livelihood lens is a grounded and multidimensional perspective that recognizes the flexibility and constraints with which people construct their complex lives and adapt their livelihoods in dynamic ways. By paying attention to the wider institutional, cultural, and policy contexts as well as shocks, seasonality, and trends, this lens reveals processes that push people onto undesirable trajectories or toward enhanced well-being. Better infrastructure and technology as well as diversification of assets, activities, and social support capabilities can boost livelihoods, spreading risks and broadening opportunities (Batterbury, 2001; Ellis *et al.*, 2003; Clot and Carter, 2009; Reed *et al.*, 2013; Carr, 2013). The sustainable livelihoods framework (Chambers and Conway, 1992) is widely used for identifying how specific strategies may lead to cycles of livelihood improvements or critical thresholds beyond which certain livelihoods are no longer sustainable (Sabates-Wheeler *et al.*, 2008). It emerged as a reaction to the predominantly structural views of poverty and "underdevelopment" in the 1970s and became adopted by many researchers and development agencies (Ellis and Biggs, 2001). With the neoliberal turn in the late 1980s, the livelihoods approach became associated with a more individualistic development agenda, stressing various forms of capital (Scoones, 2009). Consequently, it has been criticized for its analytical limitations, such as measuring capitals or assets, especially social capital, and for not sufficiently explaining wider structural processes (e.g., policies) and ecological impacts of livelihood decisions (Small, 2007; Scoones, 2009). An overemphasis on capitals also eclipses power dynamics and the position of households in class, race, and other dimensions of inequality (Van Dijk, 2011).

13.1.1.2. Multiple Stressors

Livelihoods rarely face only one stressor or shock at a time. The literature emphasizes the synergistic relationship between weather events and climate and a variety of other environmental, social, economic, and political stressors; together, they impinge on livelihoods and reinforce each other in the process, often negatively (Reid and Vogel, 2006; Schipper and Pelling, 2006; Tschakert, 2007; IPCC, 2007; Morton, 2007; Easterling *et al.*, 2007; O'Brien *et al.*, 2008; Eakin and Wehbe, 2009; Eriksen and Silva, 2009; Ziervogel *et al.*, 2010). "Double losers" may emerge from simultaneous exposure to climatic change and other stressors such as the spread of infectious diseases, rapid urbanization, and economic globalization, where climate change acts as a threat multiplier, further marginalizing vulnerable groups (O'Brien and Leichenko, 2000; Eriksen and Silva, 2009). Climatic and other stressors affect livelihoods at different scales: spatial (e.g., village, nation) or temporal (e.g., annual, multi-annual). Both direct and indirect impacts are often amplified or weakened at different levels. Global or regional processes generate a variety of stressors, typically mediated by cross-level institutions, that result in locally experienced shocks (Reid and Vogel, 2006; Thomas *et al.*, 2007; Paavola, 2008; Pouliotte *et al.*, 2009) (see Figure 13-1 in FAQ 13.1).

Multiple stressors, simultaneous and in sequence, shape livelihood dynamics in distinct ways due to inequalities and differential vulnerabilities between and within households. More affluent households may be able to capitalize on shocks and crises while poorer households with fewer options are forced to erode their assets. Limited ability to adapt and some coping strategies may result in adverse consequences. Such maladaptive actions (see Glossary, and Chapters 14, 16) undermine the long-term sustainability of livelihoods, resulting in downward trajectories, poverty traps, and exacerbated inequalities (Ziervogel *et al.*, 2006; Tanner and Mitchell, 2008; Barnett and O'Neill, 2010).

[INSERT FIGURE 13-1 HERE (within FAQ 13.1)
Figure 13-1: Multiple stressors related to climate change, globalizations, and technological change interact with national and regional institutions to create shocks to place-based livelihoods, inspired by Reason (2000).]

13.1.2. Dimensions of Poverty

Poverty is a complex concept with conflicting definitions and considerable disagreement in terms of framings, methodologies, and measurements. Despite different approaches emphasizing distinct aspects of poverty at the individual or collective level, such as income, capabilities, and quality of life (Laderchi *et al.*, 2003), poverty is recognized as multidimensional (UNDP, 1990). It is influenced by social, economic, institutional, political, and cultural drivers; its reversal requires efforts in multiple domains that promote opportunities and empowerment, and enhance security (World Bank, 2001). In addition to material deprivation, multidimensional conceptions of poverty consider a sense of belonging and socio-cultural heritage (O'Brien and Leichenko, 2003), identity, and agency, or "the culturally constrained capacity to act" (Ahearn, 2001 p.54). The AR4 identified poverty as "the most serious obstacle to effective adaptation" (Confalonieri *et al.*, 2007, p.417).

13.1.2.1. Framing and Measuring Multidimensional Poverty

Over the last six decades, conceptualizations of poverty have broadened, expanding the basis for understanding poverty and its drivers. Poverty measurements now better capture multidimensional characteristics and spatial and temporal nuances. Attention to multidimensional deprivations, such as hunger, illiteracy, unclean drinking water, lack of access to health, credit, or legal services, social exclusion, and empowerment, have shifted the analytical lens to the dynamics of poverty and its institutionalization within social and political norms (UNDP, 1994; Sen, 1999; World Bank, 2001). Regardless of these shifting conceptualizations over time, comparable and reliable measures remain challenging and income per capita remains the default method to account for the depth of global poverty.

In climate change literature, poverty and poverty reduction have been predominantly defined through an economic lens, reflecting various growth and development discourses (Sachs, 2006; Collier, 2007). Less attention has been paid to relational poverty, produced through material social relations and in relation to privilege and wealth (Sen, 1976; Mosse, 2010; Alkire and Foster, 2011; UNDP, 2011a). Yet, such framing allows for addressing the social and political contexts that generate and perpetuate poverty and structural vulnerability to climate change (McCright and Dunlap, 2000; Bandiera *et al.*, 2005; Leichenko and O'Brien, 2008). Many climate policies to date favor market-based responses using sector-specific and economic growth models of development, although some responses may slow down achievements of international development such as those outlined in the Millennium Development Goals (MDGs). For instance, the World Bank encourages “mitigation, adaptation, and the deployment of technologies” that “allow[s] developing countries to continue their growth and reduce poverty” (World Bank, 2010, p.257), mainly promoted through market tools. A relational approach to poverty highlights the integral role of poor people in all social relations (Pogge, 2009; O'Brien *et al.*, 2010; UNRISD, 2010; Gasper *et al.*, 2013; St.Clair and Lawson, 2013). It emphasizes equity, human security, and dignity (O'Connor, 2002; Mosse, 2010). Akin to the capabilities approach (Sen, 1985; Sen, 1999; Nussbaum, 2001; Alkire, 2005; Nussbaum, 2011), the relational approach stresses the needs, skills, and aims of poor people while tackling structural causes of poverty, inequalities, and uneven power relations.

The IPCC AR4 (Yohe *et al.*, 2007) highlighted that – with *very high confidence* – climate change will impede the ability of nations to alleviate poverty and achieve sustainable development, as measured by progress towards the MDGs. Empirical assessments of the impact of climate change on MDG attainment are limited (Fankhauser and Schmidt-Traub, 2011), and the failure to reach these goals by 2015 has significant non-climatic causes (e.g. Hellmuth and IRI, 2007; UNDP, 2007). The 2010 UNDP Multidimensional Poverty Index, measuring intensity of poverty based on patterns of simultaneous deprivations in basic services (education, health, and standard of living) and core human functionings, states that close to 1.7 billion people face multidimensional poverty, a significantly higher number than the 1.2 billion (World Bank, 2012a) indicated by the International Poverty Line (IPL) set at $1.25/day. Figure 13-2 depicts country-level examples of how the two poverty measures differ.

Caution is required for poverty projections. Estimates of poverty made using national accounts means (see Chapter 19) yield drastically different estimates to those produced by survey means, both for current estimates and future projections (Edward and Sumner, 2013a). Diverse conceptions of poverty further complicate projections, as multidimensional conceptions rely on concepts difficult to measure and compare. Data availability constrains current estimates let alone projections and their core assumptions (Alkire and Santos, 2010; Karver *et al.*, 2012).

[INSERT FIGURE 13-2 HERE
Figure 13-2: A) Multidimensional poverty and income-based poverty using the International Poverty Line $1.25/day (in Purchasing Power Parity terms), with linear regression relationship (dotted line) based on 96 countries (UNDP, 2011b). The position of the countries relative to the dotted line illustrates the extent to which these two poverty measures are similar or divergent (e.g., Niger). B) The map insets show the intensity of poverty in two countries, based on the Poverty Gap Index at district level (per capita measure of the shortfall in welfare of the poor from the poverty line, expressed as a ratio of the poverty line). The darker the purple shading, the larger the shortfall.]

13.1.2.2. Geographic Distribution and Trends of the World’s Poor

Geographic patterns of poverty are uneven and shifting. Despite its limitations, most comparisons to date rely on the IPL. In 1990, most of the world’s $1.25 and $2 poor lived in low-income countries (LICs). By 2008, the majority of the $1.25 and $2 poor (>70%) resided in lower and upper middle-income countries (LMICs and UMICs), in part because some populous LICs such as India, Nigeria, and Pakistan grew in per capita income to MIC status (Sumner, 2010; Sumner, 2012a). Estimates suggest about one billion people currently living under $1.25/day in MICs and a second billion between $1.25 and $2, with an additional 320m and 170m in LICs, respectively (Sumner, 2012b).

About 70% of the $1.25 poor live in rural areas in the global South (IFAD, 2011), despite worldwide urbanization. Yet, this poverty line understates urban poverty as it does not fully account for the higher costs of food and non-food items in many urban contexts (Mitlin and Satterthwaite, 2013). Of the approximately 2.4 billion living under $2/day, half live in India and China. At the same time, relative poverty is rising in HICs. Many European countries face rapid increases in poverty, unemployment, and the number of working poor due to recent austerity measures. For example, 20% of Spanish citizens were ranked poor in 2009 (Ortiz and Cummins, 2013). See also Chapter 23.

The shift in distribution of global poverty toward MICs and the increase in relative poverty in HICs challenge the orthodox view that most of the world's poorest people live in the poorest countries, and suggests that substantial pockets of poverty persist in countries with higher levels of average per capita income. Understanding this shift in the geography of poverty and available social safety nets is vital for assessing climate change impacts on poverty. To date, both climate finance and research on climate impacts and vulnerabilities are largely directed towards LICs. Less attention has been paid to poor people in MICs and HICs. In the upper and lower MICs, the incidence of $2 poverty, despite declines, remains as high as 60% and 20%, respectively (Sumner, 2012b).

Projections for 2030 suggest $2 poverty as high as 963 million people in sub-Saharan Africa and 851 million in India (Sumner *et al.*, 2012; Edward and Sumner, 2013a). However, uncertainty is high in terms of future growth and inequality trends; by 2030, $1.25 and $2 global poverty could be reduced to 300m and 600m respectively or remain at or above current levels, including in stable MICs (Edward and Sumner, 2013a). These future scenarios become more uncertain if climate change impacts on people who are socially and economically disadvantaged are taken into account or diversion of resources from poverty reduction and social protection to mitigation strategies is considered.

13.1.2.3. Spatial and Temporal Scales of Poverty

Poverty is also socially distributed, across spatial and temporal scales. Not everybody is poor in the same way. Spatially, factors such as access to and control over resources and institutional linkages from individuals to the international level affect poverty distribution (Anderson and Broch-Due, 2000; Murray, 2002; O'Laughlin, 2002; Rodima-Taylor, 2011). Even at the household level, poverty differs between men and women and age groups, yet data constraints impede systematic intra-household analysis (Alkire and Santos, 2010). The distribution of poverty also varies temporally, typically between chronic and transient poverty (Sen, 1981; Sen, 1999). Chronic poverty describes an individual deprivation, per capita income, or consumption levels below the poverty line over many years (Gaiha and Deolalikar, 1993; Jalan and Ravallion, 2000; Hulme and Shepherd, 2003). Transient poverty denotes a temporary state of deprivation, and is frequently seasonal and triggered by an individual's or household's inability to maintain income or consumption levels in times of shocks or crises (Jalan and Ravallion, 1998).

Individuals and households can fluctuate between different degrees of poverty and shift in and out of deprivation, vulnerability, and well-being (Leach *et al.*, 1999; Little *et al.*, 2008; Sallu *et al.*, 2010). Yet, the most disadvantaged often find themselves in poverty traps, or situations in which escaping poverty becomes impossible without external assistance due to unproductive or inflexible asset portfolios (Barrett and McPeak, 2006). A poverty trap can also be seen as a "critical minimum asset threshold, below which families are unable to successfully educate their children, build up their productive assets, and move ahead economically over time" (Carter *et al.*, 2007 p.837). As of 2008, a total of 320 to 443 million of people were trapped in chronic poverty (Chronic Poverty Research Centre, 2008), leading Sachs (2006) to label <$1.25/day poverty as a trap in itself. Poverty traps at the national level are often related to poor governance, reduced foreign investment, and conflict (see Chapters 10 and 12).

13.1.3. Inequality and Marginalization

Specific livelihoods and poverty alone do not necessarily make people vulnerable to weather events and climate. The socially and economically disadvantaged and the marginalized are disproportionately affected by the impacts of climate change and extreme events (*robust evidence*) (Kates, 2000; Paavola and Adger, 2006; Adger *et al.*, 2007; Cordona *et al.*, 2012). The AR4 identified poor and indigenous peoples in North America (Field *et al.*, 2007) and in Africa (Boko *et al.*, 2007) as highly vulnerable. Vulnerability, or the propensity or predisposition to be adversely affected (Field *et al.*, 2012a) by climatic risks and other stressors (see also Glossary), emerges from the intersection of different inequalities, and uneven power structures, and hence is socially-differentiated (Sen, 1999; Banik, 2009; Field *et al.*, 2012a). Vulnerability is often high among indigenous peoples, women, children, the elderly, and disabled people who experience multiple deprivations that inhibit them from managing daily risks and shocks (Eriksen and O'Brien, 2007; Ayers and Huq, 2009; Boyd and Juhola, 2009; Barnett and O'Neill, 2010; O'Brien *et al.*, 2010; Petheram *et al.*, 2010) and may present significant barriers to adaptation.

Global income inequality has been relatively consistent since the late 1980s. In 2007, the top quintile of the world's population received 83% of the total income whereas the bottom quintile took in 1% (Ortiz and Cummins, 2011). Since 2005, between-country inequality has been falling more quickly and, consequently, has triggered a notable decline in total global inequality in the last few years (Edward and Sumner, 2013b). However, within-country inequality is rising in Asia, especially China, albeit from relatively low levels, and is falling in Latin America, albeit from very high levels, while trends in sub-Saharan Africa are difficult to discern regionally (Ravallion and Chen, 2012). Income inequality is rising in many fast growing LICs and MICs (Dollar *et al.*, 2013; Edward and Sumner, 2013b). It is also growing in many HICs due to a combination of factors such as changing tax systems, privatization of social services, labor market regulations, and technological change (OECD, 2011). The 2008 financial crisis, combined with climate change, has further threatened economic growth in HICs, such as the U.K., and resources available for social policies and welfare systems (Gough, 2010). Recognizing how inequality and marginalization perpetuate poverty is a prerequisite for climate-resilient development pathways (see 13.4; and Chapters 1, 20, 27).

13.1.4. Interactions between Livelihoods, Poverty, Inequality, and Climate Change

This chapter opens its analytical lens from a conventional focus on the poor in LICs as the prime victims of climate change to a broader understanding of livelihood and poverty dynamics and inequalities, revealing the highly unequal impacts of climate change. It highlights the complex relationship between climate change and poverty. The SREX recognizes that addressing structural inequalities that create and sustain poverty and vulnerability (Huq *et al.*, 2005; Schipper, 2007; Lemos *et al.*, 2007; Boyd and Juhola, 2009; Williams, 2010; Perch, 2011) is a crucial precondition for confronting climate change (Field *et al.*, 2012a). If ignored, uneven social relations that disproportionally burden poor people with climate change's negative impacts provoke maladaptation (Barnett and O'Neill, 2010).

Poverty and persistent inequality are the "most salient of the conditions that shape climate-related vulnerability" (Ribot, 2010, p.50). They affect livelihood options and trajectories, and create conditions in which people have few assets to liquidate in times of hardship or crisis (Mearns and Norton, 2010). People who are poor and marginalized usually have the least buffer to face even modest climate hazards and suffer most from successive events with little time for recovery. They are the first to experience asset erosion, poverty traps, and barriers and limits to adaptation. As shown in 13.2 and 13.3, climate change is an additional burden to people in poverty (*very high confidence*), and it will force poor people from transient into chronic poverty and create new poor (*medium confidence*).

The complex interactions among weather events and climate, dynamic livelihoods, multidimensional poverty and deprivation, and persistent inequalities, including gender inequalities, create an ever-shifting context of risk. The SREX concluded that climate change, climate variability, and extreme events synergistically add on to and often reinforce other environmental, social, and political calamities (Field *et al.*, 2012a). Despite the recognition of these complex interactions, the literature shows no single conceptual framework that captures them concurrently, and few studies exist that overlay gradual climatic shifts or rapid-onset events onto livelihood risks. Hence, explicit attention to how livelihood dynamics interact with climatic and non-climatic stressors is useful for identifying processes that push poor and vulnerable people onto undesirable trajectories, trap them in destitution, or facilitate pathways toward enhanced well-being. Figure 13-3 illustrates these dynamics as well as critical thresholds in livelihood trajectories.

[INSERT FIGURE 13-3 HERE
Figure 13-3: Illustrative depiction of livelihood dynamics under simultaneous climatic, environmental, and socio-economic stressors and shocks leading to differential livelihood trajectories over time, based on four case studies. The red boxes indicate specific critical moments when stressors converge, threatening livelihoods and well-being. Key variables and impacts numbered in the illustrations correspond to the developments described in the captions.]

13.2. Assessment of Climate Change Impacts on Livelihoods and Poverty

This section reviews the evidence and agreement about the relationships among climate change, livelihoods, poverty, and inequality. Building on deductive reasoning and theorized linkages about these dynamic relationships, this section draws on a wide range of empirical case studies and simulations to illustrate linkages across multiple scales, contexts, and social and environmental processes and assess impacts of climate change. Although cases of observed impacts often rely on qualitative data and at times lack methodological clarity in terms of detection and attribution, they provide a vital evidence base for conveying these complex relationships. This section first describes observed impacts to date (13.2.1) and then projected risks and impacts (13.2.2).

13.2.1. Evidence of Observed Climate Change Impacts on Livelihoods and Poverty

Weather events and climate affect the lives and livelihoods of millions of poor people (Field *et al.*, 2012b). Even minor changes in precipitation amount or temporal distribution, short periods of extreme temperatures, or localized strong winds can harm livelihoods (Douglas *et al.*, 2008; Ostfeld, 2009; Midgley and Thuiller, 2011; Bele *et al.*, 2013; Bryan *et al.*, 2013). Many such events remain unrecognized given that standard climate observations typically report precipitation or temperature by month, season, or year, thus obscuring changes that shape decision making, for instance, in agriculture (Tennant and Hewitson, 2002; Barron *et al.*, 2003; Usman and Reason, 2004; Douglas *et al.*, 2008; Salack *et al.*, 2012; Lacombe *et al.*, 2012). This difficulty in detection and attribution is compounded by a lack of long-term continuous and dense networks of climate data in many LICs (UNECA, 2011). Felt experiences of events such as drought, as shown among the Sumbanese in Eastern Indonesia through phenomenological research on perceptions of climatic phenomena, such as shade and dew (Orr *et al.*, 2012), further add to the complexity.

13.2.1.1. Impacts on Livelihood Assets and Human Capabilities

Climate change, climate variability, and extreme events interact with numerous aspects of people’s livelihoods. This section presents empirical evidence of impacts on natural, physical, financial, human, and social and cultural assets (see also Chapters 22-29). Impacts on access to assets, albeit important, are poorly documented in the literature, as are impacts on power relations and active struggles in designing effective and relational livelihood arrangements.

Weather events and climate affect *natural assets* on which certain livelihoods depend directly, such as rivers, lakes, and fish stocks (*robust evidence*) (Thomas *et al.*, 2007; Nelson and Stathers, 2009; Osbahr *et al.*, 2010; Bunce *et al.*, 2010a; Bunce *et al.*, 2010b; D’Agostino and Sovacool, 2011) (see Chapters 3, 4, 5, 6, and 30). During the 20th century, water temperatures increased and winds decreased in Lake Tanganyika (Verburg and Hecky, 2009; Adrian *et al.*, 2009; Tierney *et al.*, 2010). Since the late 1970s, a drop in primary production and fish catches, a key protein source, has been observed, and climate change may exceed the effects of overfishing and other human impacts in this area (O'Reilly *et al.*, 2003). The Middle East and North Africa (MENA) face dwindling water resources due to less precipitation and rising temperatures combined with mounting water demand due to population and economic growth (Tekken and Kropp, 2012), resulting in rapidly decreasing water availability that, in 2025, could be 30-70% less per person (Sowers *et al.*, 2011). In MENA (Sowers *et al.*, 2011), the Andes and Himalayas (Orlove, 2009), the Caribbean (Cashman *et al.*, 2010), Australia (Alston, 2011), and in cities (Satterthwaite, 2011), policy allocation often favors more affluent consumers, at the expense of less powerful rural and/or poor users.

Weather events and climate also erode farming livelihoods (see Chapters 7, 9), via declining crop yields (Hassan and Nhemachena, 2008; Apata *et al.*, 2009; Sissoko *et al.*, 2011; Sietz *et al.*, 2012; Li *et al.*, 2013), at times compounded by increased pathogens, insect attacks, and parasitic weeds (Stringer *et al.*, 2007; Byg and Salick, 2009), and less availability of and access to non-timber forest products (Hertel and Rosch, 2010; Nkem *et al.*, 2012) and medicinal plants and biodiversity (Van Noordwijk, 2010). For agropastoral and mixed crop-livestock livelihoods, extreme high temperatures threaten cattle (Hahn, 1997; Thornton *et al.*, 2007; Mader, 2012; Nesamvuni *et al.*, 2012); in Kenya, for instance, people may shift from dairy to beef cattle and from sheep to goats (Kabubo-Mariara, 2008).

The most extreme form of erosion of natural assets is the complete disappearance of people's land on islands and in coastal regions (McGranahan *et al.*, 2007; Solomon *et al.*, 2009), exacerbating livelihood risks due to loss of economic and social assets (see Chapters 5 and 29) (Perch and Roy, 2010). Densely populated coastal cities with high poverty such as Alexandria and Port Said in Egypt (El-Raey *et al.*, 1999), Cotonou in Benin (Dossou and Glehouenou-Dossou, 2007), and Lagos and Port Harcourt in Nigeria (Abam *et al.*, 2000; Fashae and Onafeso, 2011) are already affected by floods and at risk of submersion. Resettlements are planned for the Limpopo River and the Mekong River Delta (de Sherbinin *et al.*, 2011) and small island states may become uninhabitable (Burkett, 2011).

Damage to *physical assets* due to weather events and climate is well documented for poor urban settlements, often built in risk-prone floodplains and hillsides susceptible to erosion and landslides. Impacts include homes destroyed by flood water and disrupted water and sanitation services. Flooding has adversely affected large cities in Africa (Douglas *et al.*, 2008) and Latin America (Hardoy and Pandiella, 2009; Hardoy *et al.*, 2011), in predominantly dense informal settlements due to inadequate drainage, and health infrastructure (UNDP, 2011c). Yet, upper middle- and high-income households living in flood-prone areas or high-risk slopes frequently can afford insurance and lobby for protective policies, in contrast to poor residents (Hardoy and Pandiella, 2009). Loss of physical assets in poor areas after disasters is often followed by displacement due to loss of property (Douglas *et al.*, 2008). Increasing flash floods attributed to climate change (Sudmeier-Rieux *et al.*, 2012) have severely damaged terraces, orchards, roads, and stream embankments in the Himalayas (Hewitt and Mehta, 2012; Azhar-Hewitt and Hewitt, 2012).

Erosion of *financial assets* as a result of climatic stressors include losses of farm income and jobs (Hassan and Nhemachena, 2008; Iwasaki *et al.*, 2009; Alderman, 2010; Jabeen *et al.*, 2010; Alston, 2011) and increased costs of living such as higher expenses for funerals (Gabrielsson *et al.*, 2012). In South and Central America, >630 weather and extreme events occurred 2000-2010, resulting in 16,000 fatalities, 46.6 million people affected, and economic losses of US$ 208 million (CRED, 2012). Income losses due to weather events mean less money for agricultural inputs (seeds, equipment), school tuition, uniforms, and books, and health expenses throughout the year (Thomas *et al.*, 2007). Flooding in informal settlements in Lagos undermines job opportunities (Adelekan, 2010).

Equally important, albeit frequently overlooked, is the damage to *human assets* as a result of weather events and climate, such as food insecurity, undernourishment, and chronic hunger due to failed crops (*medium evidence*) (Patz *et al.*, 2005; Funk *et al.*, 2008; Zambian Government, 2011; Gentle and Maraseni, 2012) or spikes in food prices most severely felt among poor urban populations (Ahmed *et al.*, 2009; Hertel and Rosch, 2010). During the Ethiopian drought (1998-2000) and Hurricane Mitch in Nicaragua (1998), poorer households tended to engage in asset smoothing, reducing their consumption to very low levels to protect their assets, whereas wealthier households sold assets and smoothed consumption (Carter *et al.*, 2007). In such cases, poor people further erode nutritional levels and human health while holding on to their limited assets. Dehydration, heat stroke, and heat exhaustion from exposure to heat waves undermine people's ability to carry out physical work outdoors and indoors (Semenza *et al.*, 1999; Kakota *et al.*, 2011). Psychological effects from extreme events include sleeplessness, anxiety and depression (Byg and Salick, 2009; Keshavarz *et al.*, 2013), loss of sense of place and belonging (Tschakert *et al.*, 2011; Willox *et al.*, 2012), and suicide (Caldwell *et al.*, 2004; Alston, 2011) (see also Chapter 11 and CC-HS).

Finally, weather events and climate also erode *social and cultural assets*. In some contexts, climatic and non-climatic stressors and changing trends disrupt informal social networks of the poorest, elderly, women, and women-headed households, preventing mobilization of labor and reciprocal gifts (Osbahr *et al.*, 2008; Buechler, 2009) as well as formal social networks, including social assistance programs (Douglas *et al.*, 2008). Indigenous peoples (see Chapter 12) witness their cultural points of reference disappearing (Ford, 2009; Green *et al.*, 2010; Bell *et al.*, 2010).

13.2.1.2. Impacts on Livelihood Dynamics and Trajectories

Weather events and climate also affect livelihood trajectories and dynamics in livelihood decision making, often in conjunction with cross-scalar socio-economic, institutional, or political stressors. Shifting in and out of hardship and well-being on a seasonal basis is not uncommon. To a large extent, the shifts from coping and hardship to recovery are driven by annual and inter-annual climate variability, but may become exacerbated by climate change. Figure 13-4 illustrates seasonal livelihood sensitivity for the Lake Victoria Basin in East Africa (Gabrielsson *et al.*, 2012).

[INSERT FIGURE 13-4 HERE
Figure 13-4: Seasonal sensitivity of livelihoods to climatic and non-climatic stressors for one calendar year, based on experiences of smallholder farmers in the Lake Victoria Basin in Kenya and Tanzania (Gabrielsson *et al.*, 2012).]

Shifts in livelihoods often occur due to changing climate trends, linked to a series of environmental, socio-economic, and political stressors (*robust evidence*). Farmers may change their crop choices instead of abandoning farming (Kurukulasuriya and Mendelsohn, 2007) or take on more lucrative income-generating activities (see Figure 13-3). Uncertainty about West Africa’s rainy season threatens small-scale farming and water management (Yengoh *et al.*, 2010a; Yengoh *et al.*, 2010b; Armah *et al.*, 2011; Karambiri *et al.*, 2011; Lacombe *et al.*, 2012). Around Mali’s drying Lake Faguibine, livelihoods shifted from water-based to agro-sylvo-pastoral systems, as a direct impact of lower rainfall and more frequent and more severe droughts (Brockhaus and Djoudi, 2008). Diverse indigenous groups in Russia have changed their livelihoods as result of Soviet legacy and climate change; for example, many Viliui Sakha have abandoned cow-keeping due to youth out-migration, growing access to consumer goods, and seasonal changes in temperature, rainfall, and snow (Crate, 2013). Under certain converging shocks and stressors, people adopt entirely new livelihoods. In South Africa, higher precipitation uncertainty raised reliance on livestock and poultry rather than crops alone in 80% of households interviewed (Thomas *et al.*, 2007). In southern Africa and India, people migrated to the coasts, switching from climate-sensitive farming to marine livelihoods (Coulthard, 2008; Bunce *et al.*, 2010a; Bunce *et al.*, 2010b). After Hurricane Stan (2005), land-poor coffee farmers in Chiapas, Mexico, turned from specializing in coffee to being day laborers and subsistence farmers (Eakin *et al.*, 2012).

13.2.1.3. Impacts on Poverty Dynamics: Transient and Chronic Poverty

Limited evidence documents the extent to which climate change intersects with poverty dynamics, yet, there is *high agreement* that shifts from transient to chronic poverty due to weather and climate are occurring, especially after a series of weather or extreme events (Scott-Joseph, 2010). Households in transient poverty may become chronically poor due to a lack of effective response options to weather events and climate, compared with more affluent households (see Figure 13-2). Often, multiple deprivations drive these shifts, with socially and economically marginalized groups particularly prone to slipping into chronic poverty. Women-headed households, children, people in informal settlements (see Chapter 8), and indigenous communities are particularly at risk, due to compounding stressors such as lack of governmental support, urban infrastructure, and insecure land tenure (see 13.2.1.5 and Chapter 12).

Poor people in urban areas in LICs and MICs in Africa, Asia, and Latin America may slip from transient to chronic poverty given the combination of population growth and flooding threats in low-elevation cities and water stress in drylands (Balk *et al.*, 2009) along with other multiple deprivations (Mitlin and Satterthwaite, 2013). Poverty shifts also occur in response to food price increases, though the strength of the relationship between weather events and climate and food prices is still debated (see Chapter 7 and 13.3.1.4). Poor households in urban and rural areas are particularly at risk when they are almost exclusively net buyers of food (Cranfield *et al.*, 2007; Cudjoe *et al.*, 2010; Ruel *et al.*, 2010). Misselhorn (2005) showed in a meta-study of 49 cases of food insecurity in southern Africa that climatic drivers and poverty were the two dominant and interacting causal factors. Poor pastoralists have collapsed into chronic poverty when livestock assets have been lost (Thornton *et al.*, 2007). In rural areas, restricted forest access may exacerbate poverty among already income-poor and elderly households who rely on forest resources to respond to climatic shocks (Fisher *et al.*, 2010). Yet, many such shifts remain underexplored, incompletely captured in poverty data and adaptation monitoring. The bulk of evidence in the literature is oriented toward extreme events, rapid-onset disasters, and subsequent impacts on livelihoods and poor people’s lives. Subtle changes are rarely tracked, making quantification of long-term trends and detection of impacts difficult.

13.2.1.4. Poverty Traps and Critical Thresholds

Poverty traps arise when climate change, variability, and extreme events keep poor people poor and make some poor even poorer. Yet, attribution remains a challenge. Among disadvantaged people in urban areas, poverty traps are reported especially for wage laborers who erode their financial capital due to increases in food prices (Ahmed *et al.*, 2009; Hertel and Rosch, 2010) and for those in informal settlements exposed to floods and landslides (Hardoy and Pandiella, 2009). In rural areas, poverty traps are reported when climate change impacts on poor people persist over decades, such as through environmental degradation and recurring stress on ecosystems in the Sahel (Kates, 2000; Hertel and Rosch, 2010; Sissoko *et al.*, 2011; UNCCD, 2011), or when people are unable to rebuild assets after a series of stresses (Eriksen and O'Brien, 2007; Sabates-Wheeler *et al.*, 2008; Sallu *et al.*, 2010). Poverty traps and destitution are also described in pastoralist systems, triggered through droughts, restricted mobility due to conflict and insecurity, adverse terms of trade, and the conversion of grazing areas to agricultural land, such as for biofuel production (Eriksen and Lind, 2009; Homewood, 2009; Eriksen and Marin, 2011). Other poverty traps result from heavy debt loads due to the inability to repay loans and distress sales (Renton, 2009; Ahmed *et al.*, 2012), persistent discrimination through legal structures and formal institutions, especially for women and other marginalized groups (Campbell *et al.*, 2009; McDowell and Hess, 2012), and at the nexus of climate, health and conflict (see Chapter 10).

Despite *limited evidence*, there is *high agreement* that critical thresholds, or irreversible damage (Heltberg *et al.*, 2009), result from the convergence of various factors, many of which are not directly related to climate change. For instance, poor people often rely on social networks, including reciprocal gifts and exchanges, to protect themselves from shocks and crises such as droughts and illness (Little *et al.*, 2006). Yet, given limited assets and ability to mobilize labor and food, particularly for smaller and women-headed households and the elderly, the exhaustion of these reciprocal ties can indicate an imminent slipping into poverty traps or chronic poverty (Pradhan *et al.*, 2007; Osbahr *et al.*, 2008). Injuries, disabilities, disease, psychological distress, for example from accidents during flood events, diminish poor people's main asset, labor (Douglas *et al.*, 2008), and may plunge them into chronic poverty.

Few studies illustrate positive livelihood impacts as a result of climate change or climate-induced shocks, and they often tend to refer to more affluent and powerful constituencies. Very scarce evidence exists of poor people escaping poverty traps (see Figure 13-2). In Cameroon, though, farming communities benefit from occasional rainfall during the dry season and more food stuffs while the drying of swamps allows maize off season (Bele *et al.*, 2013). In Lake Victoria Basin, collective action has increased as a result of HIV/AIDS and climate change, boosting social assets (Gabrielsson and Ramasar, 2012). Lessons from Hurricane Mitch (1998) in Honduras point toward more equitable land distribution and better flood preparedness that benefit the poor after disasters (McSweeney and Coomes, 2011).

13.2.1.5. Multidimensional Inequality and Vulnerability

Climate variability and change as well as climate-related disasters contribute to and exacerbate inequality, in urban and rural areas, in LICs, MICs, and HICs. Mounting inequality is not just a side effect of weather and climate but of the interaction of related impacts with multiple deprivations at the context-specific intersections of gender, age, race, class, caste, indigeneity, and (dis)ability, embedded in uneven power structures, also known as intersectionality (Nightingale, 2011; Kaijser and Kronsell, 2013) (see Figure 13-5). This section illustrates how climate impacts intersect with inequality, primarily along the lines of gender, age, and indigeneity. Other chapters are referenced.

[INSERT FIGURE 13-5 HERE
Figure 13-5: Multidimensional vulnerability driven by intersections dimensions of inequality.]

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Box 13-1. Climate and Gender Inequality: Complex and Intersecting Power Relations

Existing ***gender inequality*** (see Box CC-GC) is increased or heightened as a result of weather events and climate-related disasters intertwined with socioeconomic, institutional, cultural, and political drivers that perpetuate differential vulnerabilities (*robust evidence*) (Lambrou and Paina, 2006; Brouwer *et al.*, 2007; Shackleton *et al.*, 2007; Adger *et al.*, 2007; Carr, 2008; Galaz *et al.*, 2008; Osbahr *et al.*, 2008; Demetriades and Esplen, 2008; Buechler, 2009; Nightingale, 2009; Terry, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resurreccion, 2011; Zotti *et al.*, 2012; Heckenberg and Johnston, 2012; Shah *et al.*, 2013; Alston and Whittenbury, 2013; Rahman, 2013). While earlier studies have tended to highlight women's quasi-universal vulnerability in the context of climate change (e.g. Denton, 2002), this focus can ignore the complex, dynamic, and intersecting power relations and other structural and place-based causes of inequality (Nightingale, 2009; UNFPA, 2009; Arora-Jonsson, 2011). Moreover, the construction of economically poor women as victims denies women's agency and emphasizes their vulnerability as their intrinsic problem (MacGregor, 2010; Manzo, 2010; Arora-Jonsson, 2011).

Gendered livelihood impacts: Men and women are differentially affected by climate variability and change. The ten-year drought in Australia's Murray-Darling Basin differentially affected men and women, due to their distinct roles within agriculture (e.g. Eriksen *et al.*, 2010). Alston (2011) noted social disruption and depression, most profound in areas with almost total reliance on agriculture, no substitute employment, and limited service infra-structure (Table 13-1). In India, more women than men, especially women of lower castes, work as wage laborers to compensate for crop losses (Lambrou and Nelson, 2013) while in Tanzania, wealthier women hire poorer women to collect animal fodder during droughts (Muthoni and Wangui, 2013). Climate variability amplifies food shortages in which women consume less food (Lambrou and Nelson, 2013) and suffer from reproductive tract infections and water-borne diseases after floods (Neelormi *et al.*, 2008; Campbell *et al.*, 2009). Women farmers in the Philippines relying on high-interest loans were sent to jail after defaulting on debts following crop failure (Peralta, 2008). In Uganda, men were able to amass land after floods while droughts reduced women's non-land assets (Quisumbing *et al.*, 2011). In Ghana, some husbands prevent their wives from cultivating individual plots as a response to gradually shifting rainfall seasonality, thereby undermining both women's agency and household well-being (Carr, 2008).

Feminization of responsibilities: Campbell *et al.* (2009) and Resurreccion (2011), in case studies from Vietnam, found increased workloads for both partners linked to weather events and climate, contingent on socially accepted gender roles: men tended to work longer hours during extreme events and women adopted extra responsibilities during disaster preparation and recovery (e.g., storing food and water and taking care of the children, the sick, and the elderly) and when their husbands migrated. In Cambodia, Khmer men and women accepted culturally-taboo income-generating activities under duress, when rice cropping patterns shifted due to higher temperatures and more irregular rainfall (Resurreccion, 2011). Despite increased workloads for both sexes, women's extra work adds to already many labor and caring duties (Nelson and Stathers, 2009; MacGregor, 2010; Petrie, 2010; Arora-Jonsson, 2011; Kakota *et al.*, 2011; Resurreccion, 2011; Muthoni and Wangui, 2013; Shah *et al.*, 2013). In Nepal, shifts in the monsoon season, longer dry periods, and decreased snowfall push Dalit girls and women ('untouchable' caste) to grow drought-resistant buckwheat and offer more day labor to the high caste Lama landlords while Dalit men seek previously taboo patronage protection to engage in cross-border trade (Onta and Resurreccion, 2011). Rising male out-migration, e.g., in Niger and South Africa, leave women with all agricultural tasks yet limited extra labor (Goh, 2012). Additional workloads exhaust women emotionally and physically, shown in South Africa (Babugura, 2010).

Occupational hazards: Increasing cases of heat death are reported among male workers on sugarcane plantations in El Salvador due to kidney failure (Peraza *et al.*, 2012) and heat-related indoor work emergencies in Spain among young (<50) able-bodied urban men (García-Pina *et al.*, 2008). Anecdotal evidence suggests that women tea pickers in Malawi, Kenya, India, and Sri Lanka suffer and die from heat stress as payment by quantity discourages rest breaks (Renton, 2009) (see also Chapter 11 and CC-HS). In cases of male outmigration due to unsustainable rural livelihoods, women in Bangladesh face unsafe working conditions, exploitation, and loss of respect (Pouliotte *et al.*, 2009). Yet, male outmigration could provide opportunities for women to move beyond traditionally constrained roles, explore new livelihood options, and access public decision-making space (CIDA, 2002; Fordham *et al.*, 2011).

Emotional and psychological distress: Climate-related disasters or gradual environmental deterioration can affect women's mental health disproportionally due to their multiple social roles (UN ECLAC, 2005; Babugura, 2010; Boetto and McKinnon, 2013; Hargreaves, 2013). Increased gender-based violence within households is reported as an indirect social consequence of climate-related disasters, as well as slow-onset climate events, due to greater stress and tension, loss and grief, and disrupted safety nets, reported for Australia (Anderson, 2009; Alston, 2011;

Parkinson *et al.*, 2011; Whittenbury, 2013; Hazeleger, 2013), New Zealand (Houghton, 2009), the U.S. (Jenkins and Phillips, 2008; Anastario *et al.*, 2009), Vietnam (Campbell *et al.*, 2009) and Bangladesh (Pouliotte *et al.*, 2009).

Mortality: Social conditioning affects mortality for women and men. Rahman (2013) and Nellemann et al. (2011) confirm patterns of gender disparity with respect to swimming that contribute to high number of female deaths due to climate-related disasters. Restricted mobility keeps women in Bangladesh and Nicaragua waiting in risk-prone houses during floods (Saito, 2009; Bradshaw, 2010). Some disaster relief structures that lack facilities appropriate for women may contribute to increased harm and mortality (World Bank, 2010). When they are socio-economically disadvantaged and the disasters exacerbate existing patterns of discrimination, more women die in hurricanes and floods (Neumayer and Plümper, 2007; Ray-Bennett, 2009). Yet, men experience a higher mortality rate when fulfilling culturally-imposed roles as heroic life-savers (Röhr, 2006; Campbell *et al.*, 2009; Resurreccion, 2011).

[INSERT TABLE 13-1 HERE
Table 13-1: Examples of gendered climate experiences.]

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Medium evidence highlights impacts of climate stresses and extreme events on *children* (Cutter *et al.*, 2012; O'Brien *et al.*, 2012). Children in urban slums suffer from inadequate water supplies and malnutrition, which exacerbates impacts from heat stress, while excessive rain heightens water-borne diseases (Bartlett, 2008). Flood-related mortality in Nepal was twice as high for girls as for women (13.3 per 1,000 girls) and also higher for boys than for men, and for young children in general six times higher than before the flood (Pradhan *et al.*, 2007). Lower caloric intake due to two back-to-back droughts and price shocks in Zimbabwe in the 1980s resulted in physical stunting among children and reduced lifetime earnings (Alderman, 2010). In Mali, the incidence of child food poverty increased from 41% to 52% since the 2006 food price increases (Bibi *et al.*, 2010). See Chapter 11 for more details.

Health impacts of weather events and climate differentially affect *the elderly* and *socially isolated* (Frumkin *et al.*, 2008) (see also Chapter 11). In Vietnam the elderly, widows, and disabled people, in addition to single mothers and women-headed households with small children, were least resilient to floods and storms and slow-onset events such as recurrent droughts (Campbell *et al.*, 2009). In Australia, older citizens have shown feelings of distress as a result of familiar landscapes altered by drought, loss of home gardens, social isolation, and physical harm related to heat stress and wild fires (Pereira and Pereira, 2008; Horton *et al.*, 2010; Polain *et al.*, 2011). Elderly citizens in the U.K. may underestimate the risk and severity of heat waves through their social networks and fail to act (Wolf *et al.*, 2010). In the U.S., Europe, and South Korea, the elderly, children, and persons of lower socio-economic status have a heightened risk of heat-related mortality (Baccini *et al.*, 2008; Balbus and Malina, 2009; Son *et al.*, 2012). Preliminary evidence suggests differential harm of 2012 Superstorm Sandy in New York, observed among elderly people and medically underserved populations (Pagán Motta, 2013; Teperman, 2013; Uppal *et al.*, 2013).

Inequality and disproportionate effects of climate-related impacts also occur along the axes of *indigeneity a*nd *race*. Disproportionate climate impacts are documented for Afro-Latinos and displaced indigenous groups in urban Latin America (Hardoy and Pandiella, 2009), and indigenous peoples in the Russian North (Crate, 2013) and the Andes (Andersen and Verner, 2009; Valdivia *et al.*, 2010; McDowell and Hess, 2012; Sietz *et al.*, 2012). See Chapter 12 for impacts on indigenous cultures. In the U.S., low-income people of color are more affected by climate-related disasters (Sherman and Shapiro, 2005; Morello-Frosch *et al.*, 2009; Lynn *et al.*, 2011) as demonstrated in the case of low-income African-American residents of New Orleans after Hurricane Katrina (Elliott and Pais, 2006).

13.2.2. Understanding Future Impacts of and Risks from Climate Change on Livelihoods and Poverty

Future climate change, as projected through modeling, will continue to affect poor people in rural and urban areas in LICs, MICs, and HICs, alter their livelihoods, and make efforts to reduce poverty more difficult (*high confidence*). Studies reveal a broad range of impacts for the near- (2030-2040) and long-term (2080-2100) future, depending on the climatic, agro-economic, and demographic models employed, their key variables, and spatial scale, which vary from a country’s agro-ecological zones to the global. Few projections take into account policy options or adaptation.

Projections emphasize the complexity and heterogeneity of future climate impacts, including winners and losers in close geographic proximity. Anticipated impacts on the poor are expected to interact with multiple stressors, most notably social vulnerability (Iglesias *et al.*, 2011), low adaptive capacity and subsistence constraints under chronic poverty (Liu *et al.*, 2008), weak institutional support (Menon, 2009; Xu *et al.*, 2009; Skoufias *et al.*, 2011a; Skoufias *et al.*, 2011b), population increases (Müller *et al.*, 2011), natural resource dependence (Adano *et al.*, 2012), ethnic conflict and political instability (Challinor *et al.*, 2007; Adano *et al.*, 2012), large-scale land conversions (Assuncao and Cheres, 2008; Thornton *et al.*, 2008), and inequitable trade relations (Challinor *et al.*, 2007; Jacoby *et al.*, 2011).

Table 13-2 illustrates estimated risks and adaptation potentials for livelihoods and poverty dimensions until 2100.

[INSERT TABLE 13-2 HERE
Table 13-2: Key risks from climate change for poor people and their livelihoods and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgment by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented in three timeframes: present, near-term (2030-2040), and long-term (2080-2100). Near-term indicates that projected levels of global mean temperature do not diverge substantially across emissions scenarios. Long-term differentiates between a global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adaptive state. Bars that only show the latter indicate a limit to adaptation (see Chapter 16). Relevant climate variables are indicated by symbols. This table should not be used as a basis for ranking severity of risks.]

13.2.2.1. Projected Risks and Impacts by Geographic Region

Climate change will exacerbate risks and in turn further entrench poverty (*very high confidence*). The well known and highly referenced Wheeler data set (2011) analyzes climate risk and coping ability by country. Future increases in the frequency of extreme events are overlaid with considerable poverty, although not all poor people will be at risk. Of the 20 countries and regions most at risk, seven are LICs (Bangladesh, Ethiopia, Kenya, Madagascar, Mozambique, Somalia, and Zimbabwe), eight are LMICs (Bolivia, Djibouti, Honduras, India, Philippines, Sri Lanka, Vietnam, and Zambia), four are UMICs (China, Colombia, Cuba, and Thailand), and one is a HIC (Hong Kong). For China, Djibouti, India, Kenya, and Somalia, climate contributes between 46.4% and 87.5% to a 2008-2015 rise in national risk, compared to income and urbanization. Highest sensitivity to sea level rise by 2050, based on low-elevation coastal zones, population density, and areas of storm surge zones, is expected for India, Indonesia, China, the Philippines, and Bangladesh. India and Indonesia are projected to experience a 80% and 60% increase, respectively, in their populations at risk from sea level rise, housing a combined total of >58 million people most at risk by 2050; six million people more at risk from sea level rise in China will bring its total to 22 million, and Bangladesh's at-risk population is predicted to grow to 27 million – more than double since 2008 (Wheeler, 2011).

Specific regions at high risk are those exposed to sea-level rise and extreme events and with concentrated multi-dimensional poverty, including pockets of poor people in LICs and MICs: mega-deltas in Bangladesh, Thailand, Myanmar, and Vietnam (Eastham *et al.*, 2008; Wassmann *et al.*, 2009), drylands (Anderson *et al.*, 2009; Piao *et al.*, 2010; Sietz *et al.*, 2011), mountain areas (Beniston, 2003; Valdivia *et al.*, 2010; Gerlitz *et al.*, 2012; McDowell and Hess, 2012; Gentle and Maraseni, 2012), watersheds in the Himalayas (Xu *et al.*, 2009), ecologically-fragile areas in China (Taylor and Xiaoyun, 2012), coastal areas with severe ecosystem deterioration in eastern and southern Africa (Bunce *et al.*, 2010a; Bunce *et al.*, 2010b) and river deltas subject to resource extraction (Syvitski *et al.*, 2009).

13.2.2.2. Anticipated Impacts on Economic Growth and Agricultural Productivity

Most projected future impact studies focus on the long-term effects of climatic changes and shocks on agricultural productivity, mainly in Africa, Asia, and Latin America. They typically examine impacts on economic growth (see also Chapter 10), changes in food prices and food security, and extrapolated changes in poverty head counts.

For future poverty head counts caused by climate change, the literature shows disagreement. For the very near future, a study by Thurlow et al. (2009) estimates that, by 2016, Zambia's poverty headcount would increase by 300,000 people under average climate variability, and by 650,000 under a worst ten-year rainfall sequence. Skoufias et al. (2011b), using 2055 predictions based on the Nordhaus (2010) RICE model, state that under business-as-usual and optimal abatement, global poverty (measured at $2/day) could be reduced by 800 million people, due to annual and real per capita growth rate of 2.2% up to 2055. However, lower probability extreme events would reverse this trend, and mitigation under optimal abatement typically excludes people living in poverty (Skoufias *et al.*, 2011b). In contrast, Tubiello et al. (2008) project that, by 2080, the number of undernourished people may increase by up to 170 million, using the A2 SRES scenarios, and up to a total of 1,300 million people assuming no CO_2 fertilization.

Projections of future climate change impacts on GDP use non-disaggregated poverty data. For instance, Mendelsohn et al. (2006) use dynamic coupled ocean–atmosphere models and market response functions to simulate the distribution of climate impacts for 2100. Independent of the climate scenarios, poor countries, mainly in Africa and Southeast Asia, will face the largest losses (0.2-1.2% reduction in GDP) and, under experimental models, up to 23.8% drop in GDP; in contrast, the richest quartile will encounter both positive and negative effects, ranging -0.1% to +0.2% GDP, and up to a 0.9% GDP increase under experimental models. Changes in GDP reflect climate-sensitive economic sectors, especially water and energy, with poor nations in low latitudes already facing high temperatures and thus more vulnerable to decreased agricultural productivity with increased warming. One study for the U.S., using the SRES A2 scenario, projects that four climate change impacts – hurricane damage, energy costs, water costs, and real estate – are expected to cost 1.8% of the country's GDP by 2100, leading to higher household costs for basic necessities like energy and water (Ackerman *et al.*, 2008). Groups that spend the highest proportion of their income on these necessities will be disproportionately affected.

A growing body of literature estimates future changes in agricultural production and food prices due to climate change, variability, and extreme events (Slater *et al.*, 2007; Thomas *et al.*, 2007; Assuncao and Cheres, 2008; Burke *et al.*, 2011) (see Chapters 7, 9, and CC-HS). Mixed trends are projected for major staples for all continents until the mid-21st century. For the near-term future, the production of coarse grains in Africa may be reduced by 17-22% due to climate change; well-fertilized modern seed varieties are projected to be more susceptible to heat stress than traditional ones (Schlenker and Lobell, 2010). By 2080, a major decrease in land productivity is expected for sub-Saharan Africa (-14% to -27%) and Southeast Asia (-18% to -32%), coupled with increase in water demand, while lowest risks are projected for North America, Europe, East Asia, Russia, and Australia (Iglesias *et al.*, 2011).

13.2.2.3. Implications for Livelihood Assets, Trajectories, and Poverty Dynamics

Projections of near- and long-term climate change impacts on livelihood assets highlight the erosion of financial assets as a result of increased food prices (Thurlow *et al.*, 2009; Seo *et al.*, 2009; Ahmed *et al.*, 2009; Hertel *et al.*, 2010; Jacoby *et al.*, 2011; Skoufias *et al.*, 2011b), human assets due to decline in nutritional status (Liu *et al.*, 2008), and natural assets due to lower agricultural productivity (Thurlow *et al.*, 2009; Jones and Thornton, 2009; Skoufias *et al.*, 2011b). They also show a substantial increase in future heat-related mortality (Basu and Samet, 2002; McGregor *et al.*, 2006; Sherwood and Huber, 2010; Huang *et al.*, 2011), increasing infectious disease transmission rates (Green *et al.*, 2010), and other health impacts (see Chapter 11). Impacts on social and cultural assets have received little attention. Exceptions address losses of social identity and cultural connections with land and sea among indigenous populations threatened by sea level rise and potential relocation (Green *et al.*, 2010) and conflicts between ethnic and/or religious groups (Adano *et al.*, 2012) (see Chapter 12). Poor households with limited social networks will be worst off, including in places such as Nepal (Menon, 2009) and Indonesia (Skoufias *et al.*, 2011a).

Climate change is also projected to cause shifts in livelihood trajectories. In Mali's agricultural-pastoralist transition zone, due to temperature increase and drying projected for 2025 and coupled with a 50% increase in population, shifts from rain-fed millet and sorghum to semi-arid, predominantly livestock subsistence are expected to expose an extra six million people to malnutrition, including 250,000 children suffering from stunting (Jankowska *et al.*, 2012). Simulated probabilities of failed seasons, using current daily rainfall data and 2050 projections for the length of growing period, show transitions from cropping to livestock in other marginal cropping areas in Africa (Thomas *et al.*, 2007; Jones and Thornton, 2009). The HadCM3 and A1F1 models show that, by 2050, expanding vector populations, especially tsetse, and a >20% decline in growing period, in livestock-dependent and mixed crop-livestock livelihoods in semi-arid to arid Africa and Asia, combined with increasing water scarcity and stover loss due to maize substitution (Thornton *et al.*, 2007) will stress livelihoods of poor farmers and pastoralists.

Future climate change impacts on disaggregated poverty are mainly addressed through projected changes in food prices and earnings associated with impacts on agricultural production (Schmidhuber and Tubiello, 2007). Changes in price-induced earnings lower the welfare of low-income households, particularly urban and wage-labor dependent households that use a large income share to purchase staple crops. In the near-term future, under low productivity scenarios assuming rapid temperature increase by 2030, poverty among the agricultural self-employed in 15 LICs and MICs may drop due to benefits from selling surplus production at higher prices, by as much as 40% in Chile and the Philippines; however, higher food prices may lead to a drop in national welfare, as steep as 55% in South Africa (Hertel *et al.*, 2010). In most LICs and MICs, the poverty headcount is expected to drop in some occupational strata and increase in others; only in most African countries are yield impacts expected to be too severe to allow benefits (Hertel and Rosch, 2010). Long-term, a one-time maximum extreme dry event, simulated for 1971-2000 and 2071-2100 using the IPCC-SRES A2 scenario for 16 LICs and MICs, shows a 95-110% raise in poverty for urban wage groups in Malawi, Zambia, and Mexico, while self-employed farming households consolidate assets and face the smallest increase in vulnerability (Ahmed *et al.*, 2009). By 2100, climate change would leave low-income, minority, and politically marginalized groups in California’s agriculture with fewer economic opportunities, based on SRES B1 and A1Fi scenarios, particularly in dairy and grape production (Cordova *et al.*, 2006; Shonkoff *et al.*, 2011).

13.2.2.4. Impacts on Transient and Chronic Poverty, Poverty Traps, and Thresholds

Existing projections do not provide robust evidence to estimate whether shifts from transient to chronic poverty will occur as a result of climate change, and to what extent. However, a predicted increase in the number of urban poor, especially wage laborers, suggests that a large number may shift from transient to chronic poverty due to exposure to food price increases, or find themselves in a poverty trap, especially under scenarios with long-duration climatic shifts and prolonged droughts (Ahmed *et al.*, 2009; Hertel *et al.*, 2010). In Zambia, almost half of the 650,000 new poor under the worst historic 10-year period projected till 2016 are expected to be in urban areas while rural poverty remains high (Thurlow *et al.*, 2009). In Tanzania, Ahmed et al. (2011), based on a high precipitation volatility GCM, predict up to 1.17 million new poor into the near-term future (up to 2031). Shifts in and out of poverty may occur by 2050 for small-scale coffee farmers in Central America, as suitable coffee growing areas move to higher altitudes, especially when constrained by unequal access to agro-technical and climatic information (Laderach *et al.*, 2011).

Poor countries will face greater poverty as a result of climate change and extreme events (*medium confidence*), due to location and low-latitude high temperatures (Mendelsohn *et al.*, 2006) anticipated further decline in adaptive capacity combined with reductions in agricultural productivity (Iglesias *et al.*, 2011), greater inequality and deep-rooted poverty (Jones and Thornton, 2009), and lower levels of education and large numbers of young dependents (Skoufias *et al.*, 2011c). Although robust projections on poverty traps are lacking, they may be associated with emerging hotspots of hunger, such as those projected for Tanzania, Mozambique, and the Democratic Republic of Congo (DRC) by 2030 (Liu *et al.*, 2008). Based on SRES scenarios, Devitt and Tol (2012) project long-term coupled climate change- and conflict-induced poverty traps for the DRC and several other sub-Saharan countries.

Some climate change projections (see CC-HS and WG1 Chapters 11, 12, and 14) indicate the possibility of large impacts that may exceed thresholds of detrimental shocks to livelihoods and poverty, unless strong adaptation and/or mitigation responses are implemented in a timely manner (Kovats and Hajat, 2008; Sherwood and Huber, 2010). Since women do most of the agricultural work, they will suffer disproportionally from heat stress; for instance, in parts of Africa, women carry out 90% of hoeing and weeding and 60% of harvesting work (Blackden and Wodon, 2006). Toward the end of the century, the risk of heat stress may become acute in parts of Africa, particularly the Sahel, and the Indian sub-continent, potentially preventing people from practicing agriculture (Patricola and Cook, 2010; Dunne *et al.*, 2013). In the glacier-dependent Himalayan region, excessive runoff and flooding will threaten livelihoods (Xu *et al.*, 2009). Relocation would represent a critical threshold for indigenous groups, due to sea level rise for the Torres Strait Islanders between Australia and Papua New Guinea (Green *et al.*, 2010) and permafrost degradation and higher and seasonally erratic precipitation for the Viliui Sakha in the Russian North (Crate, 2013).

13.3. Assessment of Impacts of Climate Change Responses on Livelihoods and Poverty

Climate change responses interact with social and political processes to affect sustainable development and climate resilient pathways (Chapter 20), and in turn, livelihoods and poverty. Climate mitigation and adaptation responses include formal policies by governments, NGOs, bilateral and multilateral organizations as well as actions by individuals and communities. Such policy responses were designed to have positive effects on sustainable development or at least be neutral in terms of unintended side effects. Yet, much of the peer-reviewed literature scrutinizing these responses suggests otherwise. This section reviews empirical evidence of impacts of particular mitigation (13.3.1) and adaptation (13.3.2) responses in the context of livelihood and poverty trajectories and inequalities. Some of this evidence is preliminary as several policies are still in their infancy while other cases fail to assess multidimensional poverty or dynamic livelihood decision making in the context of climate change responses.

13.3.1. Impacts of Mitigation Responses

Many synergies between climate change mitigation policies and poverty alleviation have been identified in the literature (Klein *et al.*, 2005; Ürge-Vorsatz and Tirado Herrero, 2012), but evidence of positive outcomes is limited. Impacts of current mitigation policies on livelihoods and poverty are controversial with polarized views on the potential of such policies for sustainable development in general and poverty alleviation in particular (Collier *et al.*, 2008; Böhm, 2009; Hertel and Rosch, 2010; Michaelowa, 2011). This section assesses the observed and potential impacts of four climate change responses on livelihoods and poverty: the two mitigation responses most significant for poverty alleviation under the UNFCCC, the CDM and REDD+, and two mitigation responses outside of the UNFCCC, voluntary carbon offsets and biofuel production.

13.3.1.1. The Clean Development Mechanism (CDM)

The CDM (see Chapter 13 in WGIII) aims to promote sustainable development and thus CDM projects require approval by the host country's designated national authority. CDM projects as diverse as low-cost energy services in India, micro-hydro projects in Bhutan and Peru, efficient firewood use in Nigeria, and biogas digesters in China and Vietnam, are expected to generate livelihood benefits and employment, and reduce poverty among beneficiaries (UNFCCC, 2011; UNFCCC, 2013). The secretariat's own assessment of the CDM's development benefits along 15 indicators suggested much room for improvement (UNFCCC, 2011). Most of the statistical information in official reports on CDM is based either on project documents or on surveys of project personnel rather than in-depth studies.

The assessment of the CDM in the peer-reviewed literature is more cautious and pessimistic than UNFCCC, and three reviews (Olsen, 2007; Sutter and Parreño, 2007; Michaelowa and Michaelowa, 2011) contend that the current CDM design is neither pro-poor nor contributes to sustainable development. One reason for the low performance on sustainable development criteria is that the CDM does not have any requirements for monitoring and verification of development impacts as required for emissions reductions (Boyd *et al.*, 2009). Critiques entail obstacles and ethical dilemmas in carbon trading (Liverman, 2009; Newell and Bumpus, 2012), difficulties with implementation (Borges da Cunha *et al.*, 2007; Minang *et al.*, 2007; Gong, 2010), procedural limitations (Lund, 2010), and carbon offset goals favored over poverty reduction goals (Wittman and Caron, 2009). While some authors claim that the CDM undermines local and non-governmental input (Shin, 2010; Corbera and Jover, 2012), others stress its transparency, including the voices of local stakeholders (Michaelowa *et al.*, 2012). Also, the CDM may compete with the informal sector (Newell and Bumpus, 2012) and accentuate uneven development by eroding local livelihood security (Boyd and Goodman, 2011). In a meta-analysis of 114 CDM projects, Crowe (2013) conclude that <10% of CDM projects had successfully delivered pro-poor benefits and only one of them had positive ratings on all seven criteria for pro-poor benefits. Among the most promising examples are CDM projects in India supporting community-designed plans to strengthen participation of marginalized groups (Subbarao and Lloyd, 2011; Boyd and Goodman, 2011).

13.3.1.2. Reduction of Emissions from Deforestation and Forest Degradation (REDD+)

Experience with REDD+ and other forest carbon projects is inadequate to permit generalizations about effects on livelihoods and poverty (Cotula *et al.*, 2009; Hayes and Persha, 2010; Springate-Baginski *et al.*, 2010) (see Chapter 9). A study of 20 avoided deforestation projects prior to REDD+ in Latin America, Africa, and Asia shows that only five conducted some outcome or impact assessment, revealing a lack of rigor in evaluation (Caplow *et al.*, 2011).

Despite optimism in policy analyses about the potential of REDD+ for poverty alleviation (Angelsen *et al.*, 2009; Kanowski *et al.*, 2011; Rahlao *et al.*, 2012; Somorin *et al.*, 2013), there is growing evidence and *high agreemen*t in the peer-reviewed literature that REDD+ may not lead to poverty alleviation and that there may even be negative consequences. Concerns include threats to the poor (Phelps *et al.*, 2010; Ghazoul *et al.*, 2010; Larson, 2011; Van Dam, 2011; McDermott *et al.*, 2011; Börner *et al.*, 2011; Neupane and Shrestha, 2012; Mahanty *et al.*, 2012) and indigenous peoples (Shankland and Hasenclever, 2011). Latent negative impacts include exclusion of local people from forest use, and loss of local ownership in documenting the state of forests due to external monitoring and verification mechanisms (Gupta *et al.*, 2012; Pokorny *et al.*, 2013). Benefit flows may be unevenly distributed with regards to ethnicity (Krause and Loft, 2013), gender (UN-REDD, 2011; Peach Brown, 2011), or simply not target the poor (Hett *et al.*, 2012). The absence of a global REDD+ mechanism means that progress on REDD+ may occur as much through voluntary bilateral and public-private processes as through multilateral, regulatory requirements (Agrawal *et al.*, 2011). Positive future benefits for poor people from REDD+ will require attention to tenure and property rights, gender interests, and community engagement (Danielsen *et al.*, 2011; Mustalahti *et al.*, 2012).

The 2010 Cancun Agreements highlight safeguards for governments to observe in REDD+ implementation, such as respect for the interests, knowledge, rights, and sustainable livelihoods of communities and indigenous peoples. If these safeguards will be observed in practice is unclear due to the early implementation state of REDD+ in most countries as well as the uncertainty of the future of the global carbon market (Lohmann, 2010; Savaresi, 2013).

13.3.1.3. Voluntary Carbon Offsets

The voluntary carbon offset (VCO) market is significant from a livelihoods and poverty perspective because it typically targets smaller projects and may be better at reaching poor communities (Estrada and Corbera, 2012), though it is modest in size compared to the regulated market (~1%). Also, those involved in the VCO market, namely individuals, companies, organizations, and countries that have not ratified the Kyoto Protocol, are often more willing to pay for carbon offsets with co-benefits such as poverty alleviation (MacKerron *et al.*, 2009).

Activities under VCO are dominated by renewable energy, primarily wind power (30%), forestation projects, including REDD+ (19%), and methane destruction in landfills (7%) (Peters-Stanley and Hamilton, 2012). It is too early to tell whether these VCO projects are successful in terms of poverty alleviation and other social goals, and results to date are highly mixed (Jindal *et al.*, 2008; Swallow and Meinzen-Dick, 2009; Jindal, 2010; Estrada and Corbera, 2012; Stringer *et al.*, 2012). Reported benefits include livelihood diversification, increased disposable income, biodiversity conservation, and strengthening local organizations, while exacerbated inequalities and loss of access to local resources are known negative impacts (Estrada and Corbera, 2012). A study in Kenya, Senegal, and Peru shows reduced losses of soil fertility in three soil carbon sequestration projects, but also the inability of the poorest farmers to participate and only marginal impacts on poverty reduction (Antle and Stoorvogel, 2009). Out of 78 projects in 23 countries in sub-Saharan Africa, only one promoted local social, economic, and environmental benefits while the rest focused mainly on efficiency of emission reductions (Karavai and Hinostroza, 2013).

13.3.1.4. Biofuel Production and Large-Scale Land Acquisitions

Biofuel production, often linked to transnational large-scale land acquisitions (LSLA), is a near-term climate change mitigation response that raises two major livelihood and poverty concerns: food price increases and dispossession of land (see Chapters 4 and 9). LSLA have soared since 2008 (Von Braun *et al.*, 2009; Deininger *et al.*, 2011; Borras Jr *et al.*, 2011), partly linked to climate change responses (*medium evidence, high agreement*). Biofuel production is considered the primary driver, but there may be links to climate change through high food prices (Daniel, 2011), food insecurity (Robertson and Pinstrup-Andersen, 2010; Rosset, 2011; Sulser *et al.*, 2011), and carbon markets potentially raising land prices, e.g. REDD+ (Cotula *et al.*, 2009; Zoomers, 2010; Anseeuw *et al.*, 2012). LSLA global targets are biofuels (40%), food (25%) and forestry (3%), with much regional variation (Anseeuw *et al.*, 2012). The IPCC special report on renewable energy highlighted the uncertainties around the role of biofuels in food price increases and risks of deteriorating food security with future deployment of bioenergy (Edenhofer *et al.*, 2011).

Increasing demand for biofuels shifts land from food to fuel production, which may increase food prices (Collier *et al.*, 2008) disproportionally affecting the poor (Von Braun and Ahmed, 2008; Ruel *et al.*, 2010; Bibi *et al.*, 2010). Despite high agreement that biofuel production plays a role in food prices, little consensus exists on the size of this influence (Von Braun and Ahmed, 2008; Mitchell, 2008; Aksoy and Isik-Dikmelik, 2008; Elobeid and Hart, 2008; Baffes and Haniotis, 2010; Ajanovic, 2011; Condon *et al.*, 2013). Some studies link the 2007/08 price spike to speculation in agricultural futures markets (Runge and Senauer, 2007; Ghosh, 2010) driven partly by potential future profits from biofuels while their role was relatively less important in the 2010/11 price spike (Trostle *et al.*, 2011).

LSLA have also triggered a land rush in LICs, which affects livelihood choices and outcomes, with some distinct gender dimensions (Chu, 2011; De Schutter, 2011; Julia and White, 2012; Peters, 2013). New competition for land dispossesses smallholders, displaces food production, degrades the environment, and pushes poor people onto more marginal lands less adaptable to climatic stressors (Cotula *et al.*, 2009; Borras Jr *et al.*, 2011; Rulli *et al.*, 2013; Weinzettel *et al.*, 2013). The expansion of bioenergy, and biofuels in particular, increases the corporate power of international actors over governments and local actors with harmful effects on national food and agricultural policies (Dauvergne and Neville, 2009; Glenna and Cahoy, 2009; Hollander, 2010; Mol, 2010; Fortin, 2011; Jarosz, 2012), further marginalizing smallholders (Ariza-Montobbio *et al.*, 2010; De Schutter, 2011; Neville and Dauvergne, 2012) and indigenous peoples (Montefrio, 2012; Obidzinski *et al.*, 2012; Montefrio and Sonnenfeld, 2013; Manik *et al.*, 2013). There is growing apprehension that increased competition for scarce land undermines women's access to land and their ability to benefit economically from biofuel investment (Molony, 2011; Arndt *et al.*, 2011; Chu, 2011; Julia and White, 2012; Behrman *et al.*, 2012; Perch *et al.*, 2012). Concerns differ somewhat among regions, with the greatest risk for negative outcomes for smallholders in Africa (Daley and Englert, 2010; Borras *et al.*, 2011).

Mainstream economic modeling offers optimism that biofuels may boost investment, employment, and economic growth, in LICs such as Mozambique (Arndt *et al.*, 2009) and MICs such as India (Gopinathan and Sudhakaran, 2011) and Thailand (Silalertruksa *et al.*, 2012) yet limited evidence exists on potential benefits being realized. A major government initiative to promote jatropha cultivation in India has failed (Kumar *et al.*, 2011) and in some cases has left rural people worse off (Bastos Lima, 2012), whereas in Malawi it offered supplemental livelihood opportunities (Dyer *et al.*, 2012). Even though income and employment in Brazil may have increased due to ethanol production (Ferreira and Passador, 2011), structural inequalities in the sector remain (Peskett, 2007; Hall *et al.*, 2009; Bastos Lima, 2012). Biofuel production in itself will not transform living conditions in rural areas without being integrated into development policies (Hanff *et al.*, 2011; Jarosz, 2012; Dyer *et al.*, 2012).

13.3.2. Impacts of Adaptation Responses on Poverty and Livelihoods

Local responses to climate variability, shocks, and change have always been part of livelihoods (Morton, 2007). Formal policy responses to climate change, however, have developed more recently as the urgency of adaptation, in addition to mitigation, became a clear international policy mandate (Pielke Jr *et al.*, 2007). Even well-intentioned adaptation projects (see Chapters 14-16) and efforts may have unintended and sometimes detrimental impacts on livelihoods and poverty, and may exacerbate existing inequalities. This section assesses the near-term effects of autonomous and planned adaptation and formal insurance schemes on the livelihoods of poor populations. Since adaptation policies and projects are relatively recent, understanding of their long-term effects is very limited.

13.3.2.1. Impacts of Adaptation Responses on Livelihoods and Poverty

Autonomous adaptation strategies, such as diversification of livelihoods (Smith *et al.*, 2000; Mertz *et al.*, 2009) migration (McLeman and Smit, 2006; Tacoli, 2009) (see Chapter 12), storage of food (Smit and Skinner, 2002; Howden *et al.*, 2007) communal pooling (Linnerooth-Bayer and Mechler, 2006), market responses (Halstead and O'Shea, 2004), and saving, credit societies, and systems of mutual support (Andersson and Gabrielsson, 2012) have been found to have positive effects on poverty reduction in certain contexts, or at least prevent further deterioration due to weather events and climate, especially when supported by policy measures (Adger *et al.*, 2003; Urwin and Jordan, 2008; Stringer *et al.*, 2009). Yet, some autonomous strategies such as diversification and storage are often unavailable to the poorest, who lack the required resources or surplus (Smithers and Blay-Palmer, 2001; Osbahr *et al.*, 2008; Seo, 2010) or require more labor-intensive practices that undermine people's health and may push them over a poverty threshold (Eriksen and Silva, 2009). Moreover, autonomous adaptation strategies can increase vulnerability for others or be subject to local elite capture (McLaughlin and Dietz, 2008; Eriksen and Silva, 2009; Bhattamishra and Barrett, 2010). Men's migration in Northern Mali, for example, increases the workload of the rest of the family, especially women, and reduces children's school attendance (Brockhaus *et al.*, 2013). There is no evidence regarding the impacts of autonomous responses on people living in poverty in MICs and HICs.

Few rigorous studies about pilot adaptation projects exist outside of organizations' own assessments (Mapfumo *et al.*, 2010; Nkem *et al.*, 2011) or evaluations of how planned adaptation was implemented or integrated into development (Gagnon-Lebrun and Agrawala, 2006; Gigli and Agrawala, 2007). An assessment of the only completed GEF/WB-funded adaptation project, in the Caribbean, Colombia, and Kiribati, did not directly appraise the effects on poverty and livelihoods due to scarce baseline poverty data. Other projects, such as in India's Karnataka Watershed, are said to have increased agricultural productivity, income, and employment, benefiting the poorest and landless and improving equity (IEG, 2012). National Action Plans of Adaptation tend to overemphasize technological and infrastructural measures while often overlooking poor people's needs, gender issues, and livelihood and adaptation strategies (Agrawal and Perrin, 2009; Perch, 2011).

13.3.2.2. Insurance Mechanisms for Adaptation

Insurance mechanisms (see Glossary and Chapter 10) reflect the tendency that some formal adaptation measures reach the wealthier more easily while prohibitive costs may prevent poor people from accessing such mechanisms. Nonetheless, public and private insurance systems have been proposed by the World Bank and UNFCCC as an adaptation strategy to reduce, share, and spread climate change-induced risk and smooth consumption, especially among poor households (Mechler *et al.*, 2006; Hertel and Rosch, 2010; Akter *et al.*, 2011; Benson *et al.*, 2012). Formal insurance schemes can potentially provide a way out of poverty traps (Barnett *et al.*, 2008) caused by a household's process to rebuild assets after climate shocks over years (Dercon, 2006; Hertel and Rosch, 2010).

Poor people tend not to be insured via formal institutions, though strategies such as risk spreading, social networks, local credit, asset markets, and dividing herds between kin act as informal risk management mechanisms (Barnett *et al.*, 2008; Pierro and Desai, 2008; Giné *et al.*, 2008; Hertel and Rosch, 2010; De Jode, 2010). Unable to access insurance, they often invest in low-risk, low-return livelihood activities, which makes asset accumulation to escape chronic poverty very difficult (Elbers *et al.*, 2007; Barnett *et al.*, 2008). As a response, new insurance mechanisms such as micro-insurance directed at low-income people and weather index insurance for crops and livestock (see also Chapter 10) have emerged, showing mixed results (Barnett *et al.*, 2008; Mahul *et al.*, 2009; Akter *et al.*, 2011; Matsaert *et al.*, 2011; Biener and Eling, 2012). Experiences from South Asia and several African countries illustrate positive effects of micro-insurance on investment, production, and income under drought and flood risk, including possible longer-term impacts on future income- earning activities and health, although affordability may limit the potential for the poorest (Yamauchi *et al.*, 2009; Hochrainer-Stigler *et al.*, 2012; Karlan *et al.*, 2012; Tadesse and Brans, 2012). There is emerging evidence that weather index insurance can be specifically designed to reach the people usually uninsurable for example by premium-for-work arrangements. In such arrangements farmers provide labor and in return get an insurance certificate against rain failure in a crucial growth period for their staple crops (Brans *et al.*, 2011). Slow uptake of insurance among poor people may be related to farmers not fully understanding the schemes' merits and function or not trusting that payouts will come (Giné and Yang, 2009; Patt *et al.*, 2010).

13.4. Implications of Climate Change for Poverty Alleviation Efforts

This section assesses how climate change may affect efforts to alleviate poverty. Evidence from observed impacts and projections highlight both challenges and opportunities. The section builds on the findings from 13.1 to 13.3 and stresses the need to take into account the complexity of livelihood dynamics, multidimensional poverty, and intersecting inequalities to successfully navigate climate-resilient development pathways (see Glossary).

Observed impacts of weather events and climate on livelihoods and poverty and impacts projected from the sub-national to the global level suggest that livelihood well-being, poverty alleviation, and development are already undermined and will continue to be eroded into the future (*high confidence*). Climate change will slow down the pace of poverty reduction, jeopardize sustainable development, and undermine food security (*high confidence*) (Stern, 2009; Hope, 2009; Thurlow *et al.*, 2009; Iglesias *et al.*, 2011; Skoufias *et al.*, 2011b). Currently poor and food-insecure regions will continue to be disproportionately affected into the future (*high agreement*) (Challinor *et al.*, 2007; Lobell *et al.*, 2008; Assuncao and Cheres, 2008; Liu *et al.*, 2008; Thornton *et al.*, 2008; Menon, 2009; Jones and Thornton, 2009; Nordhaus, 2010; Jacoby *et al.*, 2011; Burke *et al.*, 2011; Skoufias *et al.*, 2011a; Adano *et al.*, 2012). Poorer countries will experience declining adaptive capacity, which will hamper development (*high confidence*). Posey (2009) flags lower adaptive capacities in communities with concentrations of racial minorities and low-income households than in more affluent areas, due to marginalization and multidimensional inequality. Iglesias *et al*. (2011) project continental disparities in agricultural productivity under progressively severe climate change scenarios with highest risks for Africa and Southeast Asia. Although there is *high agreement* about the heterogeneity of future impacts on poverty, few studies consider more diverse climate change scenarios (Skoufias *et al.*, 2011b) or the potential of four degrees and beyond (New *et al.*, 2011). The World Bank (2012b, p.65) states that "climate change in a four degree world could seriously undermine poverty alleviation in many regions."

13.4.1. Lessons from Climate-Development Efforts

Two key models have attempted to integrate climate and poverty concerns into development efforts: mainstreaming adaptation into development priorities and pro-poor adaptation (see Chapters 14-16, 20). Lessons from "adaptation as development," in which development is seen as the basis for adaptation, and "adaptation plus development," in which development interventions address future climate threats (Ayers and Dodman, 2010), typify the disagreement in policy spheres about what sustainability constitutes (Le Blanc *et al.*, 2012) and the practical gulf between climate change policy and development spheres (Ayers and Dodman, 2010). To date, observed and projected climate change impacts are not systematically integrated into poverty reduction programs, although such integration could result in substantial resilience to covariate and idiosyncratic shocks and stresses (Brans *et al.*, 2011; Béné *et al.*, 2012). At the same time, science and policy emphasis on rapid-onset events, sectoral impacts, and poverty statistics has diverted attention from threats to sustainability and resilient pathways. Even where legal reforms to secure the rights of poor people exist, as in Mexico's Climate Law, inequalities persist (MacLennan and Perch, 2012). Without addressing the climatic, social, and environmental stressors that shape livelihood trajectories, including poverty traps (see Figure 13-2), and the underlying causes of poverty, persistent inequalities, and uneven resource access and institutional support, adaption efforts and policies will be nothing more than temporary fixes. Poverty alleviation alone will not necessarily lead to more equality (Pogge, 2009; Milanovic, 2012). Box 13-2 provides insight into three examples.

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Box 13-2. Lessons from Social Protection, Disaster Risk Reduction, and Energy Access

Social protection (SP): Considerable challenges emerge at the intersection of climate change adaptation, disaster risk reduction, and social protection. SP programs include public and private initiatives that transfer income or assets to poor people, protect against livelihood risks, and raise the social status and rights of the marginalized (see Glossary). Cash transfer programs are among the principal instruments used by governments for poverty alleviation (Barrientos and Hulme, 2009; Niño-Zarazúa, 2011; Barrientos, 2011). There is *medium agreement* among scholars and practitioners that SP helps people in chronic poverty reduce risk and protect assets during crises (Devereux *et al.*, 2010; Barrientos, 2011; Dercon, 2011; Devereux *et al.*, 2011). At the regional and municipal level, SP often fails to address local government capacity to ensure risk reduction by providing water, sanitation, drainage, health care, and emergency services. Also, SP does not intentionally strengthen local collective capacity to proactively address climate change risks and take action (Satterthwaite and Mitlin, 2013).

SP that supports pro-poor climate change adaptation and disaster risk reduction by strengthening the resilience of vulnerable populations to shocks is labeled “adaptive social protection” (ASP) (Davies *et al.*, 2009). ASP should be understood as a framework rather than a package of specific measures. ASP has almost exclusively focused on LICs and some MICs with very little attention to poor people in HICs. Few studies exist on the effectiveness of ASP for addressing incremental climatic changes and rapid-onset events, and the changing nature of climate risks as part of dynamic livelihood trajectories (Heltberg *et al.*, 2009; Arnall *et al.*, 2010; Bee *et al.*, 2013). The Productive Safety Net Program in Ethiopia, for instance, had positive effects on household food consumption and asset protection (Devereux *et al.*, 2006; Slater *et al.*, 2006). Yet, this and programs such as Brazil’s *Bolsa Familia* and *Bolsa Verde* (UNDP, 2012) offer few concrete pathways to tackling systemic vulnerabilities and inequalities that inhibit effective responses to severe shocks, though they stress the role of local governments in addressing long-term livelihood security and well-being in addition to short-term disaster relief (Gilligan *et al.*, 2009; Conway and Schipper, 2011; Béné *et al.*, 2012; UNDP, 2012). Local governments in urban contexts have limited capacities to address livelihood security, but more scope to increase resilience through risk-reducing infrastructure (Satterthwaite and Mitlin, 2013).

Disaster risk reduction (DRR): The development and application of DRR (see Glossary) has been among the most important routes for highlighting risks of extreme weather among local governments and civil society, and came to the fore as the concentration of disaster deaths from extreme weather in LICs and MICs became evident (UNISDR, 2009; UNISDR, 2011). However, the accumulated effect of several small-scale events is often more damaging than large-scale ones (Aryal, 2012). DRR is now increasingly employed as an adaptation measure, for example through community-based climate risk reduction (Tompkins *et al.*, 2008; Meenawat and Sovacool, 2011; McSweeney and Coomes, 2011; Field *et al.*, 2012b) and has helped identify DRR roles for local governments (IFRC, 2010). Yet, sometimes disaster management-oriented adaptation can favor property and investments of the relatively richer and divert attention and funding from measures that address disadvantaged people, as suggested in a case study of Vietnam (Buch Hansen, 2013). The effectiveness of DRR in supporting pro-poor climate change adaptation will depend on governance structures to address changing risk contexts in policies and investments while responding to the needs and priorities of their low-income population. Lessons learned from Hurricane Katrina and the Tōhoku earthquake and tsunami showcase the multiplier effect of a disaster on top of underlying structural inequalities. Their persistence years later, as witnessed with Katrina (Schwartz, 2007; Zottarelli, 2008; Fussell *et al.*, 2010) further stresses the need for expanded analyses beyond disaster events themselves and the recognition of the many factors that perpetuate the vicious cycle of poverty, multidimensional deprivation, and inequality.

Energy access: Energy is critical for rural development (Barnes *et al.*, 2010; Kaygusuz, 2011; Kaygusuz, 2012) and for alleviation of urban poverty (Parikh *et al.*, 2012). One proposed climate-resilient pathway is to boost renewable energy use, which could increase energy access for billions of people currently without access to safe and efficient energy while cutting GHG emissions from rising non-renewable energy consumption (Casillas and Kammen, 2010; Edenhofer *et al.*, 2011). Benefits include better health (see also Chapter 11), employment, and cost savings relative to fossil fuels (Edenhofer *et al.*, 2011; Jerneck and Olsson, 2012).

_____ END BOX 13-2 HERE _____

13.4.2. Toward Climate-Resilient Development Pathways

Given the multiple challenges at the climate-poverty-development nexus, debates increasingly focus on transforming the development pathways themselves toward greater social and environmental sustainability, equity, resilience, and justice, calling for a fundamental shift toward near- and long-term climate-resilient development pathways (see Chapter 20). This perspective acknowledges the shortcomings in dominant global development pathways, above all rising levels of consumption and emissions, privatization of resources, and limited capacities of local governments and civil society to counter these trends (Pelling, 2010; Eriksen *et al.*, 2011; O'Brien, 2012; UN, 2012a).

At Rio+20 in 2012, an Open Working Group was created by the UN General Assembly to develop Sustainable Development Goals (SDGs) building on the Millennium Development Goals (MDGs), which are criticized for not explicitly addressing the root causes of poverty, inequality, or climate change (Melamed, 2012; UN, 2012b) and the anticipated failure to reach MDG 1 (eradicate extreme poverty and hunger by 2015), with or without climate change (Tubiello *et al.*, 2008). Early SDG debates reveal a stronger focus on eradicating extreme poverty and environmental problems facing poor people (UN, 2012a). This framing of development acknowledges shared global futures that require collective action from the richest, not merely promoting welfare for the poorest, to address both climate change and poverty (Ayers and Dodman, 2010; UN, 2012a; UN, 2012b). Little information exists to date to project how these SDGs will support climate-resilient development pathways. Formulating goals, however, will not suffice unless the global institutional framework for sustainable development is radically reformed (Biermann *et al.*, 2012)

Paying attention to dynamic livelihoods and multidimensional poverty and the multifaceted impacts of climate change and climate change responses is central to achieving climate-resilient development pathways (see Chapter 20). Evidence from sections 13.2 and 13.3 suggests that increasing global inequality, new poverty in MICs and HICs, and more people shifting from transient to chronic poverty overlaid with business-as-usual development and climate policies will bring poor and marginalized people precariously close to the two most undesirable future scenarios as conceptualized in the shared socio-economic pathways (SSPs) (see Chapter 1): social fragmentation (fragmented world) and inequality (unequal world). At the community level, inadequate governance structures and elite capture often propel less affluent households into deeper poverty. There is *high agreement* among scholars of global governance that fragmentation also exists at the level of the global climate regime (Biermann, 2010; Roberts, 2011; Mol, 2012), rooted in entrenched inequalities (Parks and Roberts, 2010). The extent to which fragmentation promotes positive or negative outcomes of climate and development goals is contested, ranging from polycentric governance modes (Ostrom, 2010) to conflictive fragmentation (Biermann *et al.*, 2009; Mittelman, 2013). Evidence from this chapter suggests that, in order to move toward the mid- and long-term SSP1 (sustainability), a fundamental rethinking of poverty and development will need to emphasize equity among poor and non-poor people to collectively address GHG emissions and vulnerabilities while striving toward a joint, just, and desirable future.

13.5. Synthesis and Research Gaps

Previous IPCC reports have stated that climate change would cause disproportionally adverse effects for the world's poor people. However, they presented a rather generalized view that all poor people were vulnerable, in contrast to earlier scientific studies highlighting vulnerability as contextual with variation over time and space. This chapter is devoted to exploring poverty in relation to climate change, a new theme in the IPCC. It uses a livelihood lens to assess the interactions between climate change and the multiple dimensions of poverty, not just income poverty. This lens also reveals how inequalities perpetuate poverty, and how they shape differential vulnerabilities and in turn the differentiated impacts of climate change on individuals and societies. This chapter illustrates that climate change adds an additional burden to poor people and their livelihoods, acting as a threat multiplier. Moreover, it emphasizes that climate change may create new groups of poor people, not only in low-income countries but also in middle- and high-income countries. Neither alleviating poverty nor decreasing vulnerabilities to climate change can be achieved unless entrenched inequalities are reduced. This chapter concludes that climate change policy responses reviewed in this chapter often do not benefit poor people, and highlights lessons for climate-resilient development pathways.

Eight major research gaps are identified with respect to the observed and projected impacts of climate change and climate change responses:

- Poverty dynamics are not sufficiently accounted for in current climate change research. Most research as well as poverty measurements remain focused on only one or two dimensions of poverty. Insufficient work assesses the distribution of poverty at the level of households, spatial and temporal shifts, critical thresholds that plunge some transient poor into chronic poverty, and poverty traps, in the context of climatic and non-climatic stressors. Many of these dynamics remain hidden, incompletely captured in poverty statistics and disaster and development discourses. Key assumptions in many economic models (e.g., constant within-

country distribution of per-capita income over time, linear relationship between economic growth and poverty headcounts) are ill-suited to capture local and sub-national poverty dynamics, confounding projections of future poverty levels.
- Though an abundance of studies exists that explore climate change impacts on livelihoods, the majority does not focus on continuous struggles and trajectories but only offers snapshots. An explicit analysis of livelihood dynamics would more clearly reveal how people respond to a series of climatic stressors and shocks over time.
- Few studies examine how structural inequalities, power imbalances, and intersecting axes of privilege and marginalization shape differential vulnerabilities to climate change. Although there is growing literature on climate change and gender as well as on indigeneity, other axes such as age, class, race, caste, and (dis)ability, remain underexplored. Understanding how simultaneous and intersecting inequalities determine climate change impacts shows which particular drivers of vulnerability are at play in one context, while absent in another.
- Very limited research examines climate change impacts on poor people and livelihoods in middle- to high-income countries. Despite mounting evidence of observed impacts of climatic events on the poor in MICs and HICs, as documented for the European heat wave, Hurricane Katrina in the U.S., and the ten-year drought in Australia, the majority of research on the poverty-climate nexus remains focused on the poorest countries.
- There remains a lack of rigorous data collection and analysis regarding small-scale disasters, i.e. those that go unnoticed because of their limited extent, but whose accumulated effect may exceed large-scale disasters. This gap leads to significant underestimation of lived experiences with climate change, in which particular loss and harm remain largely undetected. There is a need for more climatology research informed by the needs of poor people and vulnerable livelihoods, for instance on the effects of changing winds as a combined result of climate and land cover change, and their effects on increasing evaporation and water availability.
- Not enough consideration is given to extreme stressors and shocks, e.g., under potential global mean warming of +4°C and beyond, underestimating impacts on poor and marginalized people and limits to adaptation.
- There is a lack of in-depth research on the direct and indirect effects of mitigation and adaptation climate-related policies such as CDM, REDD+, biofuels, and insurance, on livelihoods, poverty, and inequality. More in-depth research has the potential to improve the capacity of these policies to benefit poor people.
- Limited understanding exists of how poverty alleviation and more equality between the poor and the non-poor are best built into climate-resilient development pathways to strive toward a just and desirable future for all.

Frequently Asked Questions

FAQ 13.1: What are multiple stressors and how do they intersect with inequalities to influence livelihood trajectories? *[to be placed in Section 13.1.1.2]*
Multiple stressors are simultaneous or subsequent conditions or events that provoke/require changes in livelihoods. Stressors include climatic (e.g. shifts in seasons), socio-economic (e.g. market volatility), and environmental (e.g. destruction of forest) factors, that interact and reinforce each other across space and time to affect livelihood opportunities and decision making (see Figure 13-1). Stressors that originate at the macro level include climate change, globalization, and technological change. At the regional, national, and local levels, institutional context and policies shape possibilities and pitfalls for lessening the effects of these stressors. Which specific stressors ultimately result in shocks for particular livelihoods and households is often mediated by institutions that connect the local level to higher levels. Moreover, inequalities in low-, medium-, and high-income countries often amplify the effects of these stressors. This is particularly the case for livelihoods and households that have limited asset flexibility and/or those that experience disadvantages and marginalization due to gender, age, class, race, (dis)ability, or being part of a particular indigenous or ethnic group. Weather events and climate compound these stressors, allowing some to benefit and enhance their well-being while others experience severe shocks and may slide into chronic poverty. Who is affected, how, where, and for long depends on local contexts. For example, in the Humla district in Nepal, gender roles and caste relations influence livelihood trajectories in the face of multiple stressors including

shifts in the monsoon season (climatic), limited road linkages (socio-economic), and high elevation (environmental). Women from low castes have adapted their livelihoods by seeking more day-labor employment, whereas men from low castes ventured into trading on the Nepal-China border, previously an exclusively upper caste livelihood.

FAQ 13.2: How important are climate change-driven impacts on poverty compared to other drivers of poverty?
[to be placed in Section 13.1.4]
Climate change-driven impacts are one of many important causes of poverty. They often act as a threat multiplier, meaning that the impacts of climate change compound other drivers of poverty. Poverty is a complex social and political problem, intertwined with processes of socioeconomic, cultural, institutional, and political marginalization, inequality, and deprivation, in low-, middle-, and even high-income countries. Climate change intersects with many causes and aspects of poverty to worsen not only income poverty but also undermine well-being, agency, and a sense of belonging. This complexity makes detecting and measuring attribution to climate change exceedingly difficult. Even modest changes in seasonality of rainfall, temperature, and wind patterns can push transient poor and marginalized people into chronic poverty as they lack access to credit, climate forecasts, insurance, government support, and effective response options, such as diversifying their assets. Such shifts have been observed among climate-sensitive livelihoods in high mountain environments, drylands, and the Arctic, and in informal settlements and urban slums. Extreme events, such as floods, droughts, and heat waves, especially when occurring in a series, can significantly erode poor people's assets and further undermine their livelihoods in terms of labor productivity, housing, infrastructure, and social networks. Indirect impacts, such as increases in food prices due to climate-related disasters and/or policies, can also harm both rural and urban poor people who are net buyers of food.

FAQ 13.3: Are there unintended negative consequences of climate change policies for people who are poor?
[to be placed in Section 13.3.1]
Climate change mitigation and adaptation policies may have unintended and potentially detrimental effects on poor people and their livelihoods (the set of capabilities, assets, and activities required to make a living). Here is just one example. In part as a result of climate change mitigation policies to promote biofuels and growing concern about food insecurity in middle and high income countries, large-scale land acquisition in Africa, Southeast Asia, and Latin America has displaced small landholders and contributed to food price increases. Poor urban residents are particularly vulnerable to food price increases as they use a large share of their income to purchase food. At the same time, higher food prices may benefit some agricultural self-employed groups. Besides negative impacts on food security, biofuel schemes may also harm poor and marginalized people through declining biodiversity, reduced grazing land, competition for water, and unfavorable shifts in access to and control over resources. However, employment in the biofuel industry may create opportunities for some people to improve their livelihoods.

Cross-Chapter Box

Box CC-HS. Heat Stress and Heat Waves

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Heat waves are periods of abnormally and uncomfortably hot weather during which the risk of heat stress on people and ecosystems is high. The number and intensity of hot days have increased markedly in the last three decades (Coumou et al., 2013) (*high confidence*). According to WG I, it is *likely* that the occurrence of heat waves has more than doubled in some locations due to human influence and it is *virtually certain* that there will be more frequent hot extremes over most land areas in the latter half of the 21st century. Coumou et al. (2013) predicted that, under a medium warming scenario, the number of monthly heat records will be over 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +10C or more, the habitability of large parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and they may act as triggers for tipping points (Hughes et al., 2013). Consequently, heat waves play an important role in several key risks noted in Chapter 19 and CC-KR.

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Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012). In LICs and MICs, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health [Ch 11]

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro *et al.*, 2011; Rahmstorf and Coumou, 2011; Nitschke et al., 2011; Diboulo et al., 2012; Hansen et al., 2012). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, Jan C et al., 2008). Increase in ozone concentrations due to high temperatures affects health (Smith et al., 2010), leading to premature mortality, e.g. cardiopulmonary mortality (Smith et al., 2010). High temperatures are also associated with an increase in air-borne allergens acting as a trigger for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems [Ch 4, 5, 6, 30]

Tree mortality is increasing globally (Williams et al., 2012) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult due to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013), Box 4.2.

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (Hoegh-Guldberg et al., 2007), Figure 6-5, (*medium confidence*) [Ch 6.3.1, 6.3.5; 30.4; 30.5; CC-MB]

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*). [Ch 5, 6, 30.4-30.5, CC-CR, CC-MB]

Agriculture [Ch 7]

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2011). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and

suitability for crops (*medium evidence, medium agreement*) (Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the U.S., current economic losses due to heat stress of livestock are estimated at several billion USD annually (St-Pierre et al., 2003).

Box CC-HS References

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Table 13-1: Examples of gendered climate experiences*

Experiences	Male farmers	Female farmers
Increased workload	Demanding tasks such as feeding livestock, carting water, destroying frail animals (A)	Assistance with farm tasks and working off the farm for additional income (A)
	Increased migration for wage labor, typically farther away from home (I)	Increased collection of firewood and uptake of wage labor (esp. lower castes) in neighboring villages (I)
Community interactions, isolation, and exploitation	Locked into farms, loss of political power (A)	Increased interactions and caregiving work, taking care of others' health at the expense of their own (A)
	Exploitation by labor contractors when migrating (I)	Disadvantage in accessing institutional support and climate information (I)
Physical and psychological toll	Feel demonized (farmers seen as responsible for crisis), increased stress, social isolation, depression, and high suicide levels (A)	Working lives appear indefinite, resulting in increased stress (A)
	Increased anxiety to provide food and access loans and escape trap of indebtedness, increase in domestic fights, sometimes suicide (I)	Increased pressure to provide food and save some more from sale for consumption, less food intake, increase in domestic fights (I)

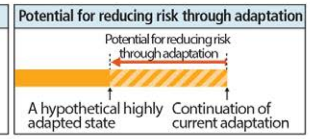
*A = Australia (ten-year drought, 2003-2012), based on Alston, 2011;
I = India (climate variability and changing climatic trends), based on Lambrou and Nelson, 2013.

Table 13-2: Key risks from climate change for poor people and their livelihoods and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgment by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented in three timeframes: present, near-term (2030-2040), and long-term (2080-2100). Near-term indicates that projected levels of global mean temperature do not diverge substantially across emissions scenarios. Long-term differentiates between a global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adaptive state. Bars that only show the latter indicate a limit to adaptation (see Chapter 16). Relevant climate variables are indicated by symbols. This table should not be used as a basis for ranking severity of risks.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Potential for reducing risk through adaptation
Deteriorating livelihoods in drylands, due to high and persistent poverty. Risk of reaching tipping points for crop and livestock production in small-scale farming and/or pastoralist livelihoods (*high confidence*)	Adaptation options are limited due to persistent poverty, declining land productivity, food insecurity, and limited government support due to marginalization. Rural-urban migration is a potential adaptation strategy.		13.2.1.2, 13.2.2.1, 13.2.2.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Destruction and deterioration of assets physical (homes, land and infrastructure), human (health), social (social networks), cultural (sense of belonging and identity) and financial (savings) due to floods in flood-prone areas, such as low-lying deltas, coasts, and small islands (*high confidence*)	Adaptation options are limited for people who cannot afford relocation to safer areas. Government support and private options (e.g. insurance) are limited for people with insecure or unclear tenure.		13.2.1.1, 13.2.1.3, 13.2.1.5, Box 13-1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Shifts from transient to chronic poverty due to persistent economic and political marginalization of poor people combined with deteriorating food security (*high confidence*)	Adaptation options are limited due to exclusion from markets and low government support. Policies for adaptation are unsuccessful because of failure to address persistent inequalities.		13.2.1.3, 13.2.2.4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Declining work productivity, morbidity (e.g. dehydration, heat stroke, and heat exhaustion) and mortality from exposure to heat waves. Particularly at risk are agricultural and construction workers as well as children, homeless people, the elderly, and women who have to walk long hours to collect water (*high confidence*)	Adaptation options are limited for people who are dependent on agriculture and too poor to afford agricultural machinery. Adaptation options are limited in the construction sector where many poor people work under insecure arrangements. Adaptation might be impossible in certain areas in a +4C world.		13.2.1.1, 13.2.1.5, 13.2.2.4, Box 13-1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Declining agricultural yields, primarily in already hot climates, with severe impacts on countries and communities highly dependent on agriculture. Declining yields may cause further deterioration of assets: financial (savings), human (health), social (social networks) and cultural (sense of belonging and identity) (*high confidence*)	Adaptation by changing livelihoods away from agriculture is limited due to poverty and marginalization. Adaptation strategies such as early or late planting, inter-cropping, and shifting crops bring mixed benefits and have limitations, often depending on household resources and access to seasonal forecasts and longer-term projections. In a +4C world, adaptation in agriculture is very limited.		13.2.2.2, 13.2.2.4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Reduced access to water for rural and urban poor people due to water scarcity and increasing competition for water (*high confidence*)	Adaptation through reducing water use is not an option for the large number of people already lacking adequate access to safe water. Access to water is subject to various forms of discrimination, for instance due to gender and location. Poor and marginalized water users are unable to compete with water extraction by industries, large-scale agriculture, and other powerful users.		13.2.1.1, 13.2.1.3, 13.2.1.5, Box 13-1	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high

Climatic drivers of impacts					
Warming trend	Extreme temperature	Drying trend	Extreme precipitation	Damaging cyclone	Sea level

Potential for reducing risk through adaptation



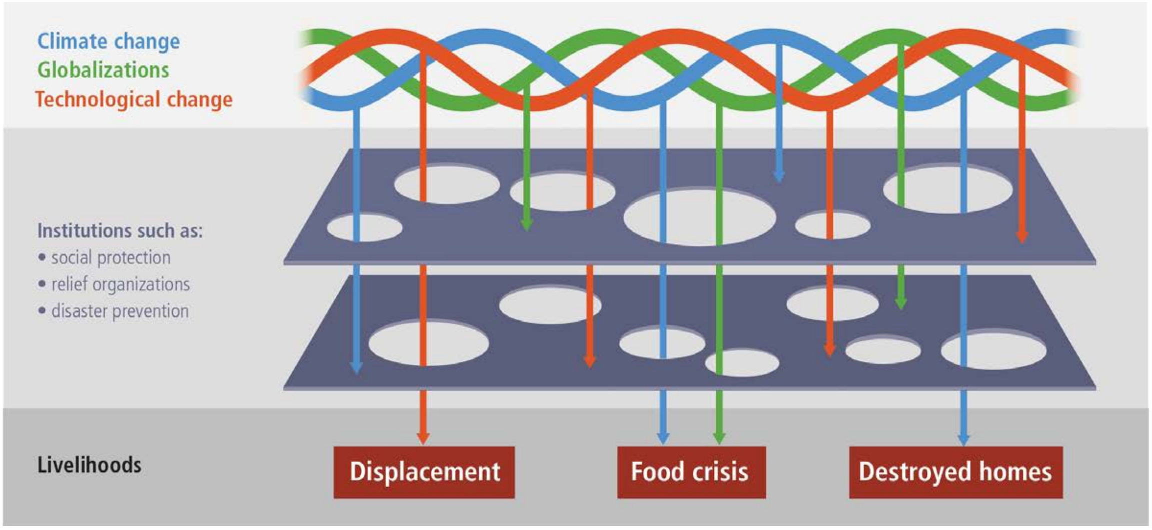


Figure 13-1: Multiple stressors related to climate change, globalizations, and technological change interact with national and regional institutions to create shocks to place-based livelihoods, inspired by Reason (2000).

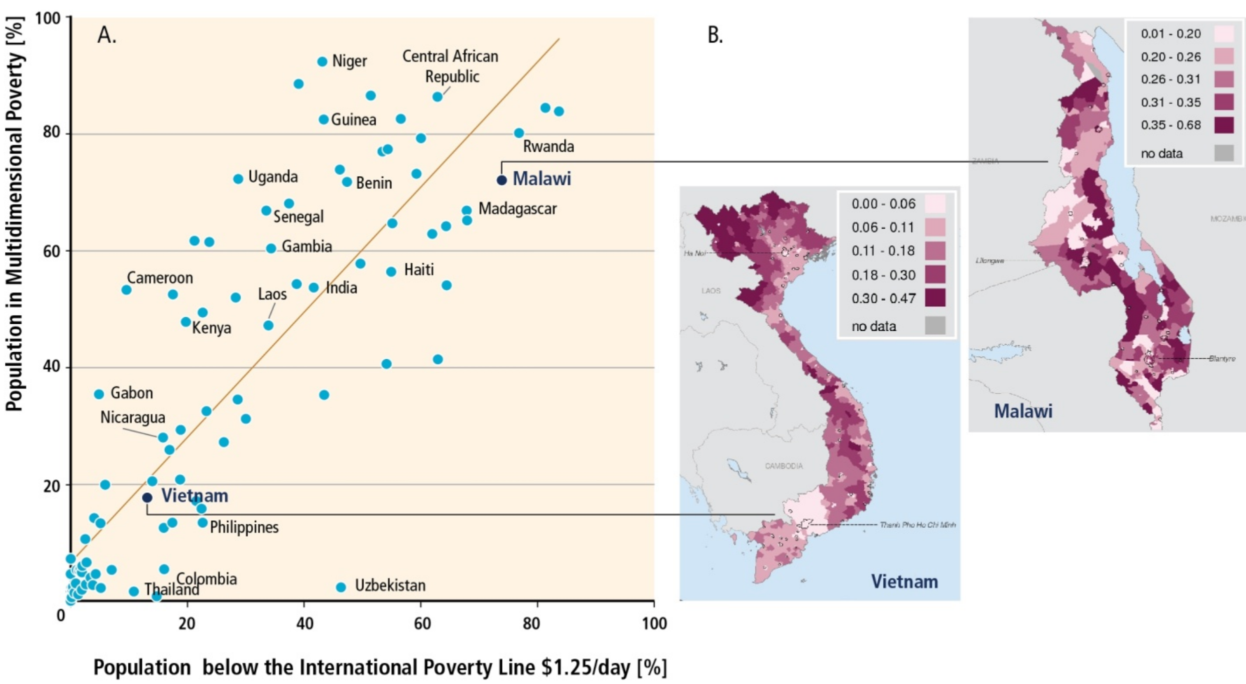
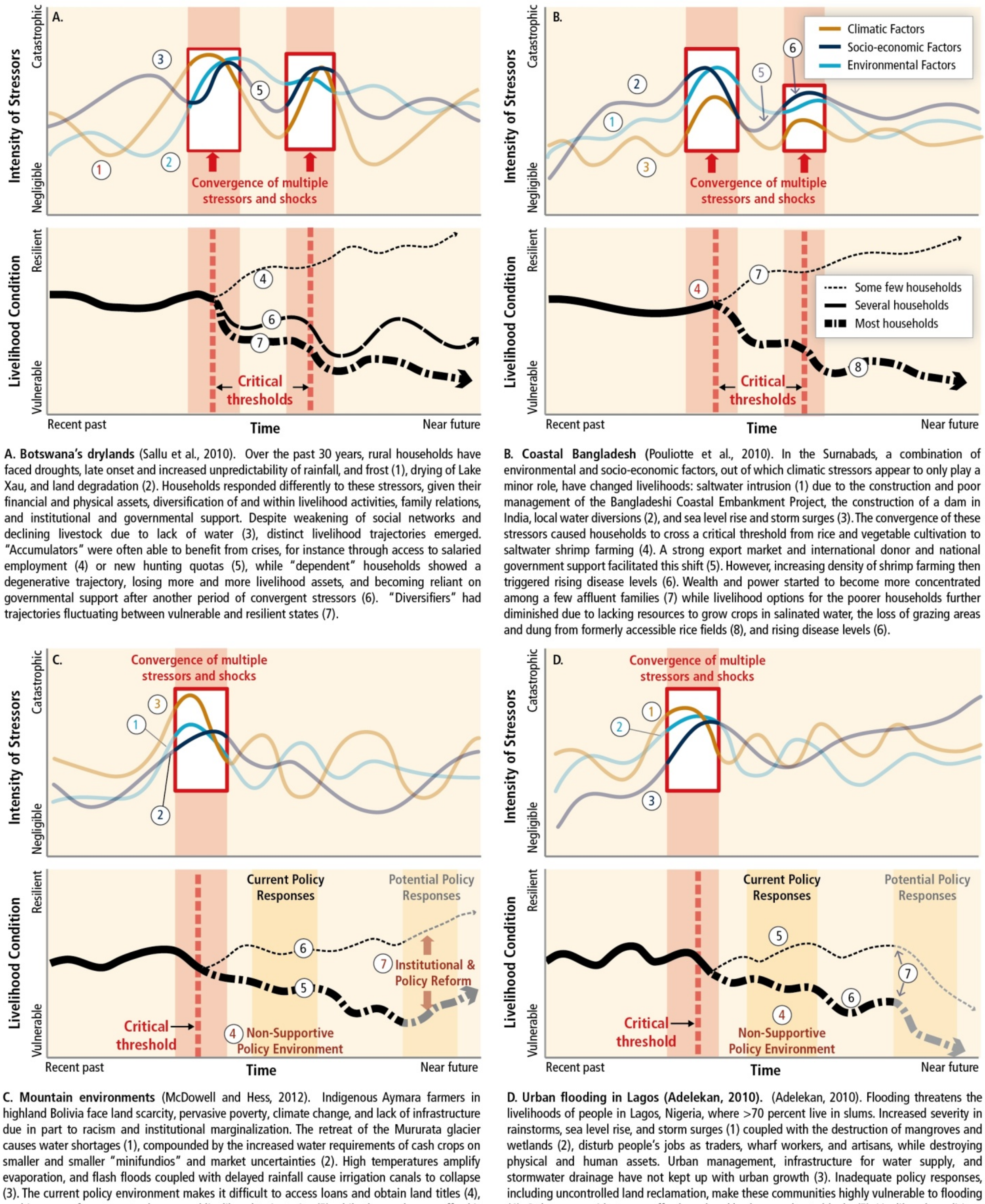


Figure 13-2: A) Multidimensional poverty and income-based poverty using the International Poverty Line $1.25/day (in Purchasing Power Parity terms), with linear regression relationship (dotted line) based on 96 countries (UNDP, 2011b). The position of the countries relative to the dotted line illustrates the extent to which these two poverty measures are similar or divergent (e.g., Niger). B) The map insets show the intensity of poverty in two countries, based on the Poverty Gap Index at district level (per capita measure of the shortfall in welfare of the poor from the poverty line, expressed as a ratio of the poverty line). The darker the purple shading, the larger the shortfall.



A. Botswana's drylands (Sallu et al., 2010). Over the past 30 years, rural households have faced droughts, late onset and increased unpredictability of rainfall, and frost (1), drying of Lake Xau, and land degradation (2). Households responded differently to these stressors, given their financial and physical assets, diversification of and within livelihood activities, family relations, and institutional and governmental support. Despite weakening of social networks and declining livestock due to lack of water (3), distinct livelihood trajectories emerged. "Accumulators" were often able to benefit from crises, for instance through access to salaried employment (4) or new hunting quotas (5), while "dependent" households showed a degenerative trajectory, losing more and more livelihood assets, and becoming reliant on governmental support after another period of convergent stressors (6). "Diversifiers" had trajectories fluctuating between vulnerable and resilient states (7).

B. Coastal Bangladesh (Pouliotte et al., 2010). In the Surnabads, a combination of environmental and socio-economic factors, out of which climatic stressors appear to only play a minor role, have changed livelihoods: saltwater intrusion (1) due to the construction and poor management of the Bangladeshi Coastal Embankment Project, the construction of a dam in India, local water diversions (2), and sea level rise and storm surges (3). The convergence of these stressors caused households to cross a critical threshold from rice and vegetable cultivation to saltwater shrimp farming (4). A strong export market and international donor and national government support facilitated this shift (5). However, increasing density of shrimp farming then triggered rising disease levels (6). Wealth and power started to become more concentrated among a few affluent families (7) while livelihood options for the poorer households further diminished due to lacking resources to grow crops in salinated water, the loss of grazing areas and dung from formerly accessible rice fields (8), and rising disease levels (6).

C. Mountain environments (McDowell and Hess, 2012). Indigenous Aymara farmers in highland Bolivia face land scarcity, pervasive poverty, climate change, and lack of infrastructure due in part to racism and institutional marginalization. The retreat of the Mururata glacier causes water shortages (1), compounded by the increased water requirements of cash crops on smaller and smaller "minifundios" and market uncertainties (2). High temperatures amplify evaporation, and flash floods coupled with delayed rainfall cause irrigation canals to collapse (3). The current policy environment makes it difficult to access loans and obtain land titles (4), pushing many farmers onto down-ward livelihood trajectories (5) while those who can afford it invest in fruit and vegetable trees at higher altitudes (6). Sustained access to land, technical assistance, and irrigation infrastructure would be effective policy responses to enhance well-being (7).

D. Urban flooding in Lagos (Adelekan, 2010). (Adelekan, 2010). Flooding threatens the livelihoods of people in Lagos, Nigeria, where >70 percent live in slums. Increased severity in rainstorms, sea level rise, and storm surges (1) coupled with the destruction of mangroves and wetlands (2), disturb people's jobs as traders, wharf workers, and artisans, while destroying physical and human assets. Urban management, infrastructure for water supply, and stormwater drainage have not kept up with urban growth (3). Inadequate policy responses, including uncontrolled land reclamation, make these communities highly vulnerable to flooding (4). Only some residents can afford sand and broken sandcrete blocks (5). Livelihood conditions in these slums are expected to further erode for most households (6). Given policy priorities for the construction of high-income residential areas, current residents fear eviction (7).

Figure 13-3: Illustrative depiction of livelihood dynamics under simultaneous climatic, environmental, and socio-economic stressors and shocks leading to differential livelihood trajectories over time, based on four case studies. The red boxes indicate specific critical moments when stressors converge, threatening livelihoods and well-being. Key variables and impacts numbered in the illustrations correspond to the developments described in the captions.

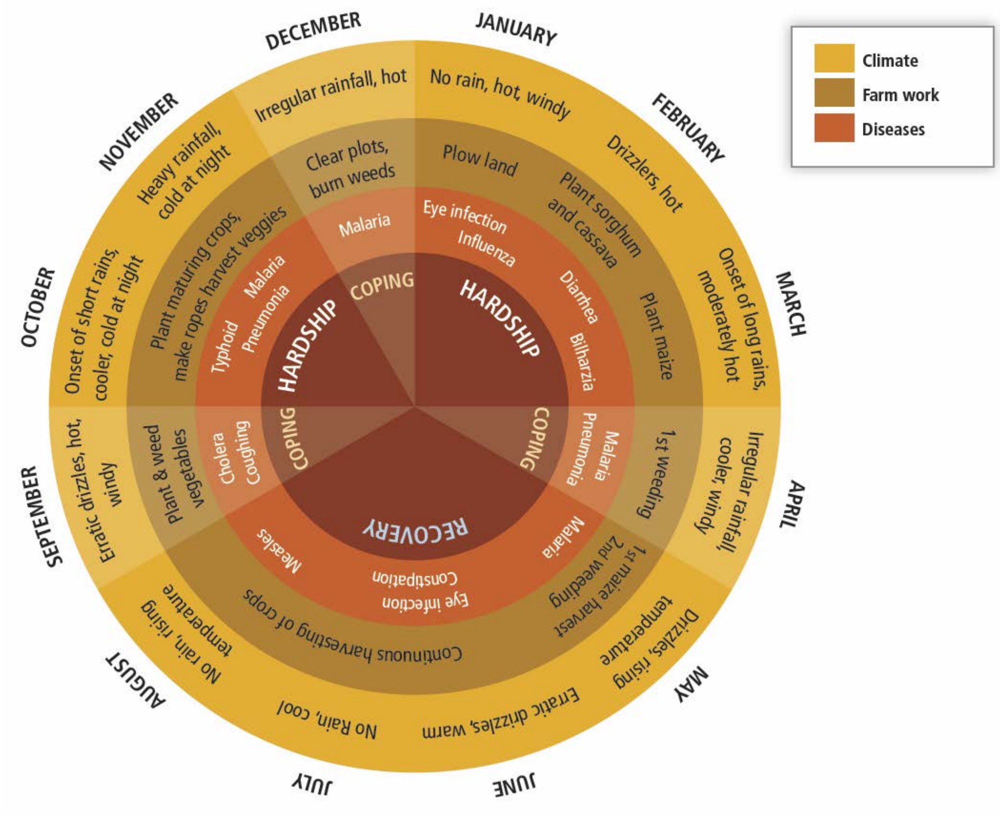


Figure 13-4: Seasonal sensitivity of livelihoods to climatic and non-climatic stressors for one calendar year, based on experiences of smallholder farmers in the Lake Victoria Basin in Kenya and Tanzania (Gabrielsson *et al.*, 2012).

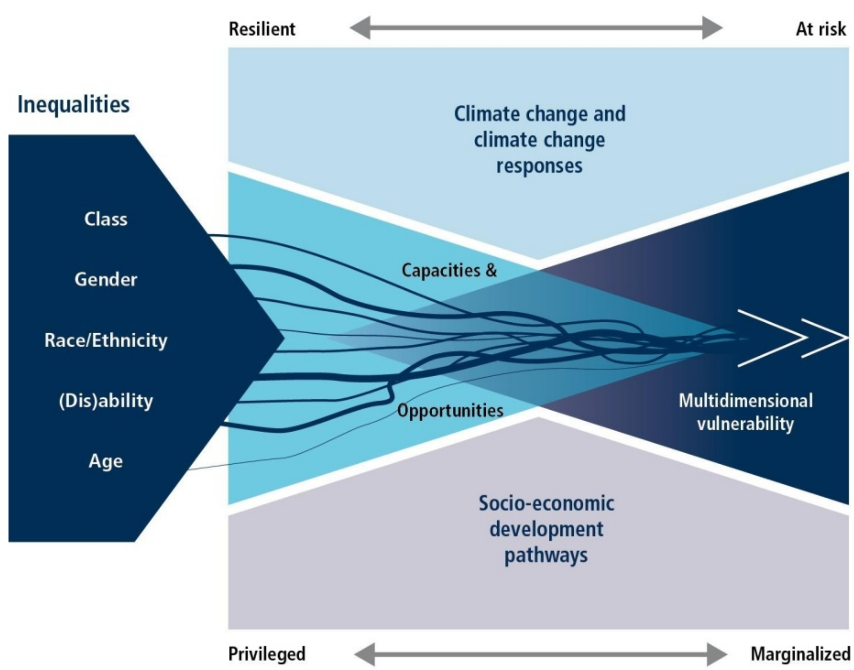


Figure 13-5: Multidimensional vulnerability driven by intersections dimensions of inequality.

Chapter 14. Adaptation Needs and Options

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Contents

Executive Summary

Since AR4 the framing of adaptation has moved further from a focus on biophysical vulnerability to the wider social and economic drivers of vulnerability and people's ability to respond. These drivers include the gender, age, health, social status and ethnicity of individuals and groups, and the institutions in place locally, nationally, regionally and internationally. Adaptation goals are often expressed in a framework of increasing resilience, which encourages consideration of broad development goals, multiple objectives and scales of operation, and often better captures the complex interactions between human societies and their environment. The convergence between adaptation and disaster risk management has been further strengthened since AR4, building upon the IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). [14.1, 14.2, 14.3] **(*High agreement, robust evidence*)**

Adaptation needs arise when the anticipated risks or experienced impacts of climate change require action to ensure the safety of populations and the security of assets, including ecosystems and their services. Adaptation needs are the gap between what might happen as the climate changes and what we would desire to happen. The use of the term needs has also shifted with the framing of adaptation. In the National Adaptation Programmes of Action (NAPAs) "needs" were usually discussed in terms of major vulnerabilities and priority adaptation activities, and in both developing and developed countries, this hazard-based approach with a focus on drivers of impacts and options to moderate them is still used often for urban or regional programmes. But more recently, the focus has been on tackling the underlying causes of vulnerability such as informational, capacity, financial, institutional, and technological needs. [14.2] ***(Moderate Agreement, medium evidence)***

Engineered and technological adaptation options are still the most common adaptive responses, although there is growing experience of the value for ecosystem-based, institutional, and social measures, including the provision of climate-linked safety nets for those who are most vulnerable. Adaptation measures are increasing and becoming more integrated within wider policy frameworks. Integration, while it remains a challenge, streamlines the adaptation planning and decision making process and embeds climate sensitive thinking in existing and new institutions and organizations. This can help avoid mismatches with the objectives of development planning, facilitates the blending of multiple funding streams and reduces the possibility of maladaptive actions. The increasing complexity of adaptation practice means that institutional learning is an important component of effective adaptation. [14.3] **(*High agreement, robust evidence*)**

Approaches to selecting adaptation options continue to emphasize incremental change to reduce impacts while achieving co-benefits, but there is increasing evidence that transformative changes may be necessary in order to prepare for climate impacts. While no-regret, low-regret and win-win strategies have attracted most attention in the past and continue to be applied, there is increasing recognition that an adequate adaptive response will mean acting in the face of continuing uncertainty about the extent of climate change and the nature of its impacts, and that in some cases there are limits to the effectiveness of incremental approaches. While attention to flexibility and safety margins is becoming more common in selecting adaptation options, many see the need for more transformative changes in our perception and paradigms about the nature of climate change, adaptation and their relationship to other natural and human systems. [14.1, 14.3.4] **(*Medium agreement, medium evidence*)**

Among the many actors and roles associated with successful adaptation, the evidence increasingly suggests two to be critical to progress; namely those associated with local government and those with the private sector. These two groups will bear increasing responsibility for translating the top-down flow of risk information and financing, and in scaling up the bottom-up efforts of communities and households in planning and implementing their selected adaptation actions. Local institutions, including local governments, NGOs and civil society organisations, are among the key actors in adaptation but are often limited by lack of resources and capacity and by continuing difficulties in gaining national government or international support, especially in developing countries. [14.2.3] Private entities, from individual farmers and SMEs (small to medium enterprises) to large corporations, will seek to protect and enhance their production systems, supply lines and markets, by pursuing adaptation related opportunities. These goals will help expand adaptation activities but they may not align with government or community objectives and priorities without coordination and incentives. [14.2.4] **(*High agreement, medium evidence*)**

Adaptation assessments, which have evolved in substance and style since AR4, have demonstrably led to a general awareness among decision makers and stakeholders of climate risks and adaptation needs and options. However, such awareness has often not translated into adaptation action. Most of the assessments of adaptation done so far have been restricted to impacts, vulnerability and adaptation planning, with very few assessing the processes of implementation and evaluation of actual adaptation actions [14.4.1]. Assessments that include both top-down assessments of biophysical climate changes and bottom-up assessments of what makes people and natural systems vulnerable to those changes will help to deliver local solutions to globally derived risks. Also, assessments that are linked more directly to particular decisions and that provide information tailored to facilitate the decision making process appear to have most consistently led to effective adaptation measures. [14.4.3] **(*High agreement, medium evidence*)**

The evidence to support the most valuable metrics of adaptation needs and effectiveness is limited, but increasing. [14.5.2, 14.5.3] At present, there are conflicting views concerning the choice of metrics, as governments, institutions, communities and individuals value needs and outcomes differently and many of those values cannot be captured in a comparable way by metrics. [14.5, 14.5.4] The demand for metrics to measure adaptation needs and effectiveness is increasing as more resources are directed to adaptation. These indicators that are proving most useful for policy learning are those that track not just process and implementation, but also the extent to which targeted outcomes are occurring. [14.5.2.3] **(*High agreement, medium evidence*)**

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one location or sector could increase the vulnerability of another location or sector, or increase the vulnerability of the target group to future climate change. [14.7.3] The definition of maladaptation used in AR5 has changed subtly to recognize that maladaptation arises not only from inadvertent badly planned adaptation actions, but also from deliberate decisions where wider considerations place greater emphasis on short-term outcomes ahead of longer-term threats, or that discount, or fail to consider, the full range of interactions arising from the planned actions. [14.6.1] **(*High agreement, medium evidence*)**

14.1. Introduction

This chapter establishes a foundation for understanding adaptation by reviewing core concepts related to adaptation, with a focus on mapping out broad categories of needs and options. Here we use adaptation needs to refer to circumstances requiring information, resources, and action to ensure safety of populations and security of assets in response to climate impacts. Adaptation options are the array of strategies and measures available and appropriate to address needs. Since identifying needs and selecting and implementing options require the engagement of individuals, organizations, and governments at all levels, this chapter also briefly considers the range of actors involved in these processes and summarizes the risks of maladaptation.

Other chapters in this report, namely Chapters 4 and in particular section 4.4, and supported by Chapters 3, 5, 6 and 7, deal with the threats of climate change on ecosystems and other predominately natural systems and their prospects and options for adaptation. For the sake of space and clarity this chapter focuses on the socioeconomic systems that support human livelihoods, although it also touches upon the services provided by ecosystems (including ecosystem based adaptation).

This chapter also highlights some important tools for implementing adaptation, namely approaches to assessing needs at national, subnational, and sectoral levels, and the challenges of applying metrics to determine adaptation needs and the effectiveness of adaptation actions. In the course of these discussions, this chapter establishes a foundation for the three adaptation chapters that follow. The existence of adaptation options does not necessarily mean that these options can be implemented when the need arises. Therefore, Chapter 15 examines adaptation planning and implementation, including the challenges faced and how these can be addressed. Chapter 16 focuses on adaptation opportunities and constraints while Chapter 17 assesses the economics of adaptation to climate change including the costs and benefits of adaptation and of inaction. This chapter also draws upon, and seeks not to repeat, the detailed discussions of human health, wellbeing, security, livelihoods, and poverty found in Chapters 11, 12, and 13 that are so important to the wider discussion of adaptation. These and other interactions among the adaptation chapters are illustrated in Figure 14-1.

[INSERT FIGURE 14-1 HERE
Figure 14-1: The relationship between the four adaptation chapters (14 to17) and other closely related chapters. Chapter 14 (Adaptation Needs and Options) draws upon and cross-references many of the issues of human wellbeing, including health, security and poverty; the treatment of adaptation of natural ecosystems is deal with mainly in Chapter 4 and is not repeated in Chapter 14. Similarly the needs and options synthesized in Chapter 14 are drawn largely from the sectoral (3 to 10) and regional Chapters (21to 30). Chapter 2 provides input to decision-making approaches relevant to Chapter 15 (Adaptation Planning and Options). All the adaptation chapters feed into the synthesis of Chapters 19 (Emerging Risks and Key Vulnerabilities) and 20 (Climate Resilient pathways: adaptation, mitigation, and sustainable development).]

Human and natural systems have a capacity to cope with adverse circumstances, but with continuing climate change, adaptation will be needed to maintain this capacity (IPCC SREX, 2012, section 1.4.1 and Box 2.1). The AR5 definition of adaptation ("The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects") follows the lead of SREX in introducing a degree of purposefulness by adding the phrase "which seeks to moderate" rather than simply "which moderates" as in AR4.[1] Human ability to cope with climate impacts can also be increased by actions that are not anticipatory or purposefully undertaken in response to observed or anticipated climate change; sometimes called unplanned actions. For example, diversifying livelihoods in response to immediate economic factors can increase long-term ability to cope with a changing climate. Such actions were often referred to as autonomous adaptation. However, the use of the term in the literature, including the IPCC Reports, has been inconsistent. The term is often used to refer to purposeful adaptation actions carried out by agents without external inputs such as policies, information or resources (see AR5 Chapters 17 and 22; Skoufias, 2012), and sometimes to refer to purposeful actions that are reactive to experienced climate impacts, rather than being proactive or anticipatory of them (e.g., AR5 Glossary and AR3 WGII 18.2.3.).

[FOOTNOTE 1: Purposefulness was introduced in the SREX definition, which introduced the phrase "in order to moderate".]

The SREX and AR5 definitions of adaptation also clarify the distinction between adaptation in human and natural systems. Natural systems have the potential to adapt through multiple autonomous processes (e.g., phenology changes, migration, compositional changes, phenotypic acclimation, and/or genetic changes), and humans may intervene to promote particular adjustments such as reducing non-climate stresses or through managed migration (see AR5 section 4.5). But successful adaptation will depend on our ability to allow and facilitate natural systems to adjust to a changing climate; thus maintaining the ecosystem services upon which all life depends.

Adaptation is becoming increasingly important in climate negotiations and implementation, and integral to AR5 are the terms incremental and transformational adaptation (sometimes referred to as a "paradigm shift" as in the Green Climate Fund Governing Instrument, 2013a). Incremental adaptation refers to actions where the central aim is to maintain the essence and integrity of the existing technological, institutional, governance, and value systems, such as through adjustments to cropping systems via new varieties, changing planting times, or using more efficient irrigation. In contrast, transformational adaptation seeks to change the fundamental attributes of systems in response to actual or expected climate and its effects, often at a scale and ambition greater than incremental activities. It includes changes in activities, such as changing livelihoods from cropping to livestock or by migrating to take up a livelihood elsewhere, and also changes in our perceptions and paradigms about the nature of climate change, adaptation, and their relationship to other natural and human systems (Kates *et al.*, 2012; Park *et al.*, 2012; IPCC SREX, 2012, section 8.6.2.3 and FAQ 8.2; IPCC AR5, section 20.5; Green Climate Fund, 2013b, 3.3). Transformational change may be driven by the pursuit of better opportunities or by the realization of the imminent or inevitable limits within existing paradigms (Dow *et al.*, 2013; AR5 section 16.4.2). Transformative change may threaten the status quo for many and require leadership and sometimes triggering events to initiate it (Kates *et al.*, 2012). However, transformational change is not called for in all responses to climate change (Pelling, 2010) and ill-prepared transformative change may bring with it social inequities (O'Brien, 2012). The triggers for transformational change and its implementation are dealt with in more detail in Chapters 16.4 and 20.5. Differentiation between incremental and transformative adaptation, although indistinct, is important since it affects how we approach adaptation, how we integrate it into planning and policy, and how we allocate adaptation funding in both developed and developing countries (IPCC, 2012, Chapter 17).

Another concept is the adaptation deficit, which is the gap between the current state of a system and a state that would minimize adverse impacts from existing climate conditions and variability (AR5 Glossary); i.e. it is essentially inadequate adaptation to the current climate conditions (Burton *et al.*, 2002; Burton, 2004; Burton and May, 2004; Parry *et al.*, 2009; AR5 Chapter 17.2.2.2, 17.6.1). Some have suggested that it is often part of a larger "development deficit" (World Bank, 2010). Delay in action in both mitigation and adaptation will increase the adaptation deficit in many parts of the world (IPCC SREX 2012). In the process of building future adaptive capacity it is important to reduce the current adaptation deficit along with designing effective risk management and climate change adaptation measures (Hallegatte *et al.*, 2011). Failure to close the adaptation deficit, both current and in the future, will result in residual damages from climate change. There have been calls for such residual damages should be evaluated and reported (Parry *et al.*, 2009).

Summary of Key Findings from AR4

In the Fourth Assessment Report (AR4), the main chapter on adaptation (Chapter 18) refined the basic terminology of adaptation and concluded that adaptation to climate change was already taking place, but on a limited basis. Societies have a long record of adapting to the impacts of weather and climate through a range of practices that include crop diversification, irrigation, water management, disaster risk management, and insurance, but climate change, along with other drivers of change, poses novel risks often outside the range of experience.

AR4 found that deliberate adaptation measures in response to anticipated climate change were being implemented by a range of public and private actors, on a limited basis, in both developed and developing countries. These measures are undertaken through policies, investments in infrastructure and technologies, and behavioral change, and they are seldom undertaken in response to climate change alone. Many actions that facilitate adaptation to climate change are undertaken to deal with current extreme events, such as heat waves and cyclones, and are often embedded within broader sectoral initiatives such as water resource planning, coastal defense, and disaster management planning.

AR4 concluded that there are individuals and groups within all societies that have insufficient capacity to adapt to climate change. The capacity to adapt is dynamic and influenced by economic and natural resources, social networks, entitlements, institutions and governance, human resources, and technology. But, high adaptive capacity does not necessarily translate into actions that reduce vulnerability. New planning processes are being implemented to attempt to overcome these barriers at local, regional, and national levels in both developing and developed countries. AR4 noted the establishment of the National Adaptation Programmes of Action (NAPAs) and that some developed countries had established national adaptation policy frameworks. Other conclusions from the AR4 relating to the implementation of adaptation policies and measures, barriers to adaptation, and the economic costs of adaptation are summarized in Chapters 15, 16 and 17.

14.2. Adaptation Needs

Adaptation involves reducing risk and vulnerability, seeking opportunities and building the capacity of nations, regions, cities, the private sector, communities, individuals, and natural systems to cope with climate impacts, as well as mobilizing that capacity by implementing decisions and actions (Tompkins *et al.*, 2010). Vulnerability is the "propensity or predisposition [of a system] to be adversely affected" (AR5 Glossary) and, until AR4, was viewed as being comprised of three elements: exposure, sensitivity, and adaptive capacity (IPCC, 2007a). However, in IPCC SREX (2012) and in this report, vulnerability focuses only on sensitivity and capacity with exposure more appropriately incorporated into the concept of risk (see AR5 Glossary and IPCC SREX section 2.2).

Adaptation requires adequate information on risks and vulnerabilities in order to identify needs and appropriate adaptation options to reduce risks and build capacity. In framing an approach to adaptation, it is important to engage people with different knowledge, experience, and backgrounds in tackling and reaching a shared approach to addressing the challenges (Preston and Stafford Smith, 2009; Tompkins *et al.*, 2010; Fünfgeld and McEnvoy, 2011; Eakin *et al*, 2012) Initially, identifying needs was most often based on impact assessments (or risk- hazard approaches), but social vulnerability or resilience assessments are increasingly being used (Fünfgeld and McEnvoy, 2011; Preston *et al.*, 2011b). The risk-hazard framework, drawn primarily from risk and disaster management, focuses on the adverse effects that natural hazards and other climate impacts can have on a given location (Füssel and Klein, 2006). The emphasis in this approach is on the physical and biological aspects of impacts and adaptation (Burton *et al.*, 2002). The social vulnerability framework focuses on the reasons and ways in which individuals, groups, and communities are vulnerable to climate impacts. Here, the focus is on how different factors, such as institutions, shape the socioeconomic conditions that place human populations at risk (Adger and Kelly, 1999, Preston *et al.*, 2011b). There are overlaps and complementarities between these frameworks. Approaches to identifying needs and options are discussed further in the section on assessments (section 14.4).

Comprehensive assessments typically provide insight into the risks and vulnerabilities that will result from climate change in communities, cities, nations, and ecosystems and, in turn, offer a means to identify the presence of adaptation needs and options for addressing those needs. The term adaptation needs is often used but rarely defined in the adaptation literature. In the wider literature, a need can be seen as a problem that can be solved (McKillip, 1987) or as a gap between current outcomes and desired outcomes (Kaufman and English, 1979). Thus, in this context, adaptation needs are the gap between what might happen as the climate changes and what we would desire to happen. Also the term adaptation needs is used in several ways in the adaptation literature. A common use is in the sense of the "urgent and immediate needs" relating to the adverse effects of climate change, as in the rational for the National Adaptation Programmes of Action (NAPAs). Although in this case, "needs" were usually discussed in terms of major vulnerabilities and priority adaptation activities (UNFCCC[2]). The most effective descriptions of these needs combined discussions of climate and non-climate drivers of impacts, and the resources, capacity, information, finance etc., needed to implement options to moderate those impacts (e.g., GEF, 2002). Assessments of adaptation needs, both in developing and developed countries, have often taken a hazard-based approach with a focus on drivers of impacts and options to moderate them (Moser 2009; Finzi Hart *et al.*, 2012). But more recently, the focus has been on tackling the underlying causes of vulnerability (Füssel, 2007). One of the few categorizations of needs is that of Burton *et al.* (2006), where they recognize information, capacity, financial, institutional, and technological needs. A similar structure is followed in this chapter. We first discuss biophysical and environmental needs upon which all lives ultimately depend. Then we discuss social needs and capacities and how they vary throughout society. Thirdly, we discuss our response to climate risks and impacts and how they are modified by the multitude of institutions through which humans work, ranging from international organisations to community based efforts. Finally, we touch upon resources, including societal needs for information and knowledge and financial resources.

[FOOTNOTE 2: https://unfccc.int/files/cooperation_support/least_developed_countries_portal/napa_project_database/application/pdf/napa_index_by_country.pdf]

Although needs are specific to particular groups and places, they fit into a set of more general categories as summarized in the sections below. For instance, vulnerability at the national and sub-national levels is affected by geographic location, biophysical conditions, institutional and governance arrangements, and resource availability, including access to technology and economic stability (Brooks *et al.*, 2005). At the macro-level, two broad classes of determinants of vulnerability are recognized: biophysical determinants and socioeconomic determinants (Preston *et al.*, 2011a). However, adaptation needs are highly diverse and context-specific; for instance, varying between islands even within nations such as the Solomon Islands (section 29.6.1). Different stakeholder groups and individuals have differential adaptation needs and vulnerabilities. Adaptation needs are also dynamic, and future adaptation needs are highly dependent on the mitigation pathway that is taken. Furthermore, the constraints and limits to adaptation (see AR5 Chapter 16) are likely to mean that not all needs will be met, thereby emphasizing the need for monitoring to avoid crossing critical thresholds (section 19.7.3).

14.2.1. Biophysical and Environmental Needs

Climate change is altering ecological systems, biodiversity, genetic resources, and the benefits derived with ecosystem services (Convention on Biological Diversity, 2009; Mooney *et al.*, 2009; Hoegh-Guldberg, 2011). Climate change is inducing shifts in habitats that can often not be followed by species (section 4.3.4.1), leading changed ecosystems, to local and global extinctions and the permanent loss of unique combinations of genes (section 4.3.2.5). For instance, González *et al.* (2010) used observed and modeled changes of global patterns of biome shifts under climate change to conclude that up to half of the terrestrial ecosystems were vulnerable due to changes from secondary stressors, such as wildfire and disease, and suggested significant changes to natural resource management plans. In addition to the responses of ecosystems to climatic change, a number of studies have identified impacts on ecosystem services, particularly the effects of climate change on agricultural productivity (Coles and Scott 2009), freshwater ecosystems (Ormerod *et al.*, 2010), and downstream industries and enterprises (Preston and Stafford Smith, 2009). Ecosystem services that are already under threat from the impacts of climate change include pollination, pest and disease regulation (section 4.3.4.2), climate regulation services (section 4.3.4.3) and potable water supply (section 4.3.4.4) and further stressors will limit our options to respond to climate change (section 14.3.2).

Natural systems underpin human livelihoods, health, welfare, food security, and prosperity. Vital ecosystem services that need to be maintained include provisioning services such as food, fiber and potable water supply; regulating services such as climate regulation, pollination, disease control and flood control; and supporting services such as primary production and nutrient cycling (section 4.3.4). Much of the water for human consumption originates on forested lands and the quality of the water is heavily dependent on the conditions of the ecosystems through which it flows. Ocean systems also provide climate regulation services (section 6.4.1.3), while coral reefs act as ecological buffers (section 6.4.1.4). For instance, healthy coastal wetlands and coral reefs can help to protect against storm surges and rising sea levels (Hoegh-Guldberg, 2011), while the maintenance of wetlands and green spaces can control run-off and flooding associated with increases in precipitation (Jentsch and Beierkuhnlein, 2008; Mooney *et al.*, 2009). Meanwhile, fisheries and aquaculture contribute more than 20% to the dietary animal protein of nearly 1.5 billion people (section 5.4.3.3).

Consequently, there is a need to protect these systems and resources within the changing climate. Goldman *et al.* (2008) found that research projects focusing on delivering ecosystem services, rather than on biodiversity goals, attracted a wider set of funders and better-encompassed the landscapes and the people within them. However, many practices to intervene to improve and maintain ecosystem services are based on limited experience and thus still untested assumptions and limited information (Carpenter *et al.*, 2009). Hence, there is a need to improve understanding and valuation of ecosystem services provided by different adaptation options. There is also an urgent need for appropriate ecosystem monitoring to avoid crossing critical thresholds (see section 19.7.4).

14.2.2. Social Needs

From a social perspective, vulnerability varies as a consequence of the capacity of groups and individuals to reduce and manage with the impacts of climate change. Among the key factors determining vulnerability are gender, age, health, social status, ethnicity, and class (Smit *et al.*, 2001; Adger *et al.*, 2009). For instance, the vulnerability to health-related impacts of climate change varies as a consequence of geographical location (section 11.3.1), gender and age (section 11.3.3), and socioeconomic status (section 11.3.4). Poverty and persistent inequality may be the most salient of the conditions that shape climate-related vulnerability (section 13.1.4). Climate change is expected to have a relatively greater impact on the poor as a consequence of their lack of financial resources, poor quality of shelter, reliance on local ecosystem services, exposure to the elements, and limited provision of basic services and their limited resources to recover from an increasing frequency of losses through climate events (Tol *et al.*, 2004; Huq *et al.*, 2007; Kovats and Akhtar, 2008; Patz *et al.*, 2008; Revi, 2008; Allison *et al.*, 2009; Shikanga *et al.*, 2009; Gething *et al.*, 2010; Moser and Satterthwaite, 2010; Rosenzweig *et al.*, 2010; Skoufias *et al.*, 2012). Due to limited financial resources and often compromised health and nutritional status, the poor, along with the sick and elderly, are at increased risk from trauma, physical and mental illness, and death from climate-impacts such as increased pollution, higher indoor temperatures, exposure to toxins and pathogens from floods, and the emergence of new disease vectors (Kasperson and Kasperson, 2001; Haines *et al.*, 2006; Costello *et al.*, 2009; O'Neill and Ebi, 2009; Tonnang *et al.*, 2010; Costello *et al.*, 2011; Ebi, 2011; Harlan and Ruddell, 2011; Huang *et al.*, 2011; McMichael and Lindgren, 2011; Semenza *et al.*, 2012). Climate change, climate variability, and extreme events can erode natural, physical, financial, human, and social and cultural assets (section 13.2.1.1), and poverty traps arise when climate change, variability, and extreme events make the poor even poorer (section 13.2.1.4).

Social needs under climate change include understanding emotional and psychological needs. In Australia, it has been found that extreme events such as floods, drought, and bushfire can lead to mental suffering, including post-traumatic stress disorder, resulting in the need for psychological support and counseling (The Climate Institute, 2011). For example, drought can increase suicide rates by 8 per cent (Nicholls *et al.*, 2006). Social psychological adaptation processes powerfully mediate public risk perceptions and understanding, psychological and social impacts, coping responses, as well as behavioural adaptation (Reser and Swim, 2011). Yet little collaborative work or research has so far focused on the nature and dynamics of individual level coping and adaptation processes and how they influence responses (Reser *et al.*, 2012).

These individual factors also are often associated with and compounded by community-level conditions. Women often have unequal access to and control over resources, including land titles and water rights (UNDP, 2010; CGIAR, 2012, Verner 2012). Many poor and ethnic minorities live in substandard housing, lack access to basic services, savings and insurance, have compromised health, and are at threat due to excessive densities, poor access roads, and inadequate access to safe water, sanitation, and drainage (Huq *et al.*, 2007; Kovats and Akhtar, 2008; Revi, 2008; Shikanga *et al.*, 2009; Moser and Satterthwaite, 2010). In rural areas, adaptation needs also are linked to the viability of agricultural activity (Bosello *et al.*, 2009). Climate change will lead to higher prices and increased volatility in agricultural markets, which might undermine global food supply security (section 9.3.3.3). Geographically, highly vulnerable regions are those exposed to sea-level rise and extreme events, overlaid with high concentrations of multidimensional poverty (section 13.2.2.1). There will be disproportionate impacts on developing countries that are dependent on climate-sensitive activities such as agriculture (Cline, 2007). However, middle-income populations can also be adversely impacted by climate change as a stressor adding to other effects.

The causes and solutions of vulnerability take place at different social, geographic, temporal, and political scales (Ribot, 2010). Therefore, in order to identify critical needs of populations, and the underlying conditions giving rise to these needs, some social assessments can benefit by looking across institutional domains and by spanning from the local to the national. Local assessments provide a means to identify existing vulnerabilities, the policies, plans, and natural hazards contributing to these vulnerabilities, as well as identifying adaptation actions. Social needs include the range of needs for human security (see section12.1.2), which include the universal and culturally specific, material, and non-material elements necessary to people to act on behalf of their interests. More specifically, at this level, social needs can be evaluated in terms of availability of natural, physical, human, political, and financial assets, stability of livelihood, and livelihood strategies (Moser, 2006; Heltberg *et al.*, 2009). Alternatively, regional and national assessments can provide a basis for ascertaining institutional conditions associated with long-standing inequities and development paths that may need to be addressed in order to generate robust options.

Although different stakeholder groups have specific needs, an overarching adaptation need for communities, households, private sector, and institutions is the need for shared learning on adaptation. Adaptation has itself been referred to as a social learning process (sections 15.3.1.2 and 22.4.5.3). In particular, there is the need for human capacity and social capital to implement adaptation actions, including education and access to information (Brooks *et al.*, 2005; Adger, 2006; Smit and Wandel, 2006). Improved information for adaptation can benefit from efforts to combine indigenous and scientific knowledge (section 12.3.4).

14.2.3. Institutional Needs

Institutions, informal and formal, are enduring regularities of human action in situations structured by rules, norms, and shared strategies, as well as by the physical world (Crawford and Ostrom, 1995) and as such they provide the enabling environment for implementing adaptation actions (Bryan *et al.*, 2009; Chuku, 2009; Aakre and Rübbelke, 2010; Compston, 2010; Moser and Ekstrom, 2011). These institutions provide the guides, incentives, or constraints that shape the distribution of climate risks, establish incentive structures that can promote adaptation, foster the development of adaptive capacity, and establish protocols for both making and acting on decisions (see section 14.2.3.2; Chuku, 2009; Agrawal, 2010; Compston, 2010). In many instances, international and national-level policies and programs can facilitate localized strategies through the creation of legal frameworks and the allocation of resources (Adger, 2001; Bulkeley and Betsill, 2005; Corfee-Morlot *et al.*, 2011). Overall, there is a need for effective institutions to identify, develop, and pursue climate-resilient pathways for sustainable development (sections 20.2 and 20.4.2), including strengthening the ability to develop new options through social, institutional, and technological innovation (section 20.4.3). Chapter 15 further considers the institutional needs to mainstream adaptation into government planning.

Governments at all levels play important roles in advancing adaptation and in enhancing the adaptive capacity and resilience of diverse stakeholder groups. National governments are integral to advancing an adaptation agenda as they decide many of the funding priorities and tradeoffs, develop regulations, promote institutional structures, and provide policy direction to district, state, and local governments. In developing countries, national governments are usually the contact point and initial recipient of international adaptation financing. In some countries, both developed and developing, state governments lead the national government in promoting and implementing adaptation (Mertz *et al.*, 2009). The engagement of national government actors can help mobilize political will, support the creation and maintenance of climate research institutions, establish horizontal networks that promote information sharing (Westerhoff *et al.*, 2011) and, in some cases, facilitate the coordination of budgets and financing mechanisms (Alam *et al.*, 2011; Kalame *et al.*, 2011). Governments have the potential to directly reduce the risk and enhance the adaptive capacity of vulnerable areas and populations by developing and implementing locally appropriate regulations including those related to zoning, storm water management and building codes, and attending to the needs of vulnerable populations through measures such as basic service provision and the promotion of equitable policies and plans (Adger *et al.*, 2003; Nelson *et al.*, 2007; Brooks *et al.*, 2005; Agrawal and Perrin, 2008; Agrawal, 2010).

Among the important institutions in both developed and developing countries are those associated with local governments[3] as they have a major role in translating goals, policies, actions, and investments between higher levels of international and national government to the many institutions associated with local communities, civil society organisations, and NGOs. IPCC SREX Chapter 5 (2012) extensively assesses the role and importance of the local scale institutions when adapting to extreme weather and climate events, highlighting that extreme weather and climate events are acutely experienced at local levels, and that local knowledge is important for managing impacts (Cutter *et al.*, 2009). As institutional actors, local governments and community institutions influence the distribution of climate risks, mediate between levels of government as well as between social and political processes, and they establish incentive structures that affect both individual and collective action at all levels (Agrawal and Perrin, 2008). They are in a pivotal position to promote widespread support for adaptation initiatives, foster intergovernmental coordination, and facilitate implementation, both directly and through mainstreaming into ongoing planning and work activities (Carmin *et al.*, 2012; Anguelovski and Carmin, 2011).

[FOOTNOTE 3: Here local government is used to refer to second or third tiers or lower of government, below national and state or provincial government levels; it includes county, district, council, municipal and similar levels of government.]

There are a number of ongoing political issues that shape the relationships national and local governments have in managing climate risks (Corfee-Morlot *et al.*, 2011). Governance failure has a significant influence on institutional vulnerability (see section 19.6.1.3.3). For instance, short-term interests, when dealing with long-term issues can limit incentives to make investments. Similarly, the proximity that authorities have to interest groups can sway their decisions toward other issues, while the drive to engage the public in planning and other activities can orient priorities in ways that do not support adaptation (Corfee-Morlot *et al.*, 2011). Local governments also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Dodman and Satterthwaite 2009*;* Hardoy and Romero Lankao, 2011). In Bangladesh, the limited access of local governments to resources has been cited as a barrier to local adaptation (Christensen *et al.*, 2012).

Tompkins *et al.* (2010) found from a survey of 300 projects identified as adaptive at local government level in the UK that more than half were driven by concerns not directly related to climate change. Nevertheless, there are a number of indicators that demonstrate whether local government has institutionalized and mainstreamed adaptation. These include the presence of an identifiable champion from within government, climate change being an explicit issue in municipal plans, resources are dedicated to adaptation, and adaptation is incorporated into local political and administrative decision making (Roberts, 2008, 2010).

Overall, it is important to match the appropriate institutional scale with the scale of implementation. For example, the Murray-Darling Basin in Australia includes significant water resources across four states requiring management institutions involving federal, state, and local governments to manage and allocate water use (Hussey and Dovers, 2006; see also Box 25-2). While governments have the potential to influence adaptive capacity, local governments often lack the human and technological capacity or mandate to develop and enforce regulations. Local governments, particularly those in developing countries, are faced with numerous challenges that limit their ability to identify needs and pursue adaptation options. Often, these governments must attend to backlogs of basic and critical services such as housing and water supply or focus their attention on addressing outmoded and outdated infrastructure. They also may lack institutional capacity or have difficulty gaining coordination among departments as conflicts emerge to obtain scarce resources (Hardoy and Romero Lankao, 2011, Villamizar, 2011). Adaptation will require an approach that devolves relevant decision-making to the levels where the knowledge and capacity for effective adaptations resides (see Box 25-5). In the Middle East and North Africa, Sowers *et al.* (2011) maintain that the largely centralized systems of planning, taxation, and revenue distribution lead to a focus on supply side issues with little consideration of changing climates and demand management, which renders their populations vulnerable to climate-induced impacts on water resources due to weak integration with local constituencies.

There are critical institutional design issues that can be evaluated in order to understand institutional needs (Agrawal**,** 2010; Gupta *et al.*, 2010). The first is the extent to which institutions are flexible to handle uncertainty. This includes flexibility across and within institutions to evaluate and reorganise delivery where necessary. The uncertainty associated with climate change, presence of rapidly changing information and conditions, and emerging ideas on how best to foster adaptation requires continual evaluation, learning, and refinement (Gupta *et al.*, 2010; Agrawal**,** 2010). Second is the extent to which adaptation is or has the potential to be integrated into short and long term policymaking, planning, and program development (Conway and Schipper, 2011). Third, is the potential for effective coordination, communication, and cooperation within and across levels of government and sectors (Schipper, 2009; Agrawal, 2010; Conway and Schipper, 2011;). Finally, in order to promote adaptive capacity, it is important to identify the extent to which institutions are robust enough to attend to the needs of diverse stakeholders and foster their engagement in adaptation decisions and actions (Urwin and Jordan, 2008; Gupta *et al.*, 2010).

14.2.4. Need for Engagement of the Private Sector

The role of the private sector is important in delivering adaptation. Often, the focus falls on the role of the private financial sector in providing risk management options including insurance and finance for large projects (see sections 15.4.4. and 17.2.1). However, the delivery of adaptation actions ranges more widely and spans different types of private enterprise, from small farmers, to SMEs (Small to Medium Enterprises), to multinational companies. KPMG International (2008) used published reports and interviews to identify the sectors where businesses considered they face the greatest climate related risks. In order of perceived importance, the core risks were regulatory, physical, reputational, and litigation risks. The sectors identified as most at risk included an expected cluster around oil and gas and aviation, and also a group less commonly perceived to be at risk, including health care, the financial sector, tourism and transport.

Khattri *et al.* (2010) have described three general ways in which the private sector can become involved in adaptation. The first, internal risk management is critical to firms and enterprises protecting their own interests and ensuring continuity of supply and markets. The second form of involvement recognizes that business is a stakeholder and therefore needs to participate in public sector and civil society initiatives, such as, The New York City Panel on Climate Change, which consists of diverse stakeholders, including representatives from the private sector (Rosenzweig *et al.*, 2011). Third, climate adaptation also provides a wide range of new opportunities to the business community. Even in developing countries, where regulations and markets are often underdeveloped and business risks are high, Khattri *et al.*, (2010) identified opportunities for working in the healthcare, waste and water management, sanitation, housing, energy, and information sectors through fostering cooperation across government departments and NGO and promoting public-private partnerships.

Despite broad-scale recognition of the need to adapt, such as the World Economic Forum’s (2012) ranking of the failure to adapt as one of the highest global risks and on a par with terrorism, and despite some examples of private sector engagement in adaptation, most assessments conclude that action in each of the potential arenas has been slow to emerge and that sharing of knowledge and experience has been limited (Khattri *et al.*, 2010, Agrawala *et al.*, 2011). KPMG International (2008) concluded that while companies are well used to managing business risk they are yet to integrate the long-term risks of climate change into these systems. Nor are they preparing to grasp the competitive advantages that will accrue to those taking early action. Most of the business interviewed appeared to be unsure of the scale of the threat and opportunities for their businesses or are awaiting further guidance and action by governments. They have trouble in accessing and applying information on the extent of the threats and impacts from climate change and have yet to engage in the detailed cost benefit analysis of adaptive actions or inaction. The ECA (2009) using case studies of both the public and private sectors in 8 countries came to similar conclusions. A survey by West and Brereton (2013) of Australian businesses also concluded that most were only vaguely aware of the breadth of adaptation actions that may be required and concerned about information sharing and disclosure. The authors suggest a framework for disclosures of relevant business activities to both in improve practice and cater for the needs of company boards, investors, and stakeholders. A survey commissioned by the Carbon Disclosure Project (Anon, 2007) found that among Standard and Poor’s (S&P) 500 companies many more (about 2/3 or respondents) were prepared to report and share information on managing climate risks and adaptation plans than they were on mitigation.

Also, there are still questions of whether and how adaptation finance should be made available to the private sector in developing countries and under what circumstances (Persson *et al.*, 2009; IFC, 2010, Agrawala *et al.*, 2011) although this is being piloted through the Pilot Program for Climate Resilience (World Bank, 2008; IFC, 2010). Private sector engagement and investment in adaptation is expected to make a substantial contribution to reducing climate risk, but the distribution of its investments will be selective and will be unlikely to match government and civil priorities (Atteridge, 2011).

14.2.5. Information, Capacity, and Resource Needs

Successful implementation of adaptation actions depends on the availability of information, access to technology and funding (Yohe and Tol, 2001; Adger, 2006; Eakin and Lemos, 2006; Smit and Wandel, 2006, World Bank, 2010). In some cases a supposed lack of relevant and legitimate information has been used as a rationale for inaction (Moser and Ekstrom, 2011). To address this concern, the Nairobi Work Program, established at COP12 in 2006 with a goal of helping developing countries make better informed decisions based on sound scientific, technical and socio-economic data, has included repeated calls for better observation systems, information sharing, and modeling capacity (UNFCCC/SBSTA/2008/3). Developed and developing countries have acted upon this priority by establishing institutions to provide information services at national, regional, and global scales (UKCIP, 2011; CCCCC, 2011; NCCARF, 2012), and there is an ongoing need to promote information acquisition and dissemination (OECD, 2009). For example, information-related adaptation needs in Africa include additional vulnerability and impact assessments with greater continuity, country-specific socio-economic scenarios, and greater knowledge on costs and benefits of different adaptation measures (section 22.4.2). Research and development, knowledge, and technology transfer are also important for promoting adaptive capacity. However, providing information does not mean that users will be able to make effective use of it, and this information will often have to be tailored or translated to the individual context (Webb and Beh, 2013). Efficacy of scientific knowledge can be improved by calibration with indigenous knowledge (section 20.4.2). There are also opportunities for technology transfer and innovation to be enhanced through information technologies (section 20.4.3).

Financial resources for adaptation have been slower to become available for adaptation than for mitigation in both developed and developing countries (see Chapter 17). Adaptation finance made up probably only a fifth of initial allocations of fast-start funding (Ciplet *et al.*, 2012); and much of this funding has been directed towards capacity-building, standalone projects, or pilot programs. This not only has left financial needs, but has meant that there is less expertise in adaptation assessment and implementation, which is further confounded by the complex relationship between adaptation and more common sustainable development and/or poverty reduction planning (McGray *et al.*, 2007). Adaptation cost estimates have been used to estimate the financial needs for adaptation, and these may well have been underestimated (see Chapter 17, section 17.6.1).

Overall, at both international and national levels there is a need to develop financial instruments that are equitable in both their delivery of resources and in sharing the burden of supporting the instruments (Levina, 2007; World Bank, 2010; Chapters 16 and 17). In this regard, the Green Climate Fund (GCF) was established in 2010 based on the commitment by developed country Parties to mobilize jointly USD 100 billion per year by 2020 to address the needs of developing countries (UNFCCC, 2007). Deliberation over how adaptation finance needs will be met has become central to the UNFCCC policy agenda (section 16.3.4). Also, financial mechanisms for disaster risk management are also inextricably linked with those for adaptation (Mechler *et al.*, 2010). Lessons from recent recovery operations have emphasized the need for disaster preparedness along with longer term goals directed to building resilience, including maximizing the employment-creation benefits of adaptation measures (Harsdorff *et al.*, 2011.)

Finances required in the future for climate change are estimated to approach levels on the order of current development expenditure, and there is a large gap in funding available for climate change responses in developing countries (Peskett *et al.*, 2009). Therefore, there is a related need to design delivery channels so that funding benefits the poor, as they often are most vulnerable to the impacts of climate change and climate-related disasters. As well as channeling adaptation finance to governments, there is a need for finance to reach the most vulnerable people and for approaches to enable stakeholder participation (section 15.2.3). For example, for adaptation financing, working at the sub-national level will be important and mechanisms like microfinance may be effective (Agrawala and Carraro, 2010). Another important concern is that with new money being made available for climate change research, policy development, and practice, people may place too much emphasis on addressing climate change as an isolated priority to the detriment of other equally pressing social, economic, and environmental issues (Ziervogel and Taylor, 2008). For example, in small islands, there are concerns that placing adaptation above the critical development needs of the present could inadvertently reduce resilience (see section 29.2).

14.3. Adaptation Options

Identifying needs stemming from climate risks and vulnerabilities provides a foundation for selecting adaptation options. Over the years, a number of categories of options have been identified. These options include a wide range of actions that, as summarized in Table 14-1, are organized into three general categories: structural/physical, social, and institutional.

[INSERT TABLE 14-1 HERE
Table 14-1: Categories and examples of adaptation options.]

There are many different ways that the range of adaptation options available could be categorized (Burton, 1996), thus any categorization is unlikely to be universally agreed upon; but this aims to take into account the diversity of adaptation options for different sectors and stakeholders. Some options cut across several categories. National, sectorial, or local adaptation plans are likely to include a number of measures that are implemented jointly from across various categories including structural, institutional, and social options. Furthermore some adaptation options are interrelated. For instance, institutions and information are prerequisites for effective early warning systems.

Adaptation constraints and limits mean not all adaptation needs will be met, and not all adaptation options will be possible (see Chapter 16, particularly section 16.7.1). Moreover, adaptation options are not available to meet all adaptation needs. For instance, adaptation options are poorly developed for the broader set of impacts on ocean systems (see section 30.6). There is also often going to be a gap between adaptation needs and the effectiveness of the options to meet these needs even when well resourced and well implemented. Some of this gap may be met by procedures to deal with loss and damage (19.7) and some adaptation deficit will remain with us. Many of the adaptation options intersect with vulnerability reduction and development options that build adaptive capacity and address the “adaptation deficit” which may be seen as part of a wider “development deficit” (McGray *et al.*, 2009; see also section 2.3.2.2).

14.3.1. Structural and Physical Options

This category highlights adaptation options that are discrete, with clear outputs and outcomes that are well defined in scope, space, and time. They include structural and engineering options, the application of discrete technologies, the use of ecosystems and their services to serve adaptation needs, and the delivery of specific services at the national, regional and local levels. This category included much of the notion of “concrete activities” that reflect the priority of the Adaptation Fund, where the focus is on “discrete activities with a collective objective(s) and concrete outcomes and outputs that are more narrowly defined in scope, space, and time” (Adaptation Fund Board, 2013).

14.3.1.1. Engineering and Built Environment

Engineering, and the multidisciplinary teams engineers work with (architects, planners, legal experts, etc.), is often at the forefront of delivering adaptation technologies and strategies (Dawson, 2007). Most engineering options are expert driven, capital-intensive, large-scale, and highly complex (McEvoy *et al.*, 2006; Morecroft and Cowan, 2010; Sovacool, 2011). While many of the engineering options, including management of storm and waste water flow (both inland and coastal), flood levees, seawalls, upgrading existing infrastructures to improve wind and flooding resilience, beach nourishment, and retrofitting buildings (Blanco *et al.*, 2009; Koetse and Rietveld, 2012; Ranger and Garbett-Shiels, 2012) are extensions and improvements of existing practices, plans, and structures, some newer projects are now integrating changed climate risk into the initial design. For example, during the engineering design of the Qinghai-Tibet Railway, various measures were proposed to ensure the stability of the railway embankment in permafrost regions (Wu *et al.*, 2008). Box 5-5 (Chapter 5) describes how new coastal protection structures in Japan are being upgraded to take into account future sea level rise.

Engineered adaptation options typically have two general limitations. First, they often must cope with uncertainties associated with projecting climate impacts arising from assumptions about future weather, population growth, and human behavior (Dawson, 2007; Furlow *et al.*, 2011). Second, the longevity and cost of engineered infrastructure affect the feasibility at the outset (Koetse and Rietveld, 2012). They also are subject to consequences that were not anticipated. For example, after coastal Eastern England was devastated by the North Sea storm surge in 1953, hard engineered sea walls were put in place to protect the coast from erosion and inundation. However, the engineered alterations resulted in a new array of coastal instabilities, including disturbances in sediment supply and damages to coastal ecosystems (Adger *et al.*, 2009; Turner *et al.*, 2010). As a result, many have promoted a "phased capacity expansion" strategy, which allows engineered projects to undertake design modification as conditions or knowledge change and facilitate incremental project construction to ease the burden of upfront financing (Colombo and Byer, 2012). An example is the Thames Estuary 2100 Plan (see Box 5-2) and in the Netherlands the Delta Works (Arnold *et al.*, 2011)

14.3.1.2. Technological Options

Recent advances in technology and information are being combined with engineering, structural adaptation measures in various applications. In food and agriculture sector, a suite of adaptation options have been developed and applied to reduce the adverse impacts of climate change on production (FAO, 2007; Stokes and Howden, 2010; Chapters 7 and 9). Technologies range from more efficient irrigation and fertilization methods, plant breeding for greater drought tolerance, adjusting planting based on projected yields (Semenov, 2006; 2008; Bannayan and Hoogenboom, 2008), to transfers of traditional technologies such as floating gardens (Irfanullah *et al.*,2011a, 2011b). Technology options for climate change adaptation include both "hard" and "soft" technologies, and not only new technologies but also indigenous and locally made appropriate technology (Glatzel *et al.*, 2012). For example, traditional construction methods have been identified across the Pacific as a means of adapting to tropical cyclones and floods, including building low aerodynamic houses and the use of traditional roofing material such as sago palm leaves to reduce the hazard of iron roofing being blown away in high winds (see section 29.6.2.1). Centralized high-technology systems can increase efficiency under normal conditions, but also risk cascading malfunctions in emergencies (section 15.3.2.5).

With the rapid diffusion of Information and Communication Technologies (ICT) such as mobile phones and the internet, the unprecedented speed at which information is produced and shared is posing a new set of possibilities for communication. ICT provides opportunities for both top-down dissemination of relevant information such as weather forecasts, hazard warnings, market information, information sharing and advisory services. It can also generate essential information through bottom-up processes such as "crowd sourcing" of useful information such as local flood levels, disease outbreaks, and the management of disaster responses. MacLean (2008) identifies three kinds of effects of the rapid advances in ICT on adaptation and development in general: direct use for monitoring and measuring climate change as described above, as a medium for raising awareness, and as an enabler for a "networked governance" based on networked open organizations. Pant and Heeks (2011) emphasize the difficulty in foreseeing additional applications that might arise from planned ICT applications that arise from local creativity and entrepreneurship, but warn that ICT itself is nor panacea and that the most effective applications are embedded in other societal behaviours.

There are repeated calls for technology transfer to and sharing between developing countries in adaptation to match the programs associated with mitigation (UNFCCC, 2006). Unlike mitigation, where low-carbon technologies are often new and protected by patents held in developed countries, in adaptation the technologies are often familiar and applied elsewhere. For example, agricultural practices that are well known in a region some distance away may now be applicable but unfamiliar within a region of interest (Irfanullah *et al.*, 2011a). Thus, technology transfer in adaptation may be easier than for mitigation. For example, to address water scarcity issues in many places, water storage, use and water efficiency technologies will all need to be more widely available. See also section 15.3.2.5 on technology transfer and diffusion.

14.3.1.3. Ecosystem-Based Adaptation

Ecosystem-based adaptation (EBA), which is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change (Convention on Biological Diversity, 2009), is becoming an integral approach to adaptation (Box CC-EA). Often, when faced with climate related threats, first consideration is given to engineered and technological approaches to adaptation. However, working with nature's capacity and pursing ecological options, such as coastal and wetland maintenance and restoration, to absorb or control the impact of climate change in urban and rural areas can be efficient and effective means of adapting (Huntjens *et al.*, 2010, Jones *et al.*, 2012). The use of mangroves and salt-marshes as a buffer against damage to coastal communities and infrastructure has been well researched and found to be effective both physically and financially in appropriate locations (Morris, 2007; Day *et al.*, 2007). They can also provide biodiversity co-benefits, support fish nurseries and have carbon sequestration value (Adger *et al.*, 2005, Reid and Huq, 2005; Convention on Biological Diversity, 2009). Other EBA activities include integrative adaptive forest management (Bolte *et al.*, 2009; Guariguata, 2009; Reyer *et al.*, 2009), and the use of agro-ecosystems in farming systems (Tengö and Belfrage, 2004,), ecotourism activities (Adler *et al.*, 2013), land and water protection and management, and direct species management (Mawdsley *et al.*, 2009). An analysis of the 44 submitted NAPAs showed that the value of ecosystem services was acknowledged in 50% of the national proposals and in 22% of the proposals included the use of ecosystem services mostly in support of other adaptation activities including infrastructure, soil conservation, and water regulation (Pramova *et al.*, 2012).

Green infrastructure (including the use of green roofs, porous pavements, and urban parks) can improve storm water management and reduce flood risk in cities, and can moderate the heat-island effect, as well as having co-benefits for mitigation (8.3.3.7). For example, New York City has a well-established program to enhance its water supply through watershed protection that is cost-effective compared to constructing a filtration plant (8.3.3.7). However, there are trade-offs relating to land-use and the availability of space for people and social, economic and environmental activities. For example, providing an effective wetland buffer for coastal protection may require emphasis on silt accumulation possibly at the expense of wildlife values and recreation (Convention on Biological Diversity, 2009; Dudley *et al.*, 2010). Similarly Goldstein *et al.* (2012) found that in land-use decision making in Hawaii tradeoffs existed between carbon storage and water quality, and between environmental improvement and financial returns. A further consideration is that ecosystem-based approaches are often more difficult to implement and assess as they usually require cooperation across institutions, sectors and communities, and their benefits are also spread across a similarly wide set of stakeholders (Jones *et al.*, 2012). One of the major barriers to EBA is the lack of comparable standards and methodologies applied to engineering approaches, thus demonstrating the need for more dialogue between the engineering and ecological communities.

14.3.1.4. Service Options

Service provision consists of a diverse range of specific and measurable activities. For instance, one measure to support to the most vulnerable populations is social safety nets. Efforts to address child malnutrition, which often result from loss of livelihood due to extreme weather events, particularly floods and droughts (Hoddinott *et al.*, 2008; Alderman *et al.*, 2009), offer an example of how safety nets can serve as a climate adaptation measure. While some studies have shown that food programs can be counterproductive to promoting livelihoods over the longer term or may not prevent malnutrition in non-emergency situations (e.g., Bhutta *et al.*, 2008), programs designed to provide support via food programs, micro-finance or insurance at times of extreme events can provide an important bridge for vulnerable populations (Alderman *et al.*, 2009; Hoeppe and Gurenko, 2006; Hochrainer *et al.*, 2007; Meze-Hausken *et al.*, 2009).

Public health services also are important for tackling projected increases of disease incidences spurred on by climate change (Ebi and Burton, 2008; Garg *et al.*, 2009; Edwards *et al.*, 2011; Huang *et al.*, 2011). For example, in countries where malaria is endemic, frequent adaptation options for addressing possible outbreaks include increasing use of mosquito nets, insecticides sprays, and controlling mosquito breeding by reclaiming land and filling drains (Garg *et al.*, 2009). Governments at all levels are often also responsible for maintaining adequate access to services that are projected to be further stressed due to climate change (Laukkonen *et al.*, 2009). Frequently cited options in this domain include, among others, clearing drainage systems to prevent floods, diversifying water supply services to account for changing water supplies (Kiparsky *et al.*, 2012), and maintaining open public spaces dedicated for disaster recovery and other emergency purposes (Hamin and Gurran, 2009).

At the local level, infrastructure associated with the provision of basic services, such as water, sanitation, solid waste disposal, power, storm water and roadway management, and public transportation are integral to increasing adaptive capacity (Paavola, 2008; Bambrick *et al.*, 2011; Barron *et al.*, 2012; see also section 8.2.4.1). Transport links enable households to take part in trade, for example to access agricultural markets (9.3.3.3.2) although supply chains can be vulnerable to climate disruption. Housing services are particularly critical because new patterns in temperature and precipitation will alter the habitability and stability of residences while increased frequency and intensity of natural disasters will place settlements and homes on both stable and unstable land at greater risk (Dodman and Satterthwaite, 2009; see section 8.3.3.3). Although one option is to relocate people inhabiting vulnerable areas, some argue that *in situ* upgrading may be more cost effective, especially for addressing informal settlements in developing countries (Revi, 2008).

14.3.2. Social Options

There are various adaptation options that target the specific vulnerability of disadvantaged groups, including targeting vulnerability reduction and social inequities. Community-based adaptation (CBA) refers to the generation and implementation of locally-driven adaptation strategies, operating on a learning-by-doing, bottom up, empowerment paradigm that cuts across sectors and technological, social, and institutional processes (section 5.5.1.4). Social protection schemes (see also section 14.3.1. above on services) include public and private initiatives that transfer income or assets to the poor, protect against livelihood risks, and raise the social status and rights of those who are marginalized (Box 13-2). An example of a social protection scheme aimed at moving beyond repeated relief interventions is Ethiopia’s Productive Safety Net Program (PSNP) (section 22.4.5.2).

The complexity of climate adaptation means that adaptation options are heavily influenced by forms of learning and knowledge sharing (Collins and Ison, 2009). Many scholars have noted that education is a key indicator for how people select adaptation options (Chinowsky *et al.*, 2011; Sovacool *et al.*, 2012), while a lack of education is a constraint that contributes to vulnerability (Paavola, 2008). For example, in a study of how farmers in the Nile Basin of Ethiopia select adaptation options, the researchers found a positive relationship between the education level of the household head and the adoption of improved technologies and adaptation to climate change (Deressa *et al.*, 2009a, 2009b). In Bangladesh, education about disaster responses was greatly assisted by rising literacy rates, especially among women (section 11.7).

Awareness raising, extension, outreach, community meetings, and other educational programs are important for disseminating knowledge about adaptation options (Aakre and Rübbelke, 2010; Birkmann and Teichman, 2010) as well as for helping to build social capital that is critical for social resilience (Adger, 2003; Krasny *et al.*, 2010; Wolf *et al.*, 2010). In this regard, education can be seen as a public good that promotes dialogue and networks (Boyd and Osbahr, 2010), and, therefore, allows the development of resilience at both the level of the individual learner and at the level of socio-ecological systems (Krasny *et al.*, 2010). Research partnerships and networks can facilitate knowledge-sharing and awareness raising at all levels from small groups of individuals to large institutions (section 8.4.2.5). Communication and dialogue on adaptation can be a two-way flow of information. Adaptation has itself been described as a social learning process (section 15.3.1.2) and a number of initiatives in Africa emphasized the importance of iterative and experiential learning for flexible adaptation planning (Suarez *et al.*, 2009; section 22.4.5.3). In Maryland a half-day role-playing process has been designed to both help local people, working with key local and state experts and planners, to plan and prepare for sea level rise and other coastal impacts. It allows them to experience first hand the diversity of stakeholders, the conflicting decisions to be made and the need to communicate throughout their community to adapt to new risks (Anon, 2009). A similar role playing game has been developed for the Chesapeake Bay of the Eastern United States (Learmonth *et al.*, 2011).

Informational strategies are integral to adaptation. Early warning systems are critical to ensuring awareness of natural hazards and to promoting timely response, including evacuation. A number of approaches being employed around the world, including tone alert radio, emergency alert system, presentations, and briefings (Van Aalst *et al.* 2008, Ferrara de Giner *et al.*, 2012). Heatwave and health warning systems (HHWS) can be designed to prevent negative health impacts, by predicting possible health outcomes, identifying triggers and communicating prevention responses (section 11.7.3).

Climate services initially emerged as an expansion of the tasks provided by weather services, and can act as “knowledge brokers” that establish a dialogue between science and the public, to facilitate decision-support (2.3.3). Linking indigenous and conventional climate observations can add value, for example in Western Kenya, where scientists have worked with local rainmakers to develop consensus forecasts (section 22.4.5.4). Awareness raising through scenario development, computer modeling, and role playing is effective in preparing both responsible authorities and the public. As previously noted, ICT is facilitating rapid dissemination of information. However, low-tech measures such as brochures, public service announcements, and direct contact with local residents also are important to fostering awareness and response especially where access to ICT is limited or expensive (National Research Council, 2010).

Behavioral measures are among the suite of options that are integral to advancing climate adaptation. Government incentives can spark behavioral change. For example, to slow runoff into storm sewers and reduce flooding, a number of cities in the U.S. run “Disconnect your Downspout” programs to urge homeowners to redirect water from their roof into a storage tank or small wetlands. These programs will provide information to households and some offer rebates on supplies. Many poor and vulnerable communities have taken steps to adapt to changes in climate, particularly those in flood prone areas. For instance, some local communities in Manila are increasing the number of floors in homes and building makeshift bridges (Porio, 2011). Behavioral adaptation can include livelihood diversification, which has long been used by African households to cope with climate shocks and spread risk (22.4.5.2). Labour migration can be an important strategy for reducing vulnerability to different sources of stress as it helps households diversify their livelihoods (Banerjee *et al.*, 2013). However migration and relocation do have implications for family relations, health and human security (see sections 11.7.4 and 12.4.2).

14.3.3. Institutional Options

Numerous institutional measures can be used to foster adaptation. These range from economic instruments such as taxes, subsidies, and insurance arrangements to social policies and regulations (Hallegatte, 2009; Heltberg *et al.*, 2009; de Bruin *et al.*, 2009). For instance, in the U.S., post-disaster funds for loss reduction are added to funds provided for disaster recovery and can be used to buy out properties that have experienced repetitive flood losses and to relocate residents to safer locations, to elevate structures, to assist communities with purchasing property and altering land-use patterns in flood-prone areas and undertaking other activities designed to lessen the impacts of future disasters not only on habitation but also more effective food production and other livelihoods (FEMA, 2010). Uptake of climate risk insurance is hindered by expensive premiums. The Caribbean Catastrophe Risk Insurance Facility (CCRIF) pools together country-level risks into a more diversified portfolio to offer lower premiums for immediate post-disaster responses (section 29.6.2.2).

Laws, regulations, and planning measures such as protected areas, building codes, and rezoning are institutional measures that can improve the safety of hazard-prone communities by designating land use to support resilience (Biderman *et al.*, 2008; Bartlett *et al.*, 2009). For example, marine protected areas (MPAs) have the potential to increase ecosystem resilience and increase recovery of coral reefs after mass coral bleaching (see Chapter 6, Box CC-CR). While zoning can be used to procure sites for low-income populations (Dodman and Satterthwaite, 2009; Biderman *et al.*, 2008; Bartlett *et al.*, 2009), if it increases property and housing values it also has the potential to exclude the poor from these areas. Legal rights can also determine adaptive capacity as well as access to resources. Land tenure security in Africa is widely accepted as being critical for enabling people to make longer-term decisions, such as changing farming practices (section 22.4.6).

A number of funding and financial issues are linked to institutions. At the international level, agreements and donors have a critical role to play in promoting and supporting the allocation and flow of financial resources (OECD, 2011). For instance, the Adaptation Fund, which is set up under the Kyoto Protocol and funded through a levy on most

CDM projects, is of particular importance to developing countries as it is pioneering the direct access mechanism which allows countries to access funds without having to work through a multi-lateral development agency. The direct access mechanism highlights the role of institutions in building and maintaining capacity, not just in the technical aspects of adaptation assessment and project design, but also in financial management and due diligence (Brown *et al.*, 2011).

Effective governance is important for the efficient operations of institutions. In general, governance rests on the promotion of democratic and participatory principles as well as on ensuring access to information, knowledge, and networks. Institutional strengthening and capacity building has been highlighted as a priority need in developing countries (Kumamoto and Mills, 2012). In assessment of river basin planning in Brazil, Engle and Lemos (2010) found that improving governance mechanisms appears to enhance adaptive capacity. Similarly water-trading schemes facilitated by new government measures reduced the impact of a major drought on the economy in Australia (Mallawaarachchi and Foster, 2009). The effectiveness of such approached depends on both government will and capacity building among those affected.

In terms of national or local adaptation planning and policy-making, Chapter 15 emphasizes that it can be challenging for governments to move beyond adaptation planning to implementation (section 15.2.2.2). In an evaluation of one of the earliest national adaptation strategies for Finland, it was found that few measures had been implemented except in the water sector (Box 23-2). Adaptation planning can occur at a number of spatial scales including at the national, regional, city, district, or local community level. Action plans can include a range of adaptation options including structural, social and regulatory measures. For example, Quito city has proposed developing dams, encouraging a culture of rational water use, reducing water losses; and developing mechanisms to reduce water conflicts (section 8.3.3.4). Table 25-5 lists various urban climate change adaptation options and their barriers to adoption. See also section 15.2.2.4 on local adaptation plans.

Institutional adaptation options include the use of various decision-making and adaptation planning tools (Chapter 15) including iterative risk management (Chapter 2). There are various decision-making paradigms that can guide adaptation actions. For example, prominent institutional frameworks used for management of coastal areas include Integrated Coastal Zone Management (ICZM) and Adaptive Management (see sections 5.5.1.4 and Box 5-4). At the local scale, community-based adaptation refers to the generation and implementation of locally-driven adaptation strategies through a learning-by-doing, bottom-up approach (section 5.5.1.4). Community-based approaches to adaptation can also be mainstreamed into local or regional plans. Refer to Table 5-7 for a description of community-based adaptation options for coastal areas.

14.3.4. Selecting Adaptation Options

Selecting specific adaptation options can be challenging partly due to the rate, uncertainty, and cumulative impacts of climate change. How adaptation is framed will have an impact on how adaptation options are selected (Fünfgeld and McEvoy, 2011). Policy and market conditions may be a stronger driver of behavior than the observed climate itself (Berkhout *et al.*, 2006). Also, rarely will adaptation options be designed to address climate risks or opportunities alone (IPCC, 2007b), instead actions will often be undertaken with other goals (such as profit or poverty reduction) in mind, while also achieving climate-related co-benefits. Gains in reduced vulnerability, enhanced resilience or greater welfare will often be co-benefits generated as a result of changes and innovations driven by other factors (Khan *et al.*, 2013). Rather than focusing on adaptation options addressing specific dimensions of climate change, more attention is being paid to mainstreaming climate change into wider government policy and private sector activities (See sections 15.2.1; 15.5.1; Sietz *et al.*, 2011a).

Selection and prioritization of adaptation options is important because not all adaptation options will be possible due to constraints such as insufficient local resources, capacities, and authority (see sections 16, 16.7.1). Furthermore, some adaptation options can be maladaptive if they foreclose other options (see 14.7 below). The viability of adaptation options is dependent on the time-scale and climate scenario emphasizing that selecting adaptation options is an iterative process.

A variety of systematic techniques have been developed for selecting options (e.g., see section 15.4; De Bruin *et al.*, 2009; Ogden and Innes, 2009; Füssel, 2009). Quantification and other systematic approaches to selecting options have many virtues. However, they also have limitations. For instance, most of these methodologies do not account for a range of critical factors such as leadership, institutions, resources, and barriers (Smith *et al.*, 2009). For example, cost-benefit analysis of adaptation options requires valuation of non-market costs and benefits, which can be impractical (section 17.3.6). Strategies dominating the early adaptation literature emphasized maintaining the current system and minimizing costs while achieving some form of benefit. For instance, no-regrets measures both reduce climate risk and provide other social, economic or environmental benefits (Hallegatte, 2009). Risk management approaches often lead to no-regrets, low regrets or win-win options; while multi-criteria analysis (MCA) allows assessment of options against different criteria, as was used in the preparation of NAPAs (UNFCCC, 2011).

As ideas about adaptation have evolved, there has been a shift in ambition from traditional approaches that emphasize maintaining the status quo to more dynamic and integrative strategies (see also sections 2.4.3, 14.1, 16.4.2, 20.5). Adaptive management places an emphasis on taking action and then using the lessons learned to inform future actions in order to make better-informed, and often incremental, decisions in the face of uncertainty (Figure 14.4; section 2.2.1.3). Lempert and Schlesinger (2000) have proposed that adaptation options should be robust against a wide range of plausible climate and societal change futures. Emerging trends in adaptation place an emphasis on the need for more transformational changes, which has a distinct logic that differs from traditional strategies (see section 14.1).

As research and experience in the practice of adaptation grows and ever increasing number of considerations have been advanced as being important in guiding the selection and sequencing of adaptation options. It is unlikely that every adaptation program can ever fully meet each of these considerations, especially as they are increasingly integrated with wider social or development goals, but Table 14-2 seeks to outline the most common considerations and point to sources in this volume and the literature for a discussion of some of the core issues.

[INSERT TABLE 14-2 HERE
Table 14-2: Considerations when selecting adaptation options.]

14.4. Adaptation Assessments

14.4.1. Purpose of Assessments

Identifying adaptation needs requires an assessment of the factors that determine the nature of, and vulnerability to, climate risks (climate change assessments, climate impacts and risk assessments and vulnerability assessments) and an assessment of adaptation options to reduce risks (adaptation assessment). The various types of climate change assessments differ in that they pursue different goals, are underpinned by different theoretical frameworks, and rely in different forms of data and may ultimately lead to different adaptation responses (Fünfgeld and McEvoy, 2011).

Assessments help decision makers understand the impacts, vulnerability and adaptation options in a region, country, community or sector. They are often characterized into “top-down” and “bottom-up” assessments. Top-down assessments are used to measure the potential impacts of climate change using a scenario and modeling driven approach. Bottom-up assessments begin at the local scale, address socio-economic responses to climate, and tend to be location-specific (Dessai and Hulme, 2004). They are often used to determine the vulnerability of different groups to current and/or future climate change and their adaptation options, using stakeholder intervention and analyzing socio-economic conditions and livelihoods (UNFCCC, 2010). There are also policy-based assessments, which assess current policy and plans for their effectiveness under climate change within a risk-management framework (UNDP, 2004; UNDP, 2005). The evolution of assessments has led to a more thorough assessment of society’s ability to respond to risks through various adaptations, which can help guide allocation of adaptation resources (Füssel and Klein, 2006). In practice assessments have become increasingly complex, often combining elements of top-down and bottom-up approaches (e.g., Dessai *et al.*, 2005). Decision-makers use both in the policy process (Kates and Wilbanks, 2003; McKenzie Hedger *et al.*, 2006).

14.4.2. Trends in Assessments

A variety of frameworks have been developed for the assessment of climate impacts, vulnerability, and adaptation (Fünfgeld and McEvoy, 2011). "Impacts-based" approaches focus primarily on the biophysical climate change impacts to which people and systems need to adapt. "Vulnerability-based" approaches focus on the risks themselves by concentrating on the propensity to be harmed, then seeking to maximize potential benefits and minimize or reverse potential losses (Adger, 2006; IPCC, 2007b). "Adaptation-based" approaches examine the adaptive capacity and adaptation measures required to improve the resilience or robustness of a system exposed to climate change (Smit and Wandel, 2006). In practice these approaches are interrelated, especially with regard to adaptive capacity (O'Brien *et al.*, 2007). An evolution in the conceptualization of risk and vulnerability in the past decade has led to more holistic and integrated approaches to assessment, aiming towards a more systemic understanding of the complexity of human-environment interactions (Preston *et al*., 2011b).

The "standard approach" to assessment has been the climate scenario-driven impacts-based approach, which developed from the seven-step assessment framework of the IPCC (Carter *et al.*, 1994; Parry and Carter, 1998): (1) Define problem (including study area and sectors to be examined), (2) select method of problem assessment, (3) test methods/conduct sensitivity analyses, (4) select and apply climate change scenarios, (5) assess biophysical and socio-economic impacts, (6) assess autonomous adjustments, and (7) evaluate adaptation strategies. This approach dominated the assessment sections of the first three IPCC reports, and aims to evaluate the impacts of climate change under a given scenario and to assess the need for adaptation and/or mitigation to reduce any resulting vulnerability to climate risks (IPCC, 2007a). These frameworks are described as "first generation" or "type 1" assessment studies (Burton *et al.*, 2002). The standard impact approach is often described as top-down because it combines scenarios downscaled from global climate models to the local scale with a sequence of analytical steps that begin with the climate system and move through biophysical impacts towards socio-economic assessment (IPCC, 2007b). The process of downscaling of Global Climate Models (GCMs) leads to issues of uncertainty and limited statistical confidence (Fünfgeld and McEvoy, 2011).

A new generation of scenario-based impact assessments has also emerged linking biophysical, economic and social analysis tools. Refer to 2.3.2 for examples of large-scale and regional-scale scenario-based vulnerability assessments that have taken place linking biophysical and socioeconomic futures. In Europe, a study by Ciscar *et al*. (2011) estimated economic welfare losses over 4 sectors of 0.2–1% by the 2080s (section 2.3.2.1). In Australia, socio-economic considerations are beginning to be used to inform assessments of adaptive capacity and vulnerability (section 25.3.2). A risk-based framework, based on the risk management approach, can also be used for assessing adaptation opportunities, constraints and limits (section 16.2). Economic assessments are also used to estimate the impacts of climate change, including distributional impacts, and adaptation costs and benefits (see Chapter 17).

The "second generation" vulnerability and adaptation assessments (Burton *et al.*, 2002) pay greater attention to information around vulnerability to inform decisions on adaptation. They are characterized by the intensive involvement of stakeholders and the participation of vulnerable groups in decision-making around adaptation options (LEG, 2012; Füssel and Klein, 2006). Local projects often use participatory vulnerability assessment (PVA) methods. In Bangladesh, community-based adaptation has combined consensus-building and participatory rural appraisal (PRA) to assess needs of the communities and propose adaptation actions (section 15.2.2.4.1). In activities by CARE, vulnerability assessments were undertaken with men and women's groups separately to ensure activities were gender-sensitive (see section 7.5.2). Participatory vulnerability assessments offer an opportunity to avoid maladaptation by involving stakeholders, for example in a vulnerability assessment of tourism in the Mamanuca Islands in Fiji, where stakeholders were explicitly integrated into each step of the process (section 29.8).

Adaptation assessments continue to evolve, but most syntheses now include "top-down" and "bottom-up" approaches, and include the assessment of both biophysical climate change risks and the factors that make people vulnerable to those risks. There is a shift towards integrating community-based planning into national adaptation plans. The Government of Nepal proposes "LAPA assessments" (Local Adaptation Plans of Action) that seek to integrate top-down and bottom-up models (Government of Nepal, 2011). There is also increasing attention to institutional capacity assessments and policy environments as key factors that can both drive vulnerability, and also determine the type and success of different adaptation options. The generic elements of adaptation and vulnerability assessment are reflected in the UKCIP guidelines presented in Figure 14-2.

[INSERT FIGURE 14-2 HERE
Figure 14-2: A generic framework for vulnerability and adaptation assessments (UKCIP, 2011).]

14.4.3. Issues and Tensions in the Use of Assessments

Adaptation and risk assessments give rise to various tensions, three of which are discussed in this section. The first is the adaptation paradox, which recognizes that climate change is a global problem while vulnerability is locally experienced (Ayers, 2011). Top-down assessments of climate scenarios are deemed necessary in order to understand the climate change scenarios that render climate risk. However, the factors that make people vulnerable to climate risks are often locally generated, so require locally driven bottom-up analysis, while factors at the national and regional levels also determine vulnerabilities. Bottom-up analysis tends to prioritize groups based on factors related to poverty and development that drive vulnerability. Top-down assessments tend to prioritize those most exposed to climate risks. Analysis in Nepal that assessed both under-development and climate change impacts showed that, at the household scale, there was a strong correlation between local measures of poverty and vulnerability to climate change (Ghimire *et al.*, 2010). However, when indicators were aggregated at district scale, the correlation was weaker - even when the vulnerability index used included poverty as a proxy for adaptive capacity alongside climate hazard risk and exposure (Ghimire *et al.*, 2010).

There are also tensions around ownership and participation. Assessments managed under global climate change governance structure of the UNFCCC are developed under an “impacts-based” paradigm (Burton *et al*., 2002). This impacts-based approach requires external scientific and technological expertise for defining climate change problems, and formulating technological adaptation solutions, based on specific knowledge of future climate conditions. Such assessments are necessarily “top-down” because this expertise exists at the global and national level. At the local level, the capacity to adapt is based on the underlying securities that determine vulnerability to these impacts in the first place (Adger *et al.*, 2003a). Accessing this information requires “bottom-up” and participatory assessments that engage local vulnerable people. These vulnerable groups and institutions often do not have access to the climate impacts science necessary to fully apply top-down impacts-based assessments. Some places also do not have accurate historical weather data, making it difficult to validate climate trends and models and hence develop evidence based scenarios of what will happen with any degree of accuracy (Conway, 2009).

The numerous assessments that have been carried out have led to increased awareness among decision makers and stakeholders of climate risks and adaptation needs and options. But this awareness is often not translated into the implementation of even simple adaptation measures within ongoing activities or within risk management planning. There is a bottleneck in adaptation assessments, which may need to be overcome by linking more directly to particular decisions and tailoring the information to local contexts to facilitate the decision making process (Preston and Stafford Smith, 2009; Brown *et al.*, 2011). Specific techniques such as decision scaling, which seeks to understand which climate conditions would result in hazardous conditions of concern for particular stakeholder groups are a step in this direction (Moody and Brown, 2012; Brown *et al.*, 2012). Decision support must recognize that human psychological dimensions play a crucial role in the way people perceive risks and make decisions (section 2.2.3). Impacts and adaptation options will also have to be successfully communicated to the local scale. One example of this is local-scale visualization of impacts and adaptation measures, as has taken place in British Columbia, Canada (see section 2.3.4). Use of ICT tools can foster new ways to assimilate or translate information (section 15.2.3.2). Vulnerability mapping, including the use of GIS (Geographic Information Systems), can help stakeholders to visualize the impacts of climate change on the landscape, while integration with participatory processes can facilitate learning and deliberation (Preston *et al*., 2011a).

14.4.4. National Assessments

Under the United Nations Framework Convention on Climate Change, all Parties are encouraged (Annex 1 countries are required) to report on their activities in relation to "vulnerability assessment, climate change impacts and adaptation measures" (FCCC/CP/1999/7). Parties are encouraged to use the IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations (Carter *et al.*, 1994) and the UNEP Handbook on Methods for Climate Change Impacts Assessment and Adaptation Strategies, which focuses on the impacts of sea level rise and uses the seven-step assessment framework (described above). Annex 1 countries are due to submit their 6th Communications by 2014 and most non-Annex I countries are due to have submitted at least one Communication and some are on their fifth. As such, National Communications have formed the first avenue for assessing and reporting on climate risk and vulnerability assessments at the national level. Most initial national communications to the UNFCCC produced by developing countries were first-generation vulnerability assessments, which did not seek to assess the feasibility of implementing adaptations (Füssel and Klein, 2006). Undertaking such assessment is resource-intensive, underscoring the need for further resources, training, and expertise.

There is a range of emerging national experiences on adaptation and vulnerability assessments. For coastal areas under sea level rise, a summary of the results from coastal vulnerability assessments is shown in Table 5-5. Such assessments show that vulnerability is highly dependent on the greenhouse gas mitigation scenario. In Kenya, a study by Stockholm Environment Institute (SEI) estimated the economics of climate change under a range of scenarios (see Figure 22-6) and estimated that by 2050, over 300,000 people could be flooded per year under a high emissions scenario. In 2012, the UK's first Climate Change Risk Assessment (CCRA) was undertaken based on a similar framework to that shown in Figure 14-2, to assess risks in and across eleven sectors to inform priorities for action and appropriate adaptation measures (DEFRA, 2012).

National Adaptation Programmes of Action (NAPAs) are designed as a vehicle for Least Developed Countries (LDCs) to communicate their most "urgent and immediate adaptation needs" to the UNFCCC for funding from the Least Developed Countries Fund (LDCF). "Urgent and immediate needs" are defined as those for which further delay in implementation would increase vulnerability or increase adaptation costs at a later stage (LDC Expert Group, 2002). The approach adopted for vulnerability assessment under NAPAs vary. Although the guidelines call for more participatory and "bottom-up" mechanisms to be adopted, time and funding limitations has meant that often the NAPA process remains largely top-down, focused on impacts and only consulting the communities to verify this information (Huq and Khan, 2006; Ayers, 2011). Moreover, available financial resources were too limited to fully assess and address the needs of all sectors and all vulnerable regions of the country (LEG, 2012, see also section 15.2.2.2).

Under the Cancun Adaptation Framework (CAF), a process was established to enable least developed country Parties (LDCs) to formulate and implement National Adaptation Plans (NAPs). NAPs are intended to build on NAPAs but shift the focus towards identifying medium- and long-term adaptation needs and developing and implementing strategies and programmes to address those needs. NAPs intend to facilitate the integration of climate change adaptation into relevant national and subnational development and sectoral planning (LEG, 2012). Other developing country Parties are also invited to employ the modalities formulated to support the national adaptation plans in the elaboration of their planning efforts. Early guidelines (LDC Expert Group, 2002) propose a country-specific approach tailored to national circumstances, mixing top-down policy-first assessments with bottom-up approaches. Recent guidelines propose that this should non-prescriptive and should facilitate country-driven, gender-sensitive, participatory action, taking into consideration vulnerable groups, communities and ecosystems (LEG, 2012). Refer also to sections 2.3.4 and 15.2.2 for further details of national and sub-national adaptation planning including NAPAs and NAPs.

14.5. Measuring Adaptation

Adaptation has tended to lag behind mitigation efforts both in research and in the climate negotiations. In part this is because adaptation and development specialists, governments, NGOs and international agencies have found it difficult to clearly define and identify precisely what constitutes adaptation, how to track its implementation and effectiveness, and how to distinguish it from effective development (Burton *et al.*, 2002; Arnell, 2009; Doria *et al.*, 2009). A contributing reason is that adaptation has no common reference metrics in the same way that tonnes of greenhouse gases or radiative forcing values are for mitigation. This section seeks to explore the feasibility of finding metrics for measuring adaptation effectiveness.

The search for metrics[4] for adaptation will remain contentious with many alternative uses competing for attention. This is inevitable as there are multiple purposes and viewpoints in approaching the measurement of adaptation (Hulme, 2009). Brooks *et al.* (2011) asked "what constitutes successful adaptation" and suggested that the criteria by which success might be assessed include, feasibility, efficacy/effectiveness, efficiency, acceptability/legitimacy, and equity (derived from Yohe and Tol, 2001; Adger *et al.*, 2005; Stern, 2006), to which they added sustainability (Fankhauser and Burton, 2011). Effective integration and coherence with wider national policies and development goals is another often sought criterion (World Bank, 2010). Also institutions, communities and individuals value things differently and many of those values cannot be captured in a comparable way within metrics (Adger and Barnett, 2009).

[FOOTNOTE 4: There is no consistent use of the terms metric, measure and indicator in the literature. Here we try to stay as close as possible to the dictionary meanings (although they overlap). A measure is the amount or degree of something; i.e. a descriptions of its (presumably current) state. A metric is often a group of values (measures) that taken together give a broader indication of the state or the degree of progress to some desired state. An indicator is a sign, or estimate of the state of something and often of the future state of something. Most often in seeking to understand the state of vulnerability or adaptation etc we need a metric (i.e. a group of measures) and we use the term in that way. In describing the components of a metric we will give preference to the term indicator over measure.]

At least three uses of metrics for adaptation are relevant each requiring different characteristics of the indicators used. The first use seeks metrics to help determine the need or determinates of that need for adaptation. These metrics usually focus on measuring vulnerability, but that term is not well defined. For example, Hinkel (2011) identifies six uses that vulnerability indicators are sometimes expected to serve and concludes that they can truly serve only their core purpose; i.e. to identify vulnerable people, communities and regions. Further, even with metrics focusing on vulnerability the goal often is not to produce a score or rating to identify vulnerable groups but to elucidate information on the nature of vulnerability and to better identify adaptation options (Smit and Wandel, 2006, Sietz *et al.*, 2011b). The second use of metrics relates to measuring and tracking the process of implementing adaptive actions, such as spending on coastal protection, the number of early warning plans implemented as part of a program, or the number of agricultural specialists with appropriate training in climate risks. Here the selection of appropriate metrics is usually less contentious but although there is disagreement as to how much they capture adaptation rather than normal development. The third use of metrics relates to measuring the effectiveness of adaptation such as in monitoring and evaluation. This set is essential to help measure progress and provide feedback on the effectiveness of actions, but are among the most difficult to identify as adaption outcomes take time to become identifiable and are often subject to evolving conditions and objectives.

14.5.1. What is to be Measured?

The measurement of vulnerability is central to many adaptation metrics and initially it was approached from an impacts point of view. Here vulnerability is usually defined as a function of (1) exposure to specific hazards or stressors, (2) sensitivity to their impacts and (3) the target population's capacity to adapt (IPCC, 2001, Chapter 17). This approach continues to be used as the basis of many assessments and adaptation prioritization efforts. Recently the emphasis has moved from better defining exposure and potential impacts to a better understanding of the factors that affect societies' sensitivity to those impacts and their capacity to adapt. This reflects the increasing recognition of the importance of considering social vulnerability alongside biophysical vulnerability. Various terms have been used to describe these different emphases including biophysical versus social vulnerability, outcome versus contextual vulnerability (sections 14.2.1.1.1 and 14.2.1.1.2; Eakin and Luers, 2006; Füssel and Klein, 2006; Eriksen and Kelly, 2007; Füssel, 2010) and scientific framing versus a human-security framing of vulnerability (O'Brien, 2006). O'Brien *et al.* (2007) argue that scientific and human-security frameworks affect the way we approach adaptation, with the scientific framework leading to building local and sectoral capacity to make changes rather than address the fundamental causes of vulnerability, or climate change itself, within their broader geopolitical and economic contexts.

Other questions also arise even within a given conceptual framework for considering vulnerability. A system of measurement is usually developed to allow comparisons between different places, social groups or sectors of activity, although experience repeatedly cautions us to be careful in doing so (Schröter *et al.*, 2005). The challenge is as much of integration across widely differing research domains and traditions (Polksy *et al.*, 2007) Also, a system's vulnerability is not static but can respond rapidly to changes in economic, social, political and institutional conditions over time (Smit and Wandel, 2006; Smit and Pilifosova, 2003). Much of the effort in relation to estimating social vulnerability is reviewed in Cutter *et al.* (2009).

It has also been suggested that a framework based on the concept of resilience is more appropriate than a vulnerability framework in many contexts (see IPCC SREX Chapter 2 and section 8.3.3 for more details). For example, in a development context resilience "evokes positive and broad development goals (e.g., education, livelihood improvements, food security), includes multiple scales (temporal and spatial) and objectives, better captures the complex interactions between human societies and their environments, and emphasizes learning and feedbacks" (Berkes, 2007; Moss *et al.*, 2012). A resilience approach also leads to more focus on interactions between social and biophysical systems (Nelson *et al.*, 2007). However, others feel that resilience promotes too great a focus on the return of the overall system to pre-impact conditions and not enough on the human agents and their need to adapt to changing conditions ((Nelson *et al.*, 2007; IPCC SREX 2012 section 8.3.3.). The concept of resilience has been difficult to apply in practice and is particularly resistant to attempts to establish commonly accepted sets of indicators. Some (e.g. Klein *et al.*, 2003) have suggested that resilience has become an umbrella concept that has not been able to support effectively planning or management.

Recently Brooks *et al.* (2011) have outlined a framework tracking adaptation that combines the establishment of upstream metrics to assess how well risks are being managed by institutions, and downstream metrics to track whether the interventions are reducing the vulnerability of affected groups. The upstream metrics would focus on assessments of institutional capacity, managerial performance, and integration of climate risk management into planning processes and tracking and feedback processes. The downstream metrics would focus on indicators to track development performance and changes in vulnerability. Attribution of these changes to particular interventions would be desirable, but not essential to track progress.

But understanding vulnerability does not necessarily translate to effective adaptation. Smit *et al.* (2001), Osman-Elasha *et al.* (2009), and others have suggested that the focus should be on increasing adaptive capacity within the context of the full range of biophysical and socio-economic stressors. However, as the scope of the metrics is widened to include aspects of development and sustainability they often become less suitable for other purposes such as helping to identify "the full and additional costs of adaptation" (McGray *et al.*, 2007).

In deriving indices of vulnerability there are again several broadly different approaches. One is to deductively identify indicators that theoretically should be strongly related to vulnerability (e.g. Dolan and Walker, 2003; Polsky *et al.*, 2007), while the other is inductive and uses observed data to seek correlations between indicators and observed consequences of vulnerability, such as the number of people killed or affected by climate related events in recent history. There is some commonality in identifying the desirable criteria for selecting indicators, and while no list can ever be complete Table 14-3, based initially on Perch-Nielsen (2010), seeks to bring together some of the most common criteria.

[INSERT TABLE 14-3 HERE
Table 14-3: Criteria for the selection of indicators. Based on multiple sources.]

14.5.2. Established Metrics

Numerous metrics continue to be prepared for a variety of purposes and at scales ranging from estimating the vulnerability of individuals and communities to comparing countries. Several reviews, including Moss (2001, 2012), Srinivasan and Prabhakar (2008), and Prabhakar and Srinivasan (2011), discuss both the design and effectiveness of many of the existing proposals for adaptation metrics.

14.5.2.1. Vulnerability Metrics

Eriksen and Kelly (2007) found strong divergence among five metrics (or indices) for comparing national vulnerability published over the period 1995 to 2003. (Namely the Dimensions of vulnerability of Downing *et al.*, 1995; the Index of Human Insecurity (IHI) of Lonergan *et al.* 1999; the Vulnerability-resilience indicators of Moss *et al.*, 2001; the Environmental Sustainability Index of the World Economic Forum, 2002; and the Country-level risk measures of Brooks and Adger, 2003). Between them, 29 indicators were used with only five indicators appearing in more than one study. They were able to compare the 20 countries ranked as most vulnerable from three of the studies and found little overlap with only five countries ranked in the top 20 in more than one study. However, it must be noted that the metrics were developed at different times and for different purposes. They concluded that the indices focused on measuring a snapshot of aggregate conditions rather than on delivering guidance on societal processes that can be targeted to reduce vulnerability.

There are a series of disaster related indices designed to assess relative risks across countries and regions, and to provide benchmarks on which to assess progress Among them are the Disaster Risk Index (UNDP, 2004); Hotspots Index (Dilley *et al.*, 2005); the Americas Index (Cardona, 2005); and an index for South Asia (Moench *et al.*, 2009). Again there has been little effort to further analyse, validate, or compare these metrics.

14.5.2.2. Metrics for Resource Allocation

Vulnerability indices have usually been selected to better understand the drivers of vulnerability or to compare countries, regions, communities etc. in terms of the risks they face from climate change and their capacity to deal with them. This is not necessarily the same as designing an allocation index or rule to be used to allocate limited resources equitably and efficiently among entities (countries, regions or other administrative groups, or different proponents of adaptation). For allocation vulnerability and coping/adaptive capacity might be expected to remain a core consideration, but so also should the relative costs of implementation in relation the potential benefits, the ability of the recipients to absorb the funding and implement policies and projects to actually achieve the projected benefits (UNFCCC, 2007; Parry *et al.*, 2009; Wheeler, 2011).

One of the longest running and prominent uses of metrics in funding is the World Bank's process of allocating IDA concessional funds to developing countries which faces many issues analogous to the same process for adaptation. The World Bank uses the Country Policy and Institutional Assessment (CPIA) based on 16 criteria, many qualitative, to estimate the extent to which a country's policy and institutional framework supports sustainable growth and poverty reduction, and consequently the effective use of development assistance. These criteria are the main components used to calculate a Country Performance Rating, which in turn is a major component, along with population and recent performance measures, in calculating allocations to the poorest developing countries with long-term, no interest (IDA) loans. The CPIA and the ultimate IDA allocation formulae are controversial, much debated (Alexander, 2010), often fine-tuned (IEG, 2009) but still commonly used as a reference point for this type of procedure (GTZ, 2008).

An explicit example of the use, and non-use, of adaptation metrics was in establishment of the Pilot Program for Climate Resilience (PPCR). The governing body made up of contributors, recipients and other stakeholders set up an independent expert group to make recommendations as to which countries might be included as pilots within the approximately USD1billion program (Climate Investment Funds, 2009). The expert group refrained from using a simple index, but instead country selection was done across 9 regions and each based on a suite of indicators appropriate for the region using expert judgment. It is interesting to note that on moving to the next step of deciding on allocation of financial resources to the selected pilot countries the governing body of the PPCR chose not to use an approach based on indicators, but to provide guidance to the countries of the possible range of funding and to base allocations on the quality of the proposals bought forward (Climate Investment Funds, 2009). Similarly, none of the other governing bodies of international adaptation funding mechanisms (e.g. the GEF, the Adaptation Fund) has chosen to use a defined set of metrics within their decision-making.

Wheeler (2011) has developed an index of vulnerability based on weather related disasters, sea-level rise and agricultural productivity. The index can be adjusted according to user preferences to develop allocation formulas based only on biophysical vulnerability, further adjusted for economic development and governance, and finally for project costs and probability of success. Klein and Möhner (2011) have discussed the options for the Green Climate Fund based on experience to date and conclude that science cannot be relied upon for a single objective ranking of vulnerability.

14.5.2.3. Metrics for Monitoring and Evaluation

The IPCC's *Fourth Assessment Report* provided little discussion of the role of evaluation and monitoring of adaptation responses as a component of building adaptive capacity (Adger *et al.*, 2007). Preston *et al.* (2011a) identify three specific roles of evaluation: (1) ensuring reduction in societal and ecological vulnerability, (2) facilitating learning and adaptive management, and (3) providing accountability for adaptation investments (see also GIZ, 2011). A central challenge in developing robust monitoring and evaluation frameworks for adaptation is the existence of multiple, valid points-of-view that can be used to evaluate adaptation actions and their continuing effectiveness (Gagnon-Lebrun and Agrawala, 2006; Perkins *et al.*, 2007; Füssel, 2008; Smith *et al.*, 2009; Ford *et al.*, 2011; Preston *et al.*, 2011b). This challenges the selection of appropriate metrics for the monitoring and evaluation of adaptation and its contribution to vulnerability reduction (Burton and May, 2004; Gagnon-Lebrun and Agrawala, 2007; McKenzie Hedger *et al.*, 2008; Ford *et al.*, 2011).

One of the central unresolved tensions in progressing evaluation is the relative merit of relatively easy and objective targeting the completion of the processes and outputs needed to implement an adaptation program versus the outcomes, such as changes in livelihood s or reduction in risks. Assessment of outcomes is less objective, subject to whether appropriate circumstances occur (e.g., that floods occur so that risk reduction can be demonstrated) and usually take much longer to establish. Preston *et al.* (2011b) suggest the evaluation of adaptation processes may be a more robust approach to evaluation, due to the difficulties in attributing future outcomes to adaptation strategies and the long-time lags that may be needed to assess the performance of a particular strategy (Berkhout, 2005; Dovers and Hezri, 2010; Ford *et al.*, 2011). The OECD analyzed the monitoring and evaluation processes across 106 adaptation projects across six development agencies and found that Results Based Management and Logical Framework approaches dominated as they do in normal development projects (Lamhauge *et al.*, 2011). They also drew attention to the need for appropriate baselines and complimentary sets of indicators that track not just process and implementation, but also the extent to which targeted changes are occurring. Monitoring programs themselves will need careful design to ensure that they remain in place over the long timeframes needed for the outcomes to be identified; that they contain incentives for beneficiaries to comply with conditions and that compliance itself does not impose undue burdens.

A number of national and international organizations have guides to monitoring and evaluating adaptation activities (McKenzie Hedger *et al.*, 2008; UNDP, 2008; WRI, 2009; World Bank, 2010; GIZ, 2011). These guides tend to focus on the wider framework of identifying and managing adaptation-related activities and within that the criteria for the selection of metrics for monitoring and evaluating those activities. These issues are dealt with in Chapters 15 and 16.

14.5.3. Validation of Metrics

The practice of developing and applying metrics in adaptation has been subject much scrutiny. Eakin and Luers (2006) express serious concerns about national-scale vulnerability assessments ranging from the quality of the available data, the selection and creation of indicators, the assumptions used in weighting of variables and the mathematics of aggregation. Nevertheless metrics will continue to be used and the challenge is to identify and maintain basic standards of best practice.

One of the most comprehensive attempts to validate a system for measuring important components of adaptation is that of Brooks *et al.*, 2005. They used the probability of national climate related mortality from the CRED data-base of climate related disasters[5] as a proxy for risk and selected a set of 46 social, governance, economic and biophysical measures as indicators of social vulnerability. They found that 11 were effective indicators of mortality rates and these were confirmed as useful by a small focus group of seven adaptation experts. These experts also ranked the variables in terms of their perception of their usefulness leading to a total of 12 different rankings to which was added an equal ranked set to give 13 measures of vulnerability. Countries were then scored against these 13 rankings and the number of times a country appeared in the top quintile of countries in a particular ranking was used as an indicator of its overall vulnerability.

[FOOTNOTE 5: CRED, the Centre for Research on the Epidemiology of Disasters, has maintained a data-base of disasters, including those that are climate related. Rationale, methodologies and data are available at http://www.cred.be/.]

Progress continues to be made in the methodologies of deriving vulnerability metrics. For example Rygel *et al.*, (2006) have demonstrated the value of using a Pareto method for combining scores from a collection of indices without having to apply either implicit or explicit weightings. Alcamo *et al.* (2008) sought to increase the consistency of incorporating expert opinion on different disciplinary approaches (sociology, environmental psychology, economics, and political science) to the estimate of vulnerability, in this case of drought events, in three regions. Based on inference models about what contributes to vulnerability to drought and using fuzzy set theory (Eierdanz *et al.*, 2008) to compute susceptibilities they were able to show that high combined susceptibilities were associated with water stress crises.

Perch-Nielsen (2010) developed an index to estimate the vulnerability of beach tourism using a systematic approach by establishing a framework to identify the types of indicators needed and a systematic approach to identify indicators that covered the range of countries and time scales. The derivation of the index from the separate indicators was also subjected to robustness (sensitivity) testing to determine the most appropriate methods of scaling and combining the measures.

14.5.4. Assessment of Existing and Proposed Metrics for Adaptation

Srinivasan and Prabhakar (2008) conducted a wide-ranging stakeholder survey to assess the attitudes to, and requirements for, indicators of adaptation. Stakeholders agreed that no single metric can capture the multiple dimensions of adaptation and that refinements of methodologies (e.g. rationale for index selection, aggregation methods, and data checking) are badly needed. Preston *et al.* (2009) has suggest that, rather than seeking particular metrics, researchers should focus on developing rigorous processes for selecting metrics that can be applied in a range of contexts. But metrics for adaptation remain a necessity. Their derivation challenges the adaptation community to clarify its goals, conceptual models, definitions and applications. But as both theory and practice has shown indices alone are not sufficient to guide decisions on which adaptation actions to take, on how to modify sustainable development activities, or on resource allocation. Downing (2003) noted that the climate change community was far from adopting common standards, paradigms or analytic language. This still appears to be true, making the search for commonly accepted metrics, even within well-specified contexts, a challenging task.

14.6. Addressing Maladaptation

The adaptation literature is replete with advice to avoid maladaptation, but it is less clear precisely what is included as "maladaptation". In a general sense maladaptation refers to actions, or inaction that may lead to increased risk of adverse climate-related outcomes, increased vulnerability to climate change, or diminished welfare, now or in the future (AR5 Glossary). For example, the construction of well-engineered climate resilient roads designed to withstand current and future climate extremes may foster new settlement into areas highly exposed to the impacts of future climates; or increased water harvesting upstream to cope with erratic rainfall may harm and reduce the opportunities for communities downstream to manage their own risks. Actions that are potentially maladaptive need not be inadvertent (as in the IPCC AR3 and AR4 definition), nor be "taken ostensibly to avoid or reduce vulnerability to climate change" (Barnett and O'Neill, 2010) as the actions may be assessed as appropriate in the context of the full range of climate and non-climate considerations and pressures that apply to the decision. There should be clarity as to what is maladaptive action, or lack of action, lest the avoidance of potential maladaptation becomes a barrier to effective implementation of adaptation. In the road example above, the immediate and multiple benefits to the community of a reliable road system (including as evacuation route in floods etc.) might be judged as outweighing the longer-term risk of inappropriate settlement patterns (Lamhauge *et al.*, 2011). This may be seen as an example of an "unavoidable" ex post maladaptation (see Chapter 17.3.6.1) as it is an appropriate decision based on the information and circumstances at the time. The true maladaptation in this case would be the failure to implement appropriate incentives or regulations to avoid vulnerable settlements in the highly exposed areas.

The wide range of actions and circumstances that have been described as maladaptive demonstrates the complexity of the concept and terminology. Thomsen *et al.* (2012) describe actions that are not respectful of the intrinsic integrity and internal self-regulation of social-ecological systems as manipulative and likely to prove maladaptive. Their example is the management of Noosa beach in northern Australia where the coastline is characterized by cycles of erosion and depletion of beach sands. Rather than enhance the self-regulatory processes and adapting by managed retreat and expansion according to the cycle, management has sought to maintain a static beach profile through hard constructions and beach nourishment. Niemeyer *et al.* (2005) also describe the state of individual beliefs about climate change that might change from to adaptive, to inaction and possibly maladaptive behaviours as the perceived magnitude of climate change increases, while Eriksen *et al.* (2011) and Brown (2011) discuss avoiding outcomes that are essentially maladaptive as they run counter to sustainable development goals.

14.6.1. Causes of Maladaptation

Maladaptation arises in many forms but several broad causes can be identified. Actions that may benefit a particular group, or sector, at a particular time may prove to be maladaptive to those same groups or sectors in future climates or to other groups or sectors in existing climates. For example, some development policies and measures that deliver short-term benefits or economic gains but lead to greater vulnerability in the medium to long-term, such as in cases where the construction of "hard" infrastructure reduces the flexibility and the range of future adaptation options (Adger *et al.*, 2003b; Eriksen and Kelly, 2007, OECD, 2009), or the failure to encompass the full range of risks in the design of new structures, such as the effects of increasing storm surge in the design of a coastal defense system (UNFCC, 2007). Adaptation efforts aimed at armoring the coastline may result in coastal erosion elsewhere while building levees along a flood-prone area provides protection to coastal population and infrastructure but might encourage unwanted development within that area often accentuated by an exaggerated sense of safety (Grothmann and Patt, 2005; National Research Council, 2010; Repetto, 2008;) and the levees may increase damage when they fail as in Bangladesh in 1999 and New Orleans in 2003 (Huq and Khan, 2006; Masozera *et al*., 2007; Pouliotte *et al.*, 2009). Similarly, agricultural policies that promote the growing of high yielding crop varieties through subsidies with the objective of boosting production and increasing revenues may achieve these objectives in the short term, but will also reduce agro-biodiversity and increase exposure and vulnerability of mono-crops to climate change and finally undermine the adaptive capacity of farmers in the long term (World Bank, 2010).

Another cause of maladaptation is the failure to account for multiple interactions and feedbacks between systems and sectors leading to inadequate or inaccurate information for developing adaptive responses and strategies that are maladaptive (Scheraga *et al.* 2003; Satterthwaite *et al*., 2009; Pittock, 2011). An assessment of the downstream impacts of upstream rainwater harvesting in a semi-arid basin in Southern India showed that, once the full range of externalities were accounted for, the net benefits were insufficient to pay back investment costs (Bouma *et al.*, 2011). Similarly, the conversion of coastal mangroves into shrimp farms that may lead to increased economic productivity and improved livelihoods, but could also lead to increased vulnerability to flooding and storm surges (Klein, 2010). Maladaptation may also occur if the true potential of an option or a technology is unduly over-emphasized making it over-rated. Floating gardening has been suggested as an example in this connection (Irfanullah, 2009, 2013). Further examples of the range of maladaptive actions across a range of sectors and regions in this Report are outlined in Table 14-4.

[INSERT TABLE 14-4 HERE
Table 14-4: A selection of examples of actual or potential maladaptive actions from this report.]

14.6.2. Screening for Maladaptation

Five dimensions of maladaptation were identified by Barnett and O'Neill (2010) including actions that, relative to alternatives: (1) increase emissions of greenhouse gases, (2) disproportionately burden the most vulnerable, (3) have high opportunity costs, (4) reduce incentives and capacity to adapt, and (5) set paths that limit future choices. These dimensions are useful pointers to the potential for maladaptation but their application depends on subjective assessments. The first suggests that any action that increases greenhouse gas emissions is maladaptive, whereas a judgment on the relative benefits and dis-benefits will need to be made in such cases; the second turns on the interpretation of "disproportionately", and the third on "high" and on how opportunity costs are compared with current benefits. The dimensions were used by Barnett & O'Neill (2010) to describe maladaptive potential of the Wonthaggi desalinization plant to improve water supply to Melbourne, Australia. The plant was included as part of a wider water management plan for Melbourne that includes both demand and supply side management and incentives (Heffernan, 2012; Porter, 2013). Barnett and O'Neill (2010) argue that the plant will (1) increase GHG emissions (even if the planned wind power energy source is completed), (2) may lead to higher water costs that will disproportionally affect the poorer households; (3) may divert money and attention from more cost effective recycling and rainwater harvesting, (4) may reduce incentives to adapt through water conservation approaches, and (5) as a large sunk cost has locked out other options. The plant also affected significant cultural sites of the Bunurong Aboriginal community (Lee and Chung, 2007).

14.6.3. Experiences with Maladaptation

Maladaptation is a cause of increasing concern to adaptation planners, where intervention in one sector could increase vulnerability of another sector or increase the vulnerability of a group to future climate change. An example is the situation experienced by subsistence and smallholder agriculturalists in Palca, Bolivia who in the face of stressors relating to land access, small holdings, etc., moved away from their long established practices of diversification of crop varieties and planting locations to more intensive farming practices and cash cropping. They are now seeing evidence of climate change and the new practices make them more vulnerable to these changes leading to a risk of insufficient adaptation and maladaptation (McDowell and Hess, 2012). But there can also be tensions between development goals and climate change goals, where people may be aware of a climate related risk but are willing to take that risk (or they may have limited choice) given their current circumstances (IPCC SREX 2012, section 4.2.2).

Some studies warn against the simplistic use of maladaptation to communicate the state of high exposure to risks resulting from certain type of livelihoods. For example, the periodic movement of the nomadic pastoralists following the grass and water is a traditional and effective way of dealing with climate variability (Agrawal and Perrin, 2008), but is increasingly being described by some as maladaptive. More focused studies such as Young *et al.* (2009) put the breakdown of traditional pastoralism in the Sudan into the wider social and political context that led to restrictions on movement, asset stripping and escalating violence and undermined by policies not conducive to mobility.

14.7. Research and Data Gaps

A long list of research questions could be identified and prioritized to address gaps and assist the practice of adaptation and many of these are found in the subsequent adaptation chapters. In this chapter research priorities would range from metrics for adaptation to the psychology of communication about livelihood and life threatening events. But, the preparation of this Report has shown that the practice of adaptation has outstripped the rate at which relevant peer reviewed research can be produced and disseminated.

Many dedicated researches have become engaged in smaller, often community-based or urban activities where results can be gathered in relatively short time frames and direct interactions between the researchers and the implementers are common. Here research and action can, and are, serving each other and these interactions can be encouraged with support for further cross community, cross-cultural and cross sectoral comparisons.

Effective and timely interaction is more difficult at larger scales. National or multinational programs are often longer, complex and it is difficult to identify the 'adaptation' effort within a wider set of policy objectives. Research inputs into decision-making too often centers only on better projections of future or conditions or *post hoc* assessments of completed projects. The task is made more difficult by relatively short term research grants, often starting late in the process, or after the process is finished, and by the often rapid turn-over of planning and implementation staff making a close working relationship difficult. But there are models that work. Models based on established and ongoing research teams with a close link to policy such as the EC programs and it formation of targeted research teams across the EU, CSIR in South Africa, CSIRO and the National Climate Change Research Facility (NCCARF) in Australia, the Corp of Engineers and the Regional Integrated Sciences and Assessments (RISAs) in the USA and UKCIP and its successors in UK do appear to be more effective in maintaining a dialogue with those 'on the ground' and this shows in the number of well designed, insightful and reviewed documents arising from these collaborations.

Unfortunately this model has not been replicated at scale in most developing countries. One might ask why is there only one reference in this volume to any lesson learned from the PPCR – a billion dollar programme set up to better understand the challenges of integrating, or mainstreaming, adaptation into development planning with on the ground implementation of many larger than normal adaptation activities? The planning for the PPCR started only in 2008, but the planning process itself is of research relevance and over the past 2 to 3 years 18 countries have been working through how to bring adaptation into their national planning programs; surely a core research interest and opportunity and one whose lifespan already exceeds that of many research projects. Similarly the Adaptation Fund is mentioned only descriptively in these chapters. So where were the groups of independent researchers observing from their point of view, comparing and contrasting countries, and simply conducting the process of independent and collaborative research? The benefit would flow not just from the research itself but from the interactions with those charged with implementing adaptation and from the challenge to interpret that research so that its implications are relevant to the users, be they government officials or small-holder farmers.

There are models in developing countries. The CGIAR (Consultative Group on International Agricultural Research) network is already making contributions, albeit in the broad domain of agriculture which may be another model. The CORDEX project (Coordinated Regional Climate Downscaling Experiment) will make high quality high-resolution climate projections available to all countries. The NEPAD Framework for African Agricultural Productivity is another, and there are numerous smaller and effective research efforts too numerous to list here, but few can claim even regional coverage. The Cancun Agreement has already raised the prospect of establishing in a developing country "an international centre to enhance adaptation research and coordination". This may provide the vehicle to tackle the some of problems described above. The UN Agencies, the MDBs and many bi-lateral agencies, which are heavy users and sometimes producers of 'research' could be major beneficiaries and supporters.

Two points in a review of a decade of experience in the RISA process in the USA stand out. One was an insistence that research team members should primarily be residents in their region of study and to paraphrase another insight "knowing what one ought to do is not the same as knowing how to do it" (Pulwarty *et al.*, 2009). In arguing for the establishment of the skills to establish an Australian film industry, Phillip Adams advised the Prime Minister[6] "It's time to see our own landscapes, hear our own voices and dream our own dreams." Those words could just as well apply to tackling adaptation.

[FOOTNOTE 6: http://www.abc.net.au/dimensions/dimensions_in_time/Transcripts/s796788.htm, accessed 3rd Oct 2013.]

Frequently Asked Question

FAQ 14.1: ***Why do the precise definitions about adaptation activities matter**?*
[to be placed before Section 14.1.1]
Humans have always adapted to changing conditions; personal, social, economic and climatic. The rapid rate of climate change now means that many groups, ranging from communities to parliaments, now have to factor climate change into their deliberations and decision making more than ever before. Having a term and working definition is always useful in discussing how to tackle as challenge as it helps define the scope of the challenge. Is adaptation all about minimising damage or are their opportunities as well; can adaptation proceed only through deliberately planned actions focused specifically on adaptation to climate change; how much must be known about future climates to make decisions about adaptation? How does the adaptation of humans systems differ from adaptation in natural systems? Can adaptation to climate change be distinguished from normal development and planning processes? Need it be? Are we adequately adapted to current climates, or do we have an 'adaptation deficit'? The phrase 'maladaptation' immediately turns thoughts to how could plans go wrong and possibly cause greater suffering. A definition does not answer all these questions but it provides a framework for discussing them.

There is also a political reason for needing a precise definition of adaptation. Developed countries have agreed to bear the adaptation costs of developing countries to human induced climate change and that these funds should represent "new and additional resources"[a] and the Cancun Agreement and subsequent discussions suggests that for adaptation these funds could amount to tens of billions USD per year[b]. In most cases adaptation is best carried out when integrated with wider planning goals such as improved water allocation, more reliable transport systems etc. How much of the cost of upgrading a coastal road that is already subject to frequent damage from bad weather should be attributed to normal development and how much to adaptation to climate change. A precise answer may never be possible but the closer we agree as to what constitutes adaptation, the easier it will be to come to workable agreements.

[FOOTNOTE A: Bali Action Plan, 2007; FCCC/CP/2007/6/Add.1]

[FOOTNOTE B: Cancun Agreements 2010, FCCC/CP/2010/7/Add.1, paras 98 & 102)]

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Table 14-1: Categories and examples of adaptation options.

Category	Examples of Options
Structural/Physical	
Engineered and built environment	Sea walls and coastal protection structures [5.5.2, Box 5-5, 24.4.3.5]; Flood levees and culverts [26.3.4]; Water storage and pump storage [23.3.4]; Sewage works [3.5.2.3]; Improved drainage [24.4.5.5]; Beach nourishment [12.4.1.3]; Flood and cyclone shelters [11.7]; Building codes [8.2.2.5]; Storm and waste water management [8.2.4.1]; Transport and road infrastructure adaptation [8.3.3.6]; Floating houses [8.3.3.4.1]; Adjusting power plants and electricity grids [10.2.2, Table 10-2];
Technological	New crop & animal varieties [7.5.1.1.1, 7.5.1.1.2, 7.5.1.1.3, Box 9.5]; Genetic techniques [27.3.4.2]; Traditional technologies and methods [7.5.2, 27.3.4.2, 28.2.6.1, 29.6.2.1]; Efficient irrigation [10.3.6, Box 20-4, 22.4.5.7]; Water saving technologies [24.4.1.5, 26.3.4] including rainwater harvesting [8.3.3.4.1]; Conservation agriculture [9.4.3.1, 22.4.5.7]; Food storage and preservation facilities [22.4.5.7]; Hazard mapping and monitoring technology [15.3.2.3, 28.4.1]; Early warning systems [15.3.2.2; 22.4.5.2]; Building insulation [8.3.3.3]; Mechanical and passive cooling [8.3.3.3]; Renewable energy technologies [29.7.2]; Second generation biofuels [27.8];
Ecosystem-based*	Ecological restoration [5.5.5, 9.4.3.3, 15.3.4, 27.3.2.2] including wetland and floodplain conservation and restoration; Increasing biological diversity [26.4.3]; Afforestation and reforestation [Box 22-2]; Conservation and replanting mangrove forest [15.3.4, 29.7.2]; Bushfire reduction and prescribed fire [24.4.2.5, Box 26-2]; Green infrastructure (e.g. shade trees, green roofs) [8.3.3.7, 11.7.4, 23.7.4]; Controlling overfishing [28.2.5.1.2, 30.6.1]; Fisheries co-management [9.4.3.4, 27.3.3.2]; Assisted migration or managed translocation [4.4.2.4, 24.4.2.5, 24.4.3.5, 25.6.2.3]; Ecological corridors [4.4.2.4]; Ex situ conservation and seed banks [4.4.2.5]; Community-based natural resource management (CBNRM) [22.4.5.6]; Adaptive land-use management [23.6.2];
Services	Social safety nets and social protection (SP) [Box 13-2, 22.4.5.2]; Food banks and distribution of food surplus [29.6.2.1]; Municipal services including water and sanitation [3.5.2.3, 8.3.3.4]; Vaccination programs [11.7.1], Essential public health services [11.7.2] including Reproductive health services [11.9.2] and Enhanced emergency medical services [8.3.3.8]; International trade [9.3.3.3.2];
Social	
Educational	Awareness raising and integrating into education [11.7, 15.3.3, 15.3.2.6, 22.4.5.5]; Gender equity in education [Box 9-2]; Extension services [9.4.4, 15.3.2.6]; Sharing local and traditional knowledge [12.3.4, 28.4.1] including integrating into adaptation planning [29.6.2.1]; Participatory action research and social learning [22.4.5.3]; Community surveys [8.4.2.2]; Knowledge-sharing and learning platforms [8.3.2.2, 8.4.2.4, 15.2.4.2, 22.4.5.4]; International conferences and research networks [8.4.2.5]; Communication through media [22.4.5.5];
Informational	Hazard and vulnerability mapping [11.7.2, 8.4.1.5, 24.4.1.5]; Early warning and response systems [15.3.2.2, 22.4.5.2] including health early warning systems [11.7.3, 23.5.1, 24.4.6.5, 26.6.3]; Systematic monitoring and remote sensing [15.2.4.3, 28.6]; Climate services [2.3.3] including improved forecasts [27.3.4.2]; Downscaling climate scenarios [8.4.1.5]; Longitudinal datasets [26.6.2]; Integrating indigenous climate observations [22.4.5.4, 25.8.2.1, 28.2.6.1]; Community-based adaptation plans [5.5.1.4, 24.4.6.5], including community-driven slum upgrading [8.3.2.2] and participatory scenario development [22.4.4.5];
Behavioral	Accommodation [5.5.2]; Household preparation and evacuation planning [23.7.3]; Retreat [5.5.2]; and Migration [29.6.2.4] which has its own implications for human health [11.7.4] and human security [12.4.2]; Soil and water conservation [23.4.3, 27.3.4.2]; Storm drain clearance; Livelihood diversification [7.5.1.1.1, 7.5.2, 22.4.5.2]; Changing livestock and aquaculture practices [7.5.1.1.2, 7.5.1.1.3]; Crop-switching [22.3.4.1]; Changing cropping practices, patterns and planting dates [7.5.1.1.1, 23.4.1, Table 24-7, 26.5.3.1, 27.3.4.2]; Silvicultural options [25.7.1.2]; Reliance on social networks [29.6.2.2];
Institutional	
Economic	Financial incentives including taxes and subsidies [Box 8-3, 8.4.3, 17.5.6]; Insurance [8.4.2.3, 13.3.2.2, 15.2.4.6, 17.5.1, Box 25-7, 26.7.4.3, 29.6.2.2] including index-based weather insurance schemes [9.4.2, 22.4.5.2]; Catastrophe bonds [8.4.2.3, 10.7.5.1]; Revolving funds [8.4.3.1]; Payments for ecosystem services (PES) [9.4.3.3, 27.6.2, Table 27-8]; Water tariffs [8.3.3.4.1, 17.5.5]; Savings groups [8.4.2.3, Box 9-4, 11.7.4]; Microfinance [Box 8-2, 12.7, 22.4.5.2]; Disaster contingency funds [22.4.5.2, 26.7.4.3]; Cash transfers [Box 13-2];
Laws and Regulations	Land zoning laws [22.4.5.7, 23.7.4]; Building standards [8.3.3.3, 10.5.2.2, 22.4.5.7]; Easements [27.3.3.2]; Water regulations and agreements [26.3.4, 27.3.1.2]; Laws to support disaster risk reduction [8.3.2.2]; Laws to encourage insurance purchasing [10.7.6.2]; Defining property rights and land tenure security [22.4.6, 24.4.6.5]; Protected areas [4.4.2.2]; Marine protected areas (MPAs) [Box CC-CR Chapter 6, 23.8.4, 27.3.3.2]; Fishing quotas [23.4.6]; Patent pools and technology transfer [15.3.2.5, 17.5.8];
Government Policies and Programs	National and regional adaptation plans [15.2.2.2, 22.4.4.2, Box 23-2] including mainstreaming climate change; Sub-national & local adaptation plans [15.2.2.3, 15.2.2.4, 22.4.4.4, Box 23-2, 27.4.4]; Urban upgrading programs [8.3.2.2]; Municipal water management programs [8.3.3.4, Box 25-2]; Disaster planning and preparedness [11.7]; City-level plans [8.3.3.3, Box 26-3, Box 27-1, 27.3.5.2], district--level plans [25.8.1.3, 26.9.2], sector plans [26.8.4.1.2], which may include: Integrated water resource management (IWRM) [3.6.1, 23.7.2]; Landscape and watershed management [4.4.2.3]; Integrated coastal zone management (ICZM) [5.5.1.4, Box 5-4, 23.7.1] ; Adaptive management (AM) [2.2.1.3; 5.5.1.4; Box 5-2]; Ecosystem-based management (EBM) [6.4.2.1]; Sustainable forest management (SFM) [2.3.4]; Fisheries management [7.5.1.1.3, 30.6.2.1]; and Community-based adaptation (CBA) [5.5.1.4, 15.2.2.4.1, 29.6.2.3];

* A number of these would fall under the term “green infrastructure” in some European Commission documents (European Commission, 2009).
Note: These adaptation options should be considered overlapping rather than discrete, and are often pursued simultaneously as part of adaptation plans. Examples given can be relevant to more than one category.

Table 14-2: Considerations when selecting adaptation options.

Consideration	Source within this volume and selected references
• Effective in reducing vulnerability and increasing resilience	9.3.5; 11.3; UNFCCC, 2007; Brooks *et al*., 2011
• Efficient (increase benefits and reduce costs)	17.2; 17.4; Stern, 2006, IFC, 2010
• Equitable, especially to vulnerable groups	Chpt 12; 13.2.1; Huq and Khan, 2006
• Mainstreamed / integrated with broader social goals, programs and activities	15.2.1; 15.5.1; Agrawala, 2005; Agrawala and van Aalst, 2008; Ayers and Dodman, 2010; Dowlatabadi, 2007; Swart and Raes, 2007
• Stakeholder participation, engagement and support	12.2; 13.1; 15.2; Swart and Raes, 2007
• Consistent with social norms and traditions	12.3; 13.1; Moser, 2006, O'Brien *et al*. 2007; Alexander *et al.* 2011
• Legitimacy and social acceptability	15.2; 20.3.2; UNFCCC, 2007; Brooks *et al*., 2011
• Sustainable (environmental and institutional sustainability)	13.1; 15.4.1; Brooks *et al*., 2007; Brown *et al*., 2011
• Flexible and responsive to feedback and learning	2.3.1; 16.3; 20.2.3.2; Suarez *et al*.,2009; Agrawal, 2010
• Designed for an appropriate scope and timeframe	15.2.3.2; 16.1; Stafford-Smith *et al*., 2010; Preston and Stafford Smith, 2009; Brown *et al*., 2012
• Likely to avoid maladaptive traps	14.6; Grothmann, & Patt 2005; Repetto, 2008
• Robust against a wide range climate and social scenarios	2.2.1.1; 17.6.3; Lempert, & Schlesinger, 2000; Carmin and Dodman, 2013
• Resources available (including information, finance, leadership, management capacity)	14.2.4; Martens *et al*., 2009; Webb, and Beh, 2013; UNFCCC, 2007; Brooks *et al*., 2011
• Need for transformative changes considered	14.1; Wilbanks and Kates, 2010; Park *et al*. 2012
• Coherence and synergy with other objectives, such as mitigation	14.6; Klein *et al*. ,2007; Barnett and O'Neill, 2010; UNFCCC, 2007

Table 14-3: Criteria for the selection of indicators. Based on multiple sources.

	Criterion	Explanation
Validity	Not ambiguous	Agreement on the direction of influence between the indicator and what is sought to be measured (target measure)
	Well founded	Based on a tested theoretical framework
	Well defined	So that unwitting errors are minimized (e.g. measuring a family or an household)
	Purpose is known	This helps fix problems in data collection; misunderstandings between different collecting agencies, etc
	Accurate	Measuring what it should, and responds quickly
	Precise	Statistical variation between measurements is low
	Quality checked	Ideally subject to independent checking; is there a cross checking mechanisms?
	Transparent	Information source and control of information flow is known
	Honest	There should be no rationale or opportunity for individuals to manipulate or distort the data (e.g. manipulating rain-gauges used for weather index insurance)
Value	Comprehensible	Relatively easy for user to understand
	Relevant	Applicable to a wide range of circumstances (geographic, social, economic)
	Responsive	Can measure usefully small changes in the target measure
	Actionable	The quality/quantity of what is being measured can be affected by human appropriate actions
	High information content	Usually quantitative is more useful than qualitative, than binary data; and real measurements more useful than modeled estimates or expert judgment
	Disaggregatable	Can the indicator be collected for specific groups (e.g. children, women and men)
	Participatory	Can local people be involved in the data collecting; does the data help inform and possibly empower them
Data	Available	Data is publicly and easily available; affordable
	Homogenous	Data collection is consistent across location and time, including matching season or time-of-day if necessary
	Periodic	Data is collected at a frequency that is suitable for tracking changes
	Long time-course	Data has been consistently collected for some years
	Spatial coverage	Spatial coverage must be sufficient to provide a fair representation of the measure (e.g. Density of rain gauges)

Table 14-4: A selection of examples of actual or potential maladaptive actions from this report.

	Broad type of maladaptive action	Examples in AR5 Report
1	Failure to anticipate future climates. Large engineering projects that are inadequate for future climates. Intensive use of non-renewable resources (e.g. groundwater) to solve immediate adaptation problem	FAQ 3.4; 22.3.7
2	Engineered defenses that preclude alternative approaches such EBA	Box CC-EA; 15.5
3	Adaptation actions not taking wider impacts into account.	22.4.5.8; 25.8.1.3; 26.8.4.1.1
4	Awaiting more information, or not doing so, and eventually acting either too early or too late. Awaiting better “projections” rather than using scenario planning and adaptive management approaches	7.5.1.2.2; 8.5.2; 16.5.2
5	Forgoing longer term benefits in favour of immediate adaptive actions; depletion of natural capital leading to greater vulnerability	13.2.1.3; 22.4.5.8; 22.4.5.8
6	Locking into a path dependence, making path correction difficult and often too late	16.4.2; FAQ 25-1
7	Unavoidable ex post maladaptation – e.g. expanding irrigation that will eventually have to be replaced in the distant future.	17.3.6.1; see also 5 & 6 above
8	Moral hazard – i.e. encouraging inappropriate risk taking based, for example, on insurance, social security net or aid backup	17.5.1; 29.8
9	Adopting actions that ignore local relationships, traditions, traditional knowledge or property rights, leading to eventual failure	12.5.2; 26.5.3
10	Adopting actions that favour directly or indirectly one group over others leading to breakdown and possibly conflict.	13.1.1; 13.1.4
11	Retaining traditional responses that are no longer appropriate	21.3.2; 22.4.5.8
12	Migration may be adaptive or maladaptive or both depending on context and the individuals involved	26.8.4.1.1; Box 29-1

Note: These examples of maladaptation represent a set of cases found in the Report and that might help the readers to understand the rich range of circumstances where maladaptive actions might arise. They do not represent a formal categorization of type of maladaptation.

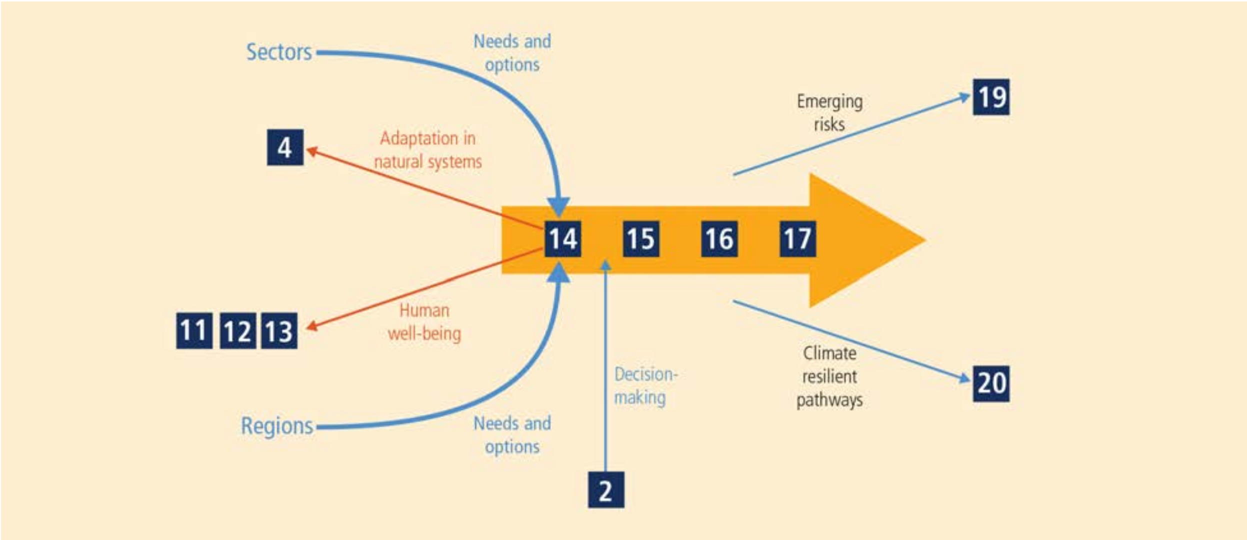

Figure 14-1: The relationship between the four adaptation chapters (14 to17) and other closely related chapters. Chapter 14 (Adaptation Needs and Options) draws upon and cross-references many of the issues of human wellbeing, including health, security and poverty; the treatment of adaptation of natural ecosystems is deal with mainly in Chapter 4 and is not repeated in Chapter 14. Similarly the needs and options synthesized in Chapter 14 are drawn largely from the sectoral (3 to 10) and regional Chapters (21to 30). Chapter 2 provides input to decision-making approaches relevant to Chapter 15 (Adaptation Planning and Options). All the adaptation chapters feed into the synthesis of Chapters 19 (Emerging Risks and Key Vulnerabilities) and 20 (Climate Resilient pathways: adaptation, mitigation, and sustainable development).

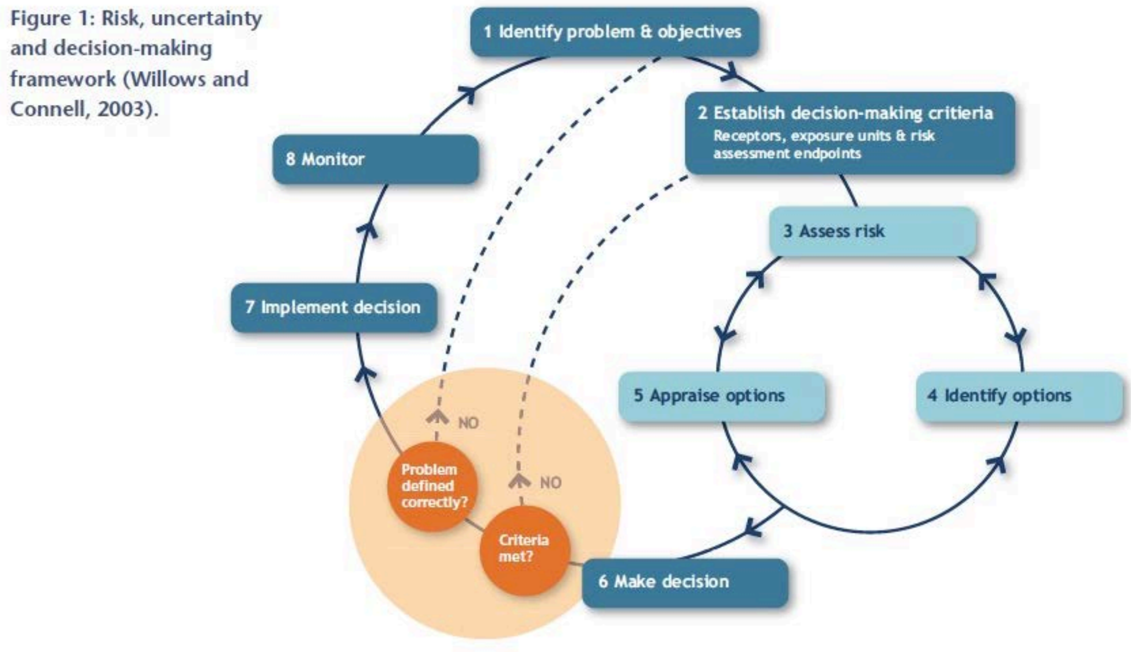

Figure 14-2: A generic framework for vulnerability and adaptation assessments (UKCIP, 2011).
[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 15. Adaptation Planning and Implementation

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Contents

Executive Summary

Adaptation to climate change is transitioning from a phase of awareness to the construction of actual strategies and plans in societies (high agreement, robust evidence). [15.2.1, 15.2.2] The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised awareness of the importance of adaptation to climate change, fostering a growing number of adaptation responses in developed and developing countries. This represents major progress since the IPCC Fourth Assessment Report (AR4). The literature illustrates heterogeneity in adaptation planning related to the context specific nature of adaptation, but also to the differences in resources, values, needs, and perceptions among and within societies. However, it is not yet clear how effective these responses currently are and will be in the future. Few adaptation plans have been monitored and evaluated. There is a tendency in the literature to consider adaptation planning a problem-free process capable of delivering positive outcomes, underestimating the complexity of adaptation as a social process, creating unrealistic expectations in societies, and perhaps overestimating the capacity of planning to deliver the intended outcome of adaptation..

The national level plays a key role in adaptation planning and implementation, while adaptation responses have diverse processes and outcomes at the subnational and local levels (high agreement, robust evidence). [15.2.1, 15.5.1] National governments assume a coordinating role of adaptation actions in subnational and local levels of government, including the provision of information and policy frameworks, creating legal frameworks, actions to protect vulnerable groups, and in some cases, providing financial support to other levels of government. In the increasing number of adaptation responses at the local level in developed and developing countries, there is a common trend that local governments are hindered by the absence of applicable guides to adaptation decision-making. Local agencies and planners are often confronted by the complexity of adaptation, and even when information is available, they are left with a portfolio of options to prepare for future climatic changes and the potential unanticipated consequences of their decisions. Therefore, linkages with national and subnational levels of government, as well as the collaboration and participation of a broad range of stakeholders are important. Steps for mainstreaming adaptation have been identified but challenges remain in their operationalization within the current structures or operational cultures of national, subnational and local agencies.

Institutional dimensions in adaptation governance play a key role in promoting the transition from planning to implementation of adaptation. (high agreement, robust evidence). [15.2.2, 15.5.1] While institutional dimensions may both enable and limit adaptation planning and implementation, the literature have so far mostly reported on how current institutional arrangements restrict the mainstreaming of climate adaptation. The most commonly emphasized barriers or enablers of institutional change in planning and implementation identified for both developing and developed countries are: 1) multilevel institutional co-ordination between different political and administrative levels in society; 2) key actors, advocates and champions initiating, mainstreaming and sustaining momentum for climate adaptation; 3) horizontal interplay between sectors, actors and policies operating at similar administrative levels; 4) political dimensions in planning and implementation; and 5) coordination between formal governmental, administrative agencies and private sectors and stakeholders to increase efficiency, representation and support for climate adaptation measures.

Adaptation planning and implementation are dynamic iterative learning processes recognizing the complementary role of adaptation strategies, plans and actions at different levels (national, subnational and local) (high agreement, robust evidence). [15.2.1, 15.3.2, 15.3.3, 15.5.1] Climate change adaptation (CCA) takes place as a response to multiple stresses, which highlights the need of connecting CCA with development strategies and plans, and disaster risk management (DRM). The importance of CCA is influenced by how the issue is framed in particular contexts, and the extent that it is viewed as a public safety issue or a development issue, it has greater resonance within national and local policies. In many cases, the most attractive adaptation actions are those that offer development benefits in the relatively near term, as well as reductions of vulnerabilities in the longer term. There is a growing recognition in the literature that, the linkages between adaptation, development and DRM need to be more explicit targeting co-benefits among the societal goals. Considering adaptation planning and implementation learning processes can help carrying out periodic adjustments to accommodate changes in climate and socioeconomic conditions that can strengthen the role of planning as a societal tool for CCA and DRM.

There is no single approach to adaptation planning because of the complex, diverse and context dependent nature of adaptation to climate change. Although top-down and bottom-up approaches are widely recognized, the actions in practice are combinations of these approaches. (high agreement, medium evidence). [15.2.1, 15.3.1, 15.3.3, 15.5.1.2, Box 15-1] The literature illustrates that the debate of climate change is dominated at present by impacts-led approaches that focus on climate risks through the construction of defensive infrastructure rather than on human vulnerability. It is unclear at this point if these adaptation plans consider impact-led approaches just the start of an adaptation process rather than its culmination. Knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions. This is partly due to the uncertainty associated with future climate and socioeconomic conditions but also to the context specificity of adaptation. The literature suggests that coupling adaptive improvements in infrastructure with efforts to improve ecosystem resilience, governance, community welfare, and development improve community resilience. It also suggests combining top-down and bottom-up approaches strengthens adaptation planning and implementation.

A variety of tools are being employed in adaptation planning and implementation depending on social and management context (high agreement, robust evidence). [15.4] Uncertainties in climate change coupled with the complexities of social-ecological systems emphasize the need for a variety of tools in adaptation planning and implementation. Information and knowledge on climate change risks from various stakeholders and organizations are essential resources for making adaptation planning. Multidisciplinary efforts have been engaged to develop, assess and communicate climate information and risk assessments across timescales. These efforts employ a mixed portfolio of measures from simple agroclimate calendars to computerized decision-support tools. Although a wide range of adaptations are possible with current technologies and management practices, development and diffusion of technologies can expand the range of adaptation possibilities by expanding opportunities or reducing costs. Monitoring and early warning systems play an important role in helping to adjust and revise adaptation implementation, especially on the local scale. Inovative tools have also been developed such as ecosytem-based adaptation and a range of insurance tools.

15.1. Introduction

As impacts of climate change have become apparent around the world, adaptation has attracted increasing attention. The impacts are expected to be particularly severe in the developing world and among marginalized communities because of limited adaptive capacity. Adaptation is an important pillar for the response to climate change, and the IPCC Assessment reports highlight the complimentary roles of mitigation and adaptation in climate policy. Particularly, IPCC Fourth Assessment Report (AR4) (IPCC, 2007) provided an evaluation of adaptation that is the departure point for the present report. The AR4 emphasized that adaptation will be necessary to address impacts resulting from climate change that is already unavoidable due to past emissions. A wide array of adaptation options were noted, but also that the level of adaptation was inadequate for a reduction in vulnerability to future climate change. Moreover, the report showed there are barriers, limits and costs which are not fully understood.

Since the publication of IPCC AR4, significant progress has been made on the adaptation activities both quantitatively and qualitatively. In particular, there is substantial progress in development of national adaptation strategies and plans. These include climate change adaptation (CCA) legislation and formal national strategies. As of 2012, 26 of the OECD countries have developed or are currently developing strategic frameworks for national adaptation (Mullan *et al*., 2013). Forty-nine least developed countries produced and submitted National Adaptation Programmes of Action (NAPAs) to the United Nations Framework Convention on Climate Change (UNFCCC) as of 2013. At the same time, the academic literature and reports from multilateral development agencies, international organizations and NGOs document numerous cases of community-based activities for CCA in developing countries. Through these activities, a range of lessons are being learnt, while barriers and limits are also emerging. The wider social dimensions of adaptation have also attracted more attention since AR4. As the diverse, complex and context specific nature of adaptation becomes apparent (differences in resources, values, needs, and perceptions among and within societies), the related areas expand in the wider social-ecological system, and the number of the stakeholders increases. Based on this recognition, the importance of mainstreaming adaptation and the integration of adaptation policies within those of development increase.

Current research has expanded its focus to reflect these advances (Biesbroek *et al*., 2010). Until the mid-1990s, research on climate change focused almost exclusively on understanding of climate system dynamics and modeling of future climate. Several programs developed recently give prominence to studies of vulnerability and adaptive capacity, and associated adaptation options, measures and strategies, including local, regional, and sectoral studies. As adaptation activities progress, many challenges have emerged, such as how to manage the decision-making process, how to develop strategies and plans, and how to implement them. In this regard, the roles within multi-level governance become an issue, such as horizontal coordination among different agencies and departments, and vertical coordination of various stakeholders from regional, national, to local actors. Furthermore, many countries face challenges in moving from the development of adaptation strategies and plans to implementation. These provide challenges for the research community as well.

There are many definitions and characteristics of adaptation strategies (Carter *et al*., 1994; Burton *et al*., 2005). For the purpose of this chapter, adaptation strategies are defined as a general plan of action for addressing the impacts of climate change, including climate variability and extremes. Such strategies include a mix of policies and measures that have the overarching objective of reducing vulnerability to climate change impacts. This chapter examines and evaluates the literature on CCA, in order to assess the progress made toward CCA and explore difficulties encountered in the implementation of adaptation plans. The IPCC Working Group II (WGII) Fifth Assessment Report (AR5) has four inter-related chapters about adaptation that discuss complementary aspects of the process (see Figure 14-1). This chapter focuses on the actions taken from international to local levels, in various sectors in order to assess; 1) the recent status of climate change adaptation planning and implementation across the globe; 2) the characteristics of adaptation in different settings; 3) the strategies, approaches and tools used in the adaptation practices; and 4) the governance of adaptation including building adaptive capacities. This chapter also draws attention to factors that motivate and facilitate the development of adaptation strategies, as well as how scientific and technical information, support and collaborative mechanisms are utilized in the process.

15.2. Status of Adaptation Planning and Implementation

15.2.1. Adaptation Planning at Different Levels

15.2.1.1. Common Recognition and International Mechanisms

The combined efforts of a broad range of international organizations, scientific reports, and media coverage have raised the importance of adaptation to climate change since the publication of AR4. Adaptation is transitioning from a phase of awareness and promotion to the construction and implementation of plans, strategies, legislation and projects at national, subnational, and local levels (Biesbroek *et al*., 2009; Preston *et al*., 2009; Tompkins *et al*., 2010; Berrang-Ford *et al*., 2011; Romero-Lankao and Dodman, 2011; Dodman, 2012). The review of the literature identifies a high heterogeneity of adaptation planning. There is significant heterogeneity in adaptation planning that is related to the context specific nature of adaptation (differences in resources, values, needs, and perceptions among and within societies). This heterogeneity also results from different approaches among countries, multilateral development agencies and international organizations that promote and fund adaptation, and from differences in knowledge, information and awareness on adaptation alternatives across societies.

Although attention to climate change impacts and disaster risk management are key elements of adaptation, they appear to have a more prominent role in the early stages of planning and implementation (Few *et al*., 2007; Hofstede, 2008; Mitchell *et al*., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig *et al*., 2011; Rumbach and Kudva, 2011; Etkin *et al*., 2012; IPCC, 2012). Several authors express concern that a strong focus on impacts can overshadow the analysis of the underlying stressors of hazards, neglecting the drivers of vulnerability, and thus, limiting the effectiveness for interventions (Sabates-Wheeler *et al*., 2008; Boyd and Juhola, 2009; Orlove, 2009; Ribot, 2010; Rumbach and Kudva, 2011). This approach could obscure opportunities for connecting development pressures, poverty, social inequality and climate change, particularly for the reduction of social vulnerability (Lemos *et al*., 2007; Hardee and Mutunga, 2010; Sietz *et al*., 2011). Furthermore, other scholars suggest that knowledge of impacts and vulnerabilities does not necessarily lead to the most cost-effective and efficient adaptation policy decisions (Hulme *et al*., 2009; Barnett and Campbell, 2010).

The importance of climate adaptation is also influenced by how the issue is framed. For example, to the extent that adaptation is viewed as a development issue (current development stressors and challenges, existing policy and existing agendas, knowledge, risks, and issues communities already face), it may have greater resonance within local government (Ewing *et al*., 2008; Moser and Satterthwaite, 2008; Dovers, 2009; Hodson and Marvin, 2009; Stringer *et al*., 2009; Measham *et al*., 2010; Sanchez-Rodriguez, 2012). Multilateral development agencies encourage efforts in this direction through a number of guidelines, publication and development assistance (UNDP, 2005; USAID, 2007; OECD, 2009; UNEP, 2010; World Bank, 2010a; UN-HABITAT, 2011a). Central to these efforts is the role of planning that connects adaptation to development needs and challenges (Blanco and Alberti, 2009; Dovers, 2009; Juhola and Westerhoff, 2011; Sanchez-Rodriguez, 2012). A critical issue commonly emphasized in the literature is the consideration of adaptation planning as a problem-free process capable of delivering positive outcomes. There is the risk of underestimating the complexity of adaptation planning as a social process, and it can lead to creating unrealistic expectations in societies, and overestimating the capacity of planning to deliver the intended outcome of preparing societies to adapt to the negative impacts of climate change. This highlights the importance of monitoring, evaluating and reviewing adaptation planning and implementation (Adger *et al*., 2009b; Preston *et al*., 2009; Tompkins *et al*., 2010; Wolf *et al*., 2010).

The fast growth of international mechanisms for supporting adaptation planning has assisted in the creation of adaptation strategies, plans, and actions at the national, subnational and local level. The directives and initiatives of the European Commission (EC) have fostered the creation of a large number of national adaptation strategies and plans in EU member countries since the last IPCC report (Biesbroek *et al*., 2009, 2010; Ford *et al.*, 2011). Other relevant regional initiatives are the South Pacific Regional Environmental Programme (SPREP) supported by a number of international agencies, and in the Caribbean through the Caribbean Catastrophic Risk Insurance Facility (Pulwarty *et al*., 2010). The literature reports a growing number of mechanisms developed by multilateral development organizations, development cooperation agencies from developed countries, United Nations programs (UNDP, 2005, 2010a; UNEP, 2010; UN-HABITAT, 2010, 2011a), multilateral development agencies (USAID, 2007; OECD, 2009; World Bank, 2010a, 2011, 2012), and non-governmental organizations (ICLEI, 2008; IFRC *et al*., 2009; Pew Centre on Global Climate Change, 2009; Braman *et al*., 2010; ActionAid *et al*., 2012; Crane, 2013). These organizations focus on their particular geographic and thematic areas of interest in their support for adaptation planning. Particularly relevant are the activities of UNFCCC for least developing countries through the National Adaptation Programmes of Action (NAPAs) and for less developed countries through the National Adaptation Plans (NAPs).

Keyt funding mechanisms are associated with the Global Environmental Facility (GEF) adaptation funds (Least Developed Countries Climate Adaptation Fund and Special Climate Change Fund), support for the Pilot Program for Climate Resilience (PPCR), and special purpose adaptation funds for UN agencies. The Adaptation Fund (AF) set up under the Kyoto Protocol has pioneered direct access mechanisms to developing countries, allowing countries to access essential funds without having to work through a multilateral development agency.

15.2.1.2. National Initiatives

The movement to introduce adaptation into national policies has accelerated in both developed and developing countries. These diverse national adaptation initiatives reflect the characteristics of the domestic political structures, socio-economic conditions, values and perceptions, as well as development stresses and opportunities. National governments are assuming a coordinating role in adaptation actions in subnational and local levels of government. National level coordination includes the provision of information about potential risks, in order to strengthen actions of state and local governments. These activites provide policy frameworks that guide decisions at subnational levels, to spur and coordinate the creation of legal frameworks, to direct action in sectors and resources for national development (agriculture, fisheries, health, ecosystem protection, among others), to protect vulnerable groups, and to provide financial support to other levels of government (Hulme *et al*., 2009; Biesbrock *et al*., 2010; Birkmann and Teichman, 2010; Berrag-Ford *et al*., 2011; Westerhoff *et al*., 2011). National governments also facilitate the coordination of budgets and financing mechanisms (Alam *et al*. 2011; Kalame *et al.* 2011).

In recent years, Europe's creation of national adaptation strategies and plans has been particularly dynamic. Twelve European countries have created National Adaptation Strategies-Austria, Belgium, Denmark, Finland, France, Germany, Hungary, the Netherlands, Norway, Portugal, Spain, and United Kingdom (only two of them were created before the AR4, Finland and Spain) (Biesbroek *et al*., 2010). Moreover, some countries have programmed the evaluation of their national adaptation strategies because they recognize the need to learn from the adaptation process (UK, Germany, Australia, the U.S, Mexico among others) (Bierbaum *et al*. 2013). Most strategies are regarded as the start of a policy process rather than its culmination, providing the important perspective of considering iterative evaluation as part of planning and implementation (Hulme *et al*.,2009, Biesbroek *et al*. 2011, Pulwarty *et al*. 2012).

The Least Developed Countries national adaptation responses, implemented through UNFCCC's NAPAs, provide data on efforts to link local level adaptation and development (Agrawal, 2008; Agrawal and Perrin, 2008; Stringer *et al*., 2009; Ciplet *et al*., *in press*). More than 50% of the projects under this program are concentrated in three key sectors for development and livelihoods: food security, terrestrial ecosystems and water resources. They attract the support of a greater range of actors, but some suggest that linkages between development and adaptation need to be made more explicit (Stringer *et al*., 2009). Sustained monitoring, evaluation and feedback that is needed to learn from the NAPAs process would help these countries transcend from a project by project effort, to a more complete union of adaptation and domestic and local development.

15.2.1.3. Sub-National and Local Activities

Adaptation planning and implementation initiatives illustrate differences on the role of subnational governments in the governance structure of countries, from those with strong concentration of political and economic power to a very minor role in governance and decision-making. Subnational governments often have a complementary role to national governments in adaptation planning that is reflective of the governance structure (Moser, 2005; West and Gawith, 2005; Lemmen *et al*., 2008; Pew Centre on Global Climate Change, 2009; USGCRP, 2009). Although guiding frameworks have not created for subnational governments in many countries, the states and provinces in some countries have an active role in climate change adaptation (CCA) (Brekke *et al*., 2009; Dinse *et al*., 2009; Staples, 2011; Barsugli *et al*., 2012; Bierbaum *et al*., 2013; Mukheibir *et al*., 2013).

There is a significant increase in the number of planned adaptation responses at the local level in rural and urban communities of developed and developing countries since AR4. Climate adaptation is context dependent and it is uniquely linked to location, making it predominantly a local government and community level of action (Corfee-Morlot *et al*., 2009; Glaas *et al*., 2010; Mukheibir *et al*., 2013). Among these efforts are adaptation plans that utilize local knowledge. Local knowledge based adaptation is primarily focused on the use of traditional knowledge to increase adaptive capacity at the community level as examples are shown in Table 15.1. In addition to raising adaptive capacity, local knowledge often highlights vulnerabilities and impacts that may not be well known, especially when the areas where local knowledge is still held are remote and poorly monitored (e.g., Majule *et al*., 2013).

Local councils and planners are often confronted by the complexity of adaptation without adequate access to guiding information or data on local vulnerabilities and potential impacts. Even when information is available, they are left with a portfolio of options to prepare for future climatic changes but without effective guidance on decision-making and the potential for unanticipated consequences arising from those decisions (Wilson, 2006; Storbjörk, 2007; Patt and Schröter, 2008; Urwin and Jordan, 2008; Gupta *et al*., 2010; Mathew *et al*., 2012; Rodima-Taylor *et al*., 2012; Mukheibir *et al*., 2013).

Local governments play a central role addressing the challenges of adaptation planning and implementation (Blanco and Alberti, 2009; Sanchez-Rodriguez, 2009; Rosenzweig and Solecki, 2010; Simon, 2010; Matthews, 2012). However, scholars stress the important role of partnerships among public, civic, and private sectors in CCA (Berkhout *et al*., 2006; Agrawal, 2010; Tompkins *et al*., 2010; Howe, 2011; Tompkins and Eakin, 2012). Inclusive and participatory approaches in adaptation planning at the local level are encouraged by international organizations (UNDP, 2005, 2010a; Moser, 2008; Moser and Satterthwaite, 2008; Ensor and Berger, 2009; Geiser and Rist, 2009; World Bank, 2010a; Ford *et al*., 2011; UN-HABITAT, 2011a).

Urban areas are also the locus of a growing number of planning initiatives (Revi, 2008; Roberts, 2008; Stren, 2008; Blanco and Alberti, 2009; Hamin and Gurran, 2009; Hardoy and Pandiella, 2009; Lowe *et al*., 2009; O'Demsey, 2009; Parzen, 2009; Sanchez-Rodriguez, 2009; Tanner *et al*., 2009; Corfee *et al*., 2010; Rosenzweig and Solecki, 2010; Simon, 2010; New York, 2011; Romero-Lankao and Dodman, 2011; Rosenzweig *et al*., 2011; Carmin *et al*., 2012; Matthews, 2012; Rotterdam, 2012). The primary determinants in creating adaptation plans has been a response to current climate extremes as well as potential future impacts (Rosenzweig and Solecki, 2010; Rosenzweig *et al*., 2011; Carmin *et al*., 2012). The difference in approaches has implications for adaptation governance, institutional arrangements, resources, and stakeholders involvement in the planning and implementation processes. Understanding how these approaches work merits further analysis. Enforcing parallel agendas for DRM and CCA runs the risk of duplicating efforts and resources, creating competing actions and potential conflicts with unintended negative consequences, including maladaptation. Institutional arrangements would need to bridge the divide between CCA and DRM, particularly in terms of legislation, operational and management structures, working agendas, and time horizons (Schipper and Pelling, 2006; Birkmann and Teichman, 2010; Falaleeva *et al*., 2011).

[INSERT TABLE 15-1 HERE
Table 15-1: Application of local knowledge in climate change adaptation.]

15.2.2. Adaptation Implementation

There is a minority of academic literature that provides information on the implementation of adaptation plans in contrast with the large accumulation of literature that discusses concepts, strategies, and plans of adaptation. Projects and cases of adaptation, including those implemented, are mainly presented in reports from international organizations, multi-lateral development organizations, national and sub-national governments and NGOs (e.g., UNFCCC, 2011; Mullan, 2013). In addition, the sectoral and regional chapters in the IPCC WGII AR5 have segments that discuss adaptation planning and implementation, that provide an additional database of sectors and practices. Therefore, this section will assess the status of adaptation implementation based on these chapters in addition to other literature.

Adaptation practices reflected in the WGII AR5 include agriculture, public health for heat-related risks, disaster risk reduction, water resources, coasts, and urban areas among others. Options and approaches used in implementation vary widely ranging from traditional and exiting to new and innovative measures. For example, farmers have been adapting to climate change worldwide, and current common practices include altering sowing times, crop cultivars and species, or irrigation and fertilizer control (Fujisawa and Koyabashi, 2010; Lasco *et al*., 2011; Olesen *et al*., 2011), reduced tillage practices and technical measures to more effectively capture rainwater and reduce soil erosion (Thomas *et al*., 2007; Marongwe, 2011) (see 7.5.1; 22.4.5.7; 23.4.1; 24.4.4.5; 27.3.4.2). These have proven to be effective in many cases, while some measures faced other problems; for example, earlier sowing is often prevented by lack of soil workability and frost-induced soil crumbling (Oort, 2012). Furthermore, simple options such as changes in sowing and harvesting dates may become less successful in a more variable climate (Morindo et al., 2010; see 23.4.1). Adaptation in agriculture is also linked with water management. Adaptation to water scarcity can be improved by taking into account a set of agronomic practices and irrigation such as deficit irrigation (Geerts and Raes, 2009; see 27.3.4.2). For public health for heat-related risks, major approaches are developing early warning systems and air pollution control. According to the Chapter 11 on Human Health, some studies report that heat wave early warning systems is effective to reduce heat-related mortality, and makes fewer deaths during heat waves after implementation of the system (e.g., Ebi, et al., 2004; Tan *et al.*, 2007; Fouillet *et al.*, 2008). A national assessment attributed the lower death toll to greater public awareness of the health risks of heat, improved health care facilities, and the introduction in 2004 of a heat wave early warning system (Fouillet *et al.*, 2008; see 11.7.3).

Mullan (2013) indicated that implementation of adaptation plans are still at an early stage despite the rapid development of strategies and plans that have occurred in OECD countries. In many sectors, adaptation to both environmental conditions and climate change includes accumulating traditional experience and knowledge for adaptation. Furthermore, each country has also developed its own policies and options to prevent, cope with, mitigate and utilize various environmental changes. As the occurring adaptive actions are usually based on such existing knowledge and options, they are incremental. Research has shown that local governments that have started implementing adaptation plans mostly tend to adopt a reactive or event-driven approach to adaptation relying upon technical measures. Often the focus is on climate variability and current weather extremes rather than long-term climate change (Næss *et al*., 2005; Wall and Marzall, 2006; Tompkins, 2005; Crabbé and Robin, 2006; Storbjörk, 2007; Blanco and Alberti, 2009; Amundsen *et al*., 2010; Glaas *et al*., 2010; Anguelovsky and Carmin, 2011; Measham *et al*., 2011; Preston *et al*., 2011; Dannevig *et al*., 2012; Romero-Lankao *et al*., 2012; Runhaar *et al*., 2012). Climate adaptation efforts reported on at present are often piecemeal and fragmented approaches, dealing with partial solutions and approaches to climate adaptation, rather than more full scale implementation (Granberg and Elander, 2007; Blanco and Alberti, 2009; Bulkeley *et al*., 2009; Amundsen *et al*., 2010; Burch, 2010; Tompkins *et al*., 2010; Preston *et al*., 2011; Dannevig *et al*., 2012; Mees *et al*., 2012; Romero-Lankao *et al*., 2012; Runhaar *et al*., 2012). In many cases, these practices have been embedded in existing policies, and thus not necessarily framed or made visible as climate adaptation actions (Tompkins *et al*., 2010; Berrang-Ford *et al*., 2011; Kenny, 2011; see Box 25-5). It should be noted that several of these reports on local climate adaptation actions have been taking place without explicit regulative demands for climate adaptation.

A particular challenge is implementation of local and short-term decisions in the context of long-term climate information. Improving the use of climate risk information across timescales, especially in the context of early warning systems, has helped bridge these gaps (van Aalst, 2009; IPCC, 2012; Pulwarty and Verdin, 2013). Independent from the growing attention for extremes in climate change adaptation, there has also been a shift in disaster risk management policy and practice, aiming to shift the balance of attention and expenditure from disaster response and reconstruction to disaster risk reduction and building resilience (not limited to climate-related extreme events).

There is growing awareness of the need for ecosystem-based, institutional, and social measures, although engineered and technological adaptation options are the most common adaptive responses (see Box CC-EA). A feature captured in the WGII AR5 is that integrated approaches have been pursued in many areas such as integrated water resource management and integrated coastal management (see Table 3.3, Table 8.3.3.4, Table 23.7.2 for water; Tables 5.5 and 5.4 for coasts). These integrated policies aim at addressing multiple objectives including climate change adaptation, development and disaster risk reduction. For example, the US Water Utilities Climate Alliance (WUCA, 2010) provides a comprehensive overview of ways of delivering water management which incorporates climate change and its uncertainty. Climate change has been incorporated into water resources planning in England and Wales (Arnell, 2011; Wade *et al.*, 2013) and in the Netherlands (de Graaff *et al.*, 2009). Guidance has been also developed on the inclusion of adaptation in water management (UNECE, 2009) and river basin management plans (EC, 2009b; see 23.7.2). Many sectors promote adaptive management in climate change adaptation to improve flexibility in its implementation.

Targets of early adaptation are focused on capacity building within governments and communities. These important first steps include increasing awareness of the risk of climate change, access to the scientific information, development of common goals and creation of operational institutions, which are important premises for adaptation.

Capacity building itself is often a target of adaptation implementation particularly in developing countries (e.g., van Aalst *et al*., 2008; Simões *et al*., 2010; UNFCCC, 2013; see Table 15.1 for capacity building cases). There are many factors to promote or hinder the implementation of adaptation, as Table 15.2 shows examples where the drivers and motivations for transition to implementation are highlighted. The role of institutional dimensions is analyzed in Section 15.5 for both planning and implementation of adaptation.

[INSERT TABLE 15-2 HERE
Table 15-2: Transition from planning to implementation.]

15.2.3. Financing for Adaptation

Adapting to the impacts of climate change requires the mobilization of a significant amount of funding for adaptation measures in a wide range of sectors. A number of studies suggest that the annual amount of adaptation funding needed by developing countries by 2030 is on the order of several tens of billions of dollars (e.g., UNFCCC, 2007; World Bank, 2010a; Smith *et al*., 2013). However, the annual costs could potentially range into the hundreds of billions of dollars (Parry *et al*., 2009). The differences between these estimates highlight the high degree of uncertainty in how they are derived. Key factors that contribute to this uncertainty include differences in the sets of sectors that are included in the analyses and the analytical methodologies used; uncertainties related to future climate changes and how best to adapt to them; and the lack of an agreed operational definition of adaptation (e.g., Christiansen *et al*., 2012; Naidoo *et al*., 2012; Fankhauser and Burton, 2011; Smith *et al*., 2013).

Adaptation financing broadly refers to resources that are deployed to support climate-resilient development (World Bank Group, 2011). Funding for adaptation can be mobilized through a range of international and domestic, public and private financing mechanisms, and can take various forms (e.g., loans and grants). Public financing sources are typically used to support projects in the infrastructure sectors, where returns on investments (ROIs) are usually less attractive to private investors. Sources of public financing for adaptation include contributions from national budgets, multilateral and bilateral development funds, and UNFCCC operational funds – the Adaptation Fund, the Least Developed Countries Fund, and the Special Climate Change Fund (Christiansen *et al*., 2012; Haites and Mwape, 2013; Romani and Stern, 2013). A potentially key source of future public financing for adaptation is the Green Climate Fund that was officially designated at the 17th Conference of the Parties to the UNFCCC in Durban, but is not yet operational.

Example of ongoing work targeting challenges in priority adaptation themes in several countries are provided by the Climate Change and Water Resources program at the Inter-American Development Bank. The lessons from emerging adaptation experiences are, first, that infrastructure investments (e.g., dams, levees, canals) remain critical for climate adaptation and reducing vulnerability to climate and weather related events; and, second, that infrastructure investments need to be complemented by previously neglected investments in soft infrastructure (e.g., watershed management, land use planning and information, and stakeholder engagement) (Miralles-Wilhelm, 2012). Efforts are also being supported by other regional development banks; for example, the Climate Adaptation for Rural Livelihoods and Agriculture (CARLA) project is supported by the African Development Bank Group).

Adaptation measures that offer reasonably predictable ROIs that are comparable to the returns on investments for non-adaptation measures with similar risk profiles have more opportunities to receive private financing (Christiansen *et al*., 2012). The fisheries and agriculture sectors, where operations are often locally owned, are examples of sectors that typically draw relatively high proportions of private financing in developing countries (often from domestic sources). Sources of private financing for adaptation traditionally include a range of financial institutions, such as international banks, multinational corporations, private equity and pension funds, insurance companies, and sovereign wealth funds. Charitable foundations and social investors are also sources of private financing for adaptation; compared to the financial institutions, these sources are often more motivated to provide financing for measures that generate lower ROIs (Christiansen *et al*., 2012)

Private financing for adaptation is primarily of two types: debt and equity. Debt-based financing typically consists of loans (e.g., bank loans) or bonds that must be paid back over time with interest. Equity-based financing generally involves a transfer of ownership rights through stocks or other assets. Export credits and foreign direct investment are two additional potential forms of private financing for adaptation. Export credits include guarantees, insurance, and other support that can help make developing country exports more competitive on the global market. Foreign direct investment is seen as having only limited potential for adaptation financing because it is highly concentrated in a few sectors and in a limited number of countries (Christiansen *et al*., 2012).

In both the public and private arenas, financing for adaptation is currently substantially less than financing for mitigation. According to an assessment of the total amount of climate finance available in 2009/2010 by Buchner *et al*. (2011), financing for mitigation outnumbered financing for adaptation by a ratio of more than 20:1; whereas $93 billion was provided for mitigation measures, only $4.4 billion was directed to adaptation measures. Buchner *et al*. (2011) also noted that the vast majority (approximately 90%) of adaptation financing during that period came from public sources, primarily bilateral institutions. Private adaptation financing remains limited due to market, institutional, and policy barriers that depress ROIs on these activities (World Bank Group, 2011). However, public-private partnerships that use public financing to leverage private investment are currently used to fund projects in several climate-sensitive sectors, such as infrastructure projects in the energy, transport, and water and sewage sectors (World Bank, 2011; World Bank Group, 2011). These partnerships are not necessarily focused on climate adaptation, but can serve as models for future adaptation projects.

15.3. Strategies and Approaches

15.3.1. Diverse Strategies and Mixed Portfolio Approaches

Strategies and approaches in adaptation planning and implementation vary according to context and level of government. National plans assume a coordinating role in adaptation actions for subnational and local levels of government providing policy frameworks that guide decisions at subnational level, spurring and coordinating the creation of legal frameworks, and directing action in key sectors for national development (Biesbroek *et al*., 2010; Bierbaum *et al*., 2013; ; see 15.2.1). Sub-national governments often have a complementary role to national governments by reflecting of the governance structure in each country (West and Gawith, 2005; Lemmen *et al*., 2008; Pew Centre on Global Climate Change, 2009; USGCRP, 2009). States and provinces in a number of countries have begun to have an active role in CCA (Dinse *et al*., 2009; Staples, 2011; Barsugli *et al*., 2012; Bierbaum *et al*., 2013; Mukheibir *et al*., 2013).

In contrast, local level strategies are more diverse because climate change impacts occur locally and adaptation is context dependent. The scale of community engagement and the approaches used may provide key elements for the success of adaptation programs (Patt and Schröter, 2008; Ensor and Berger, 2009; Ford *et al*., 2011; Pelling, 2011; Picketts *et al*., 2012). Methodological guidelines for community adaptations plans and actions fostered by international organizations emphasize strategies focused on the use of local and traditional knowledge to increase adaptive capacity at the community level (CARE, 2009; IFRC *et al*., 2009; IISD, 2012; Crane, 2013). Moreover, community adaptation planning has been strengthened through the use of geographic information systems (GIS), modeling, climate change scenarios, ecosystem services, and other scientific research methods applied to foster the ability of the community to design adaptation (Shaw *et al*., 2009; Bardsley and Sweeney, 2010; IAPAD, 2010). Multilateral development agencies recognize the importance of inclusive approaches for adaptation planning and implementation, but they tend to focus on strengthening the role of local governments (USAID, 2007; OECD, 2009; UNDP, 2010; World Bank, 2010b; International Bank for Reconstruction and Development and World Bank, 2011; UN-HABITAT, 2011; World Bank, 2012).

The diversity of approaches for local adaptation fosters opportunities for creating and strengthening adaptation planning and its implementation. But local governments and actors can face difficulties to make sense of such diversity of approaches and identify the most suitable and efficient approaches to follow as mentioned in 15.2.1. Lessons learned from the DRM experiences illustrate that a lack of coordination occurs among the strategies taken to reduce the risk of disaster at the local level (ISDR *et al*., 2010; ISDR, 2011). Local CCA strategies can face similar problems. To be effective, local governments and actors critically identify, select, and combine the strengths of diverse approaches. The coordinating role of national and subnational governments can provide support in this direction. However, multilevel institutional coordination between different political and administrative levels in society can be an institutional barrier to planning and implementation in developed and developing countries (Few *et al*., 2007b; Urwin and Jordan, 2008; Corfee-Morlot *et al*., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham *et al*., 2011; Robinson and Berkes, 2011; Sietz *et al*., 2011; Rodima-Taylor *et al*., 2012; Nilsson *et al*., 2012; Glaas and Juhola, 2013). There appear to be few national guidelines to assist local governments in selecting relevant approaches (Storbjörk, 2007; Glaas *et al*., 2010; Mozumder *et al*., 2011; Carmin *et al*., 2012; Hedensted Lund *et al*., 2012; Adhikari and Taylor, 2012; Peach Brown *et al*., 2013). Similar barriers have been reported in DRM (ISDR *et al*., 2010; ISDR, 2011). A combination of top-down and bottom-up activities may strengthen local adaptation planning and implementation (Urwin and Jordan, 2008; Bulkeley *et al*., 2009; Preston *et al*., 2013). Connecting adaptation planning strategies and local development needs and plans (USAID, 2007; OECD, 2009; UNDP, 2010a; World Bank, 2010b; International Bank for Reconstruction and Development and World Bank, 2011; UN-HABITAT, 2011; World Bank, 2012) and the use of low-regret strategies can also support local adaptation strategies and their implementation (Hallegatte, 2009; UNDP, 2010a).

15.3.2. Adaptation and Disaster Risk Management

The UN Hyogo Convention (2005-2015) has fostered the creation of a significant number of disaster risk management (DRM) plans and actions at the national and local level in developed and developing countries (UN, 2005; UNISDR, 2011). The IPCC SREX Report (IPCC, 2012) highlighted the complementary aspects and differences between DRM and climate change adaptation. Measures that provide benefits under current climate and a range of future climate change scenarios, called low-regrets measures, have been identified as starting points for addressing projected trends in exposure, vulnerability, and climate extremes in national and regional adaptation plans (see 8.3.2.2). These measures have the potential to offer benefits now and lay the foundation for addressing projected changes. Furthermore, the evaluation of DRM implementation helps to strengthen climate change adaptation (CCA) because climate change impacts and DRM are key elements of adaptation and have a prominent role in these early stages of CCA (Few *et al*., 2007b; Hofstede, 2008; Mitchell *et al*., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig *et al*., 2011; Rumbach and Kudva, 2011; Etkin *et al*., 2012; IPCC, 2012).

DRM includes managing hazards from extreme weather events and helps communities to deal with the uncertainty of climate change (Mitchell *et al*., 2010). On the other hand, disaster risk management strategies often fail to account for the differing spectrum of threats, and time and spatial scales needed to address the root causes of climate change vulnerability and open opportunities for CCA (Etkin *et al*., 2012). Proponents of merging DRM with CCA stress the mutual benefits of this approach. They also note that currently, CCA and disaster risk reduction are within separate agencies, although they share similar objectives and challenges that can duplicate efforts if there is not an effort towards better coordination and integration (USAID, 2007; IFRC *et al*., 2009; UNDP, 2010b; World Bank, 2010b; UN-HABITAT, 2011b; EIRD, 2012; Turnbull and Turvill, 2012; World Bank, 2012).

Current institutional structure and operation cultures are not congruent with the need for multidimensional approaches for DRM at the national and local level in a number of countries (ISDR, ITC, UNDP, 2010; ISDR, 2011). This chapter identified similar institutional barriers in adaptation planning and implementation discussed in Section 15.5.1.2 (Few *et al*., 2007b; Urwin and Jordan, 2008; Corfee-Morlot *et al*., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham *et al*., 2011; Robinson and Berkes, 2011; Sietz *et al*., 2011; Nilsson *et al*., 2012; Rodima-Taylor *et al*., 2012; Glaas and Juhola, 2013). Addressing these institutional barriers in DRM and CCA jointly can help create more efficient and effective strategies and actions to adapt to short, middle, and long-term climate impacts. Planning has been highlighted as key tool for DRM and adaptation but it requires also transformations in its operational structure and practices to fulfill this role (Wilson, 2006; Blanco and Alberti, 2009; Roberts, 2010; Preston *et al*., 2011; Carmin *et al*., 2012; Mathew *et al*., 2012; Rodima-Taylor *et al*., 2012; Sanchez-Rodriguez, 2012).

DRM experiences reveal the importance of linking development and disaster risk prevention and reduction. Strengthening the integration of CCA with development has been also suggested (Lemos *et al*., 2007; Ewing *et al*., 2008; Hodson and Marvin, 2009; Hardee and Mutunga, 2010; Sietz *et al*., 2011). Connecting DRM and CCA to existing development pressures, agendas, policies, governance structures, and community welfare can help reduce the risk of unintended consequences of adaptation. DRM would also facilitate the support and acceptance of adaptation by decision-makers and stakeholders at the subnational and national level (Dovers, 2009; Sovacool *et al*., 2012). Integrating DRM and CCA with development strategies, policies, plans, actions, and pressures can help address social vulnerability to climate change while providing opportunities for adaptation.

National and local efforts in disaster risk reduction recognize the importance of considering DRM a continuous learning process. Adaptation to climate change can also be viewed as a continuous learning process (not a single outcome), requiring regular monitoring and evaluation, as climatic and socioeconomic conditions change, and knowledge of the impacts increases (Adger and Barnett, 2009; Hinkel *et al*., 2009; Hulme *et al*., 2009; Preston *et al*., 2009; Arnell, 2010; Hofmann *et al*., 2011). Considering DRM and CCA learning processes assists in creating integrated approaches for national and local development strategies and plans. The process can also attend to intersecting social processes and help aleviate differing vulnerabilities that result from inequalities in socioeconomic status, income, and exposure to climate risks.

Lessons from DRM highlight the importance of participatory approaches and the use of local knowledge in the design and implementation of disaster risk prevention and reduction and CCA(Few *et al*., 2007b; van Aalst *et al*., 2008; ISDR *et al*., 2010; UNDP, 2010b; EIRD, 2012). By the same token, local knowledge based adaptation is primarily focused on the use of traditional knowledge to increase adaptive capacity at the community level (see Table 15.1 for examples). Local knowledge often highlights vulnerabilities and impacts that may not be well known due to the close interactions between climatic and non-climatic stressors associated with structural inequalities to vulnerability in societies (exposure, sensitivity, and adaptive capacity) (Majule *et al*., 2013). Combining top-down and bottom-up approaches and using low-regret strategies and actions in DRM and in adaptation planning and implementation increase climate resilience, improve livelihoods, reduce development pressures, and strengthen economic and social well-being (Moser and Satterthwaite, 2008; Hallegatte, 2009; UNDP, 2010b; World Bank, 2010b). It can also help alleviate the concerns of limiting the effectiveness of policy interventions, as mentioned in 15.2.1.

15.3.3. Adaptation and Development

Discussions of the relationships between sustainable development and climate change have increased over the past decades (Cohen *et al*., 1998; Yohe *et al*., 2007; Bizikova *et al*., 2010). As impacts of climate change hinder the achievement of development goals at all scales, O'Brien *et al*. (2012) emphasizes that disaster risk management is increasingly considered as one of the frontlines of adaptation, and a promising arena for mainstreaming or integrating climate change adaptation into sustainable development planning. In many cases, the most attractive adaptation actions are also those that offer development benefits in the near term, as well as reductions of vulnerabilities in the longer term (Agrawala, 2005; Klein *et al*., 2007; McGray *et al*., 2007; Hallegatte, 2008; NRC, 2010). In developing countries, adaptation has been embedded in the development context in NAPAs and national adaptation strategies.

Attention to the social dimensions of adaptation, including rates of change in social conditions, in part of the literature coincides with the interest of international organization and scholars in the relationship between adaptation planning and implementation and development (UNDP, 2005; Lemos *et al*., 2007; Dovers, 2009; OECD, 2009; Stringer *et al*., 2009; UNEP, 2010; World Bank, 2010b; UN-HABITAT, 2011b). The literature supports the standing contention that adaptation takes place as a response not just to climate change but to multiple stresses (Adger *et al*., 2005; Thomas and Twyman 2005). Linking existing policy, agendas, knowledge, risks, and issues communities already face with adaptation planning can help reduce the unintended consequences of adaptation (Dovers, 2009). The importance of climate change adaptation is also influenced by how the issue is framed. For example, to the extent that it is viewed as a public safety issue or a development issue, it may have greater resonance within local government (Measham *et al*., 2010). Other authors consider integrating local knowledge and experience, including households, into multidimensional and multi-scale approaches to guide the construction of adaptation responses to climate change, and integrate them with development strategies (Ewing *et al*., 2008; Moser and Satterthwaite, 2008; Blanco and Alberti, 2009; Hodson and Marvin, 2009).

Other literatures emphasize the role of planning as a switchboard for adaptation and development (Füssel, 2007; Hallegatte, 2009; Preston *et al*., 2011). This might require systemic changes to enable planning approaches capable of managing complexity, uncertainty, multidimensional, and multi-level coordination (Pahl-Wostl, 2009; Tompkins *et al*., 2010; Huntjens *et al*., 2011; Huntjens *et al*., 2012).

15.4. Tools Used for Decision-Making, Planning, and Implementation

15.4.1. Decision Support Tools

Adaptation decision making is informed by various tools present in both top-down and bottom-up forms. Top-down tools often include downscaled simulated climate scenarios for regional level projections, accompanied by expert opinions. These are applied using multi-criteria optimization methods, evaluation of feasibility that may include cost-effectiveness such as cost-benefit analyses, and assessment of potential impact severity (Carter *et al*., 1994; IPCC-TGICA, 2007; Adger *et al*., 2009a, b; see 5.5.3, 9.4.2).

In the bottom-up approach, those affected or at risk examine their own impacts and vulnerabilities and incorporate adaptive options for the appropriate sector or community. Stakeholders may organize social and institutional activities in the light of actions and interactions among those engaged in the process. Advances in stakeholder participatory methods have significantly enhanced the development of this type of decision making tool in recent years (Epstein and Axtell, 1996; Wolfram, 2002; Kaner *et al*., 2007; see 2.4.4).

No single tool suits all circumstances of adaptation decision making, although information development tools such as Community-based Risk Screening Tool-Adaptation and Livelihoods (CRiSTAL) can manage diverse vulnerabilities and risks (IISD, 2012). By outlining the problems and the available inputs to the adaptation decision process, this tool may provide a suitable option (Gimblett, 2002). IPCC (2012) notes there are distinct differences in problem orientation and solution space depending on whether an adaptation plan commences with climate modeling outputs, versus that of a risk and vulnerability-based framework.

15.4.2. Tools for Planning

Uncertainties in climate change coupled with the complexities of social-ecological systems require a dynamic approach to adaptation planning and implementation. Knowledge about climate change risks from various stakeholders and organizations are essential resources for adaptation planning. Multidisciplinary efforts, some of which are discussed below, have engaged in development, assessment and communication of climate information and risks across different timescales.

15.4.2.1. Monitoring, Modeling, and Spatially Integrated Tools

The integration of monitoring and/or modeling systems with the techniques of geographical information systems (GIS) can strengthen adaptation planning and implementation. The complex, multi-scale, interdisciplinary nature of climate change impact on socio-ecological systems has made the computer-based modeling approach a tool for understanding the evolving processes and future conditions (Alter, 2004; Pyke *et al*., 2007). These include remote sensing and global positioning systems and discussion support or a dynamic dialogue between researchers and practitioners. As a result, much more powerful, process-visual and spatially implicit decision support systems have been developed. One example is the development of the Invasive Species Forecasting System (ISFS) (Stohlgren *et al*., 2005) that combines USGS science and NASA Earth observations with software engineering to provide regional-scale patterns of invasive species and vulnerable habitats. Similarly, in the Yellow River, the second largest drainage basin of China, low-flow seasons caused the lower channel to dry up and forced governments to develop a basin-scale decision support system (Li and Li, 2009). The European Spatial Planning Adapting to Climate Events

Project (ESPACE) asserts that that urban planning contributes to adaptive efforts by uutilizing tools for adaptation through both conventional and green infrastructure and design (porous surfacing, green roofs, etc.) (ESPACE, 2008).

15.4.2.2. Communication Tools

There are a wide range of communication tools that can play an important role in adaptation implementation. These tools include brochures, bulletins, posters, magazines, policy briefs, videos, TV and radio broadcasts, internet, and many more that are being employed to carry out multi-way participatory dialogues. These provide avenues for communication among information developers (e.g. scientists, trainers, project implementers, government agencies, etc.) and community members, groups at risk, etc., who also influence the nature of information disseminated. At the local level, interactive strategies include theater, role-playing, music, learning-by-doing, hands-on exercises. There are also group discussions of community members to debate climate risks and possible solutions to cope with impacts that positively affect behavior and practices. Reports, concept notes, brochures, magazines, presentations and workshops provide a more effective tool to communicate with policy makers at local and national levels. At country/regional level, broad dissemination channels such as TV, radio and internet broadcast, and high-level summits, have been effective in creating widespread awareness as demonstrated in Advancing Capacity for Climate Change Adaptation (ACCCA) project (http://www.acccaproject.org/accca/), UK Climate Impacts Program (UKCIP) (Pringle, 2011) and the SREX report (IPCC, 2012).

To assist the syntheses, a variety of rule- or matrix-based methods has been applied for screening adaptation options such as relative cost-effectiveness of alternative adaptation measures (Benioff and Warren, 1996), and for adaptive opportunities for coastal zone management (Uljee *et al*. 1999). Greater emphasis on user interaction, sensitivity analysis and capabilities currently provides more effective visualization and customized reports (Sarewitz *et al*., 2000; Sarewitz, 2004). Multi-criterion and multi-actor participatory approaches allow users to consider alternative adaptation strategies and evaluate tradeoffs, typically in the development of tools for environmental assessment and management (Julius and Scheraga, 2000).

15.4.2.3. Early Warning and Information Systems

Monitoring and early warning systems (EWS) have long-played important roles in helping in adjustment, and adaptation especially on the local scale. The disaster research community has shown that successful warnings of impending events are those that are complemented by information on the risks actually posed by the hazards, but also the potential strategies and pathways to mitigate damage within a particular context (Drabek, 1999; UNISDR, 2006). The use of climate data analyses and projections in early warning and information systems is an important and established mechanism to inform disaster risk mitigation (Pulwarty and Verdin, 2013) or climate-related health risks (see 11.7.3). It helps to ensure the link between generation and application of climate knowledge for management of climate-related risks and CCA. In this regard, interest in climate services in growing in many countries (see 2.4.1).

EWS include a diversity of approaches. These range from technological advances systems satellite information and climate modeling (UNISDR, 2006; Smith *et al*., 2009; Bierbaum *et al*., 2013), to local level early warning based on traditional knowledge needed to develop and inform strategic responses options in adaptation planning and implementation. The value of local knowledge can be complemented with scientific climatic data, research and planning tools (GIS, modeling, etc.) to strengthen community-based monitoring and vulnerability assessment in disaster risk management and adaptation to climate change (Green and Raygorodetsky, 2010; Kalanda-Joshua *et al*., 2011; Newsham and Thomas, 2011; Nakashima *et al*. 2012).

Current science and technology do not resolve the uncertainties in modeling, and in the response of ecosystems to climate change and management interventions at levels needed for probabilistic early warning, the need for precise climate information is often overstated (Smith *et al*., 2009). The long-standing experience with climate extremes and variability offers many usable lessons in spite of these uncertainties. The impacts of climate change will be most strongly felt by resource insecure populations, who are more vulnerable to changes in the distribution and magnitude of extreme weather and climate events, as these affect crops, disease outbreaks and soil and water quality. The diverse type of EWS in developed and developing countries are valuable tools that could help societies develop strategies to cope and adapt to climate-related risks.

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Box 15-1. Examples of Tools and Measures

Conventional and Green Infrastructure

- Large investment has been made on engineered structure to protect coastal areas against climate-related events. In New York City, infrastructure adaptation strategies to climate change include both hard and soft measures. Hard structures in the New York City region include seawalls, groins, jetties, breakwaters, bulkheads, and piers, but these have not yet been strengthened and elevated over time in response to projected rates of sea-level rise (Gornitz, 2001). Storm-surge barriers have been recommended to protect against high water (Aerts *et al*., 2009; Zimmerman and Faris, 2010). Such barriers are also used in the Thames in London (UK Environment Agency, 2010; see Box 5-1) and Rotterdam (Aerts *et al*., 2009). Soft measures involve wetland and dune restoration, beach nourishment, enhancement and expanding the Staten Island Bluebelt - a stormwater management system to other areas (NYCDEP, 2008).
- In the Netherlands, during the second half of the twentieth century, large structures had been built to protect the coastal area (Kabat *et al.,* 2009). To keep the country flood-proof over the 21st century, an estimated total cost of implementing of a new ambitious plan is €2.5-3.1 billion a year to 2050, representing a 0.5% of the current Dutch annual GDP (Stive *et al.,* 2011). The new plan is a paradigm shift which addresses coastal protection ”working with nature” and providing ”room for river” instead of only ”fighting” the forces of nature with engineered structures.
- Development of engineered structures can lead to more GHG emission and potential negative impacts on ecosystems (see 5.5.6). On the contrary, green infrastructure (porous surfacing, green roofs, etc.) have been used in parts of Europe (ESPACE, 2008), Portland, Philadelphia, New York (Foster *et al.,* 2011), London (GLA, 2011), Quy Nhon in Vietnam (Brown *et al*., 2012) (see 8.3.3.7).

Use of Information and Communication Technologies

- Information and communication technologies (ICTs) can help strengthen the physical preparedness of livelihood systems for climate change-related events. These can contribute to design of defences and determination of their optimal location, and make the livelihood system more robust. GIS technology was applied to foster the ability of the community to deal with climate change hazards and trends in the Philippines (IAPAD, 2010) and form modelling processes of climate change adaptation which supported regional stakeholders to develop better protection of key spaces in the landscape (Bardsley and Sweeney, 2010). Visualization of sea level rise and climate change damage in Delta in British Columbia, Canada, increased awareness of long-term risks and response challenges to local community, government and the public (Shaw *et al*., 2009).
- By sharing observations and reflections through ICT tools, users foster new ways of assimilating or translating information, which can be shared through wider networks, and then influence action, enabling new experiments/practices to take place. This generation of new and broader learning cycles will in turn strengthen systematic resilience (Ospina and Heeks, 2010). Karanasios (2011) outlines the range of new and emergent ICTs (e.g., wireless broadband, sensor networks, GIS and Web-based tools) being applied to climate change issues, and investigates their use in developing countries.

Other Tools

- Other tools are being used such as insurance (see also 8.4.2, Table 10.8), linking CCA to ICZM (see 5.5.3.) or DRR (see 8.3.2.2), reduction of emissions from deforestation and forest degradation (see 13.3.1.2), using CC scenarios (see Box 14-1), ecosystem-based adaptation (see Box CC-EA, Box 8-2, 22.4.5.6, Figure 22-6), and land-use (see Box 25-10).

_____ END BOX 15-1 HERE _____

15.4.3. Technology Development, Transfer, and Diffusion

Development and diffusion of technologies and management practices will continue to be critical to many adaptation efforts. While a wide range of adaptations are possible with current technologies and management practices, technologies expand the range of adaptation possibilities by expanding opportunities or reducing costs (Smith *et al*., 2009). Technologies related to information collection and diffusion are particularly important for adaptation planning, including technologies for data collection and information dissemination during extreme events and emergencies. Despite remaining uncertainties, technologies to project climate changes, and identify potential impacts and vulnerabilities are frequently seen as precursors to successful adaptation planning. Developing countries require enhanced access to improved climate models, but also adaptation planning tools that focus on robustness in the face of uncertainty (Dessai *et al*., 2009).

Technology choices can both reduce and exacerbate risk, and their use in adaptation planning and implementation requires considering their potential effects (Jonkman *et al*., 2010). For example, technologies can strengthen physical infrastructure, such as bridges and buildings, so that they can withstand more extreme hazards. However, relatively centralized high-technology systems increase efficiency under normal conditions but risk cascading malfunctions in the event of emergencies. In some circumstances, technologies to reduce short-term risk and vulnerability contribute to increased future vulnerability to larger extreme events (Etkin, 1999; Moser, 2010). This was seen in the impacts of Hurricane Katrina on New Orleans, where a flood defense system enabling construction in a floodplain was subject to catastrophic failure in the face of a particularly large extreme event (Freudenburg *et al*., 2008; Link, 2010).

International efforts for technology transfer have been concentrated in the UNFCCC framework's five themes: technology needs and needs assessments, technology information, enabling environments, capacity building, and mechanisms for technology transfer. A key project is developing a technology transfer clearinghouse called TT:CLEAR, and establishing a Technology Centre and Network (UNFCCC, 2012). However, successful technology transfer requires not only exchange of technological solutions, but also strengthening policy and regulatory environments, and capacities to absorb, employ and improve appropriate technologies. In both developed and developing countries, multilateral institutions can support collaboration which engages private interests in regulatory planning and possibly activities, particularly if ongoing funding is expected (Tessa and Kurukulasuriya, 2010).

15.4.4. Insurance and Social Protection

Insurance is widely seen as a cost-effective tool for adaptation planning and implementation for increasing financial resilience, especially when compared to ex-post disaster aid (Warner *et al*., 2009; Linnerooth-Bayer *et al*., 2011). It is in this context that insurance has received the attention of those planning and managing climate adaptation: The IPCC's SREX report (IPCC, 2012) recognizes that risk sharing and transfer mechanisms at local, national, regional and global scales can increase resilience to climate extremes, while for slow-onset impacts it is usually considered unsuitable (Collier *et al*., 2009). The main question is if and how insurance products, particularly natural disaster and agricultural cover, can be designed so that they trigger adaptive behaviour. The insurance price signal is widely considered as the first step in taking risk reduction measures (Fankhauser *et al*., 1999), but it does not imply that action will be taken. In fact those at risk, such as local farmers, may not have the capacity to act because they lack tools, methods or financial means. The role of insurance is also discussed in 10.7 of Chapter 10 in this report.

Many scholars agree on the theoretical potential for insurance to facilitate climate risk reduction through a wide scale of activities, these include awareness raising, sharing of modelling and risk mapping data and tools, to providing economic incentives for risk reduction and by mandating adaptation as a condition for granting insurance (Crichton, 2008; Suarez and Linnerooth-Bayer, 2011; Surminski and Oramas-Dorta, 2011; Paudel, 2012). Evidence of how this is successfully achieved is limited to private insurance and reinsurance companies, scientists and governments aiming at adaptation – most notably through sector initiatives such as ClimateWise and UNEPFI's Insurance Working Group (Mills, 2004).Existing insurance schemes for flooding in the US (Michel-Kerjan and Kunreuther, 2011) and the UK (Ball *et al*., 2013) show the challenges of fostering risk reduction through insurance.

Those two schemes are on opposite ends of a broad scale – the US National Flood Insurance Program being a public sector scheme, while the UK's flood insurance is provided by a private insurance market. Both systems struggle with the implementation of risk based pricing as the guiding principle of insurance. Picard (2008) highlights the trade-off between the effectiveness of risk based pricing and equity – as those most vulnerable struggle to pay for risk-based premiums. Public-private partnerships may be able to assist through premium subsidies, or broader collaboration on risk management, as seen in the case of the UK's flood insurance.

The use of insurance to manage extreme weather events varies across the world, with penetration of insurance cover mainly determined by income levels (Ranger and Surminski, 2012) with insurance in most low- and middle-income countries still in its infancy (Churchill, 2007; Warner *et al*., 2009). Demand-side limitations include access to and affordability of cover, desirability of products and financial literacy (Linnerooth-Bayer *et al*., 2011).

Over the last decade, risk transfer schemes have been developed in low-income countries, often run as pilot-projects between the private sector and public authorities. Analysis of the existing disaster risk transfer activities in low- and middle-income countries indicates that the potential for utilizing risk transfer for risk reduction is far from exhausted, with only very few schemes showing an operational link between risk transfer and risk reduction (Surminski and Orama-Dorta, 2011; IPCC, 2012, p.355;). Some innovative efforts are currently being tested to address these challenges, such the ENSO insurance scheme in Peru, an index-based forecast insurance that pays out on the basis of a seasonal forecast, giving policyholder the opportunity to use the pay-out for preventive measures, such as the purchase of drainage cleaning machinery or to improve transport infrastructure or adjust cash flows in anticipation of possible income reduction (GIZ, 2012). A regional insurance system is also an innovative tool for sharing disaster risks among participating countries. For example, the Caribbean Catastrophic Risk Insurance Facility (CCRIF) was established as a risk pooling facility, attended by sixteen countries, to limit the financial impact of catastrophic hurricanes and earthquakes to Caribbean governments by quickly providing short term liquidity. Another approach is the agricultural insurance scheme in Sudan, where farmers are required to adopt more resilient farming practices to gain access to the risk transfer scheme and the Horn of Africa Risk Transfer for Adaptation (HARITA) scheme in Ethiopia (Oxfam, 2009).

15.5. Governance for Adaptation Planning and Implementation

15.5.1. Institutional Dimensions for Planning and Implementing Adaptation

15.5.1.1. Importance of Institutional Dimensions

Since the AR4 findings on substantial barriers to mainstreaming adaptation and suggested research challenges in further understanding adaptation processes of mainstreaming adaptation (Adger *et al*., 2007), academic literature identifying drivers and barriers to climate adaptation planning and implementation has increased. A recent review has shown that more than 200 context dependent barriers have been identified in 81 peer-review papers, mostly but not exclusively based on small-n inductive case studies (Biesbroek *et al*., 2013). The message from the literature is clear; adaptive capacity signals potential but does not guarantee adaptive action (O'Brien *et al*., 2006; Adger and Barnett, 2009; Burch, 2010; Tompkins *et al*., 2010). While there is growing recognition that adaptation planning is essential (Ayers and Huq, 2009; Wilbanks and Kates, 2010; Ford *et al*., 2011), research reporting on planning and implementation have increased appreciation of the magnitude of the institutional dimension for limiting or enabling the mainstreaming of climate adaptation (Moser and Ekstrom, 2010; Berkhout, 2012; Biesbroek *et al*., 2013). Several studies, in different settings e.g. river basin management in Brazil (Engle and Lemos, 2010), municipalities in Canada (Burch, 2010) and Australia (Measham *et al*., 2011), villages in Western Nepal (Jones and Boyd, 2011), and pastoralist groups in Kenya (Eriksen and Lind, 2009; Robinson and Berkes, 2011; Adhikari and Taylor, 2012) illustrate such difficulties. Adaptation studies, targeting specifically how institutional dimensions limit or enable the mainstreaming of climate change considerations in policy-making, planning and decision-making at different levels and in different sectors, has grown in number (Crabbé and Robin, 2006; Koch *et al*., 2007; Roberts, 2008; Bulkeley *et al*., 2009; Engle and Lemos, 2010; Glaas *et al*., 2010; van den Brink *et al*., 2011; Storbjörk and Hedrén, 2011; Huntjens *et al*., 2012; Termeer *et al*., 2012; Glaas and Juhola, 2013).

Institutions are comprised of tangible formal procedures, laws and regulations and tacit informal values, norms, traditions, codes and conducts that shape expectations and guide actions among actors and organizations, serving as manifestations of institutions (Ostrom, 1990; Dovers and Hezri, 2012). Adaptation planning and implementation follows formal institutions associated with regulations, policies, and standards created and enforced by government actors but also requires the participation of informal institutions through interactions among stakeholders according to cultural, social, and political conditions in societies (Moser and Satterthwaite, 2008; Carmin *et al*., 2012). Chapter 14 describes the importance of these institutional frameworks for adaptive capacity. Chapter 16 presents a framework for adaptation, opportunities and limits, where governance and institutional arrangements are included. This section assesses the literature on how institutional dimensions limit or enable adaptation planning and implementation and what lessons can be learned from these experiences.

15.5.1.2. Institutional Barriers

While the literature clearly states that institutional dimensions may both enable and limit adaptation planning and implementation, the literature referred to in Section 15.5.1.1 have so far mostly reported on how current institutional arrangements restrict the mainstreaming of climate adaptation. Biesbroek *et al.* (2013) have stated that although studies in developed countries are more common and comparative approaches of institutional dimensions, exploring differences and similarities in different countries, are rare, institutional dimensions are highlighted for both developing and developed countries. Low-income developing countries report on weak institutional environments and middle and high income countries emphasize institutional barriers that prevent the mobilization of adaptive capacity. Barriers in general are seen as dynamic and context dependent across sectoral, spatial and temporal scales, meaning that how a particular institutional barrier operates to either strengthen or limit adaptation planning and implementation can vary both between and within countries, depending on case study locations. Also, the importance and severity of each barrier to the proposed change supposedly changes over time and interacts with other constraints (Burch, 2010; Moser and Ekstrom, 2010; Biesbroek *et al*., 2013). Barriers are also shown to differ in different stages of planning and implementation, e.g. initial problem framing and agenda setting, planning and strategy-making, implementation, monitoring and evaluating, which studies have increasingly made clear (Moser and Ekstrom, 2010; Mees *et al*., 2012; Dannevig *et al*., 2012). The following sections illustrate five of the most commonly emphasized barriers or enablers of institutional change.

First, the importance of multilevel institutional coordination between different political and administrative levels in society is increasingly cited in both developing and developed countries as challenging (Few *et al*., 2007; Urwin and Jordan, 2008; Corfee-Morlot *et al*., 2009; Keskitalo, 2009; Pahl-Wostl, 2009; Measham *et al*., 2011; Robinson and Berkes, 2011; Sietz *et al*., 2011; Nilsson *et al*., 2012; Rodima-Taylor *et al*., 2012; Glaas and Juhola, 2013). Several studies report on unclear roles and responsibilities between levels and actors inhibiting climate adaptation. They show that there are few national requirements or guidelines to help local governments approach climate adaptation, stressing the importance of developing regulations, policies, and codes to support the institutionalization of local climate actions (Næss *et al*., 2005; Crabbé and Robin, 2006; Storbjörk, 2007; Glaas *et al*., 2010; Mozumder *et al*., 2011; Adhikari and Taylor, 2012; Carmin *et al*., 2012; Hedensted Lund *et al*., 2012; Peach Brown *et al*., 2013). Vammen Larsen *et al*. (2012) stress that climate change does not possess clear institutional characteristics as a municipal professional area. Rather, it is viewed as a void with no clear rules and norms according to which politics is to be conducted and policy measures agreed upon. This has meant that climate adaptation remains ad hoc and based on processes of “muddling through” in a sense that increases risks of failure (Preston *et al*., 2011).

Further, the literature shows that the lack of clear national agendas and incentives may burden local governments differently, based on their different capacities (Juhola and Westerhoff, 2011; Anguelovski and Carmin, 2011; Dannevig *et al*., 2012). Authors have also cautioned against a too heavy emphasis on national guidance, suggesting that centralized approaches may in some cases constrain local initiatives and create unfortunate dependencies. Instead a combination of top-down and bottom-up activities is proposed where national actors sets a proactive agenda for climate adaptation and supports implementation that occurs at sub-national levels (Urwin and Jordan, 2008; Bulkeley *et al*., 2009; Preston *et al*., 2013). Connected to this question of guidance and support is also a large strand of research showing that simply producing more and better knowledge is not sufficient. This illustrates the role of knowledge-brokers, policy entrepreneurs, and bridging organizations to communicate and mediate the co-production of knowledge between science and practice and make climate knowledge consistent and credible at appropriate decision-making scale (Tribbia and Moser, 2008; Tompkins *et al*., 2010; Mozumder *et al*., 2011; Amundsen *et al*., 2010).

Second, the literature show that key actors, advocates and champions are decisive for initiating, mainstreaming and sustaining momentum for climate adaptation planning and implementation in different national settings (Bulkeley *et al*., 2009; Burch, 2010; Moser and Ekstrom, 2010; Tompkins *et al*., 2010; Garrelts and Lange, 2011; Runhaar *et al*., 2012; Romero-Lankao, 2012). Key actors can be particularly important in the absence of strong national level (Anguelovski and Carmin, 2011; Dannevig *et al*., 2012). Champions further involve actors in different roles, from junior staff to senior executives and elected representatives (Measham *et al*., 2011). The literature on leadership have distinguished between different types of leadership, where visionary leadership means showing direction and motivating others, entrepreneurial leadership means ability to get things done and, finally, collaborative leadership means bridging gaps, spanning boundaries and building coalitions (Gupta *et al*., 2010; van den Brink *et al*., 2011). Although there is wide agreement that leaders are key for driving change, a dependency on personal commitments and dedication of key individuals may render adaptation planning and implementation fragile if it takes place at the prize of organizational learning (Næss *et al*., 2005; Crabbé and Robin, 2006; Storbjörk, 2010).

Third, the horizontal interplay between actors and policies operating at similar administrative levels is seen as key in institutionalizing climate adaptation. Several international studies have shown that local governments and administrations consists of different professional silos with their own internal norms, values and priorities and that the institutional rigidity of existing administrative and political sectors creates unfortunate compartmentalization where climate adaptation is seen as the isolated task of a singular sector which may hinder the mainstreaming and horizontal coordination across sectors and departments (Mickwitz *et al*., 2009; Burch, 2010; Roberts, 2010; Storbjörk, 2010; Runhaar *et al*., 2012; Vammen Larsen *et al*., 2012; van den Berg and Coenen, 2012; Wilby and Keenan, 2012;). Preston *et al*. (2011) have determined that adaptation plans from Australia, the UK and the US, largely frame adaptation in a narrow sense overlooking the capacity and institutional challenges involved in the process of mainstreaming in other sectors. Institutional rigidity also takes the form of path dependency where past policies, decisions, habits and traditions, constrain the extent to which systems can learn or adapt to climate change (Garrelts and Lange, 2011; Berkhout, 2012; Preston *et al.*, 2013; Runhaar *et al*., 2012). Some authors have identified such cultures of reactive management or structural engineered approaches to climate adaptation negatively influencing institutional change (Næss *et al*., 2005; Measham *et al*., 2011; Harries and Penning-Rowsell, 2011). Several writers have emphasised the need to facilitate improved cross-sectoral interaction, exchange and organizational learning to drive institutional change (Berkhout *et al*., 2006; Crabbé and Robin, 2006; Pelling *et al*., 2008; Hinkel *et al*., 2009; Burch, 2010). How cross-sectoral coordination is achieved in practice, remains one of the major challenges in transitioning for planning to implementation.

Fourth, the need to acknowledge political dimensions in planning and implementation are highlighted in several studies, both in developing and developed countries. Studies indicate that politicians have not recognized climate adaptation as being politically urgent enough to elevate on the policy agenda. Subsequently they identify a tendency to prioritize other political concerns, often more short-term tangible issues (O'Brien *et al*., 2006; Storbjörk, 2007; Glaas *et al*., 2010; Corfee-Morlot *et al*., 2011; Measham *et al*., 2011; Runhaar *et al*., 2012; Preston *et al*., 2013). This has implications for the availability of resources and financial means in the form of staff and time (Tribbia and Moser, 2008). Other studies document competing values, conflicting objectives, tensions and trade-offs between different policy agendas and priorities in planning and implementing climate adaptation (Næss *et al*., 2005; Berkhout *et al*., 2006; Adger *et al*., 2009a; O'Brien and Wolf, 2010; Measham *et al*., 2011; Storbjörk and Hedrén, 2011). In a developing country context, a study in the drylands of Kenya call for increased consideration of political dimensions of local adaptation by showing how power relations at multiple geographic scales and interaction of informal institutions e.g. clans and spiritual leaders and government institutions shape the local negotiation of conflicting interests (Eriksen and Lind, 2009).

Fifth, improved coordination between formal governmental and administrative agencies and private stakeholders is highlighted in the literature. Private sector involvement is often seen as a way to increase the efficiency of climate adaptation (Engle and Lemos, 2010; Mees *et al*., 2012; Tompkins and Eakin, 2012). As part of highlighting private sector involvement, studies from developing and developed countries emphasize the need for stakeholder participation, representation, accountability, and equality to influence the sharing and shaping of knowledge in adaptation decision-making and achieve change on the ground (Gupta *et al*., 2010; Harries and Penning-Rowsell, 2011; Robinson and Berkes, 2011; Adhikari and Taylor, 2012; Huntjens *et al*., 2012; McNeeley, 2012; Tompkins and Eakin, 2012;). Participatory approaches potentially allow maintaining regard for the highly localized and contextual nature of climate adaptation, balance standardization and context in adaptation planning and implementation and bolster support for and facilitate implementation (Preston *et al*., 2011; Mees *et al*., 2012). Elaborate forms of participatory designs for facilitating a co-production of knowledge, interactive learning and stakeholder exchange, mediated by boundary organizations and knowledge brokers, is being undertaken but more are needed (Pahl-Wostl, 2009; Pulwarty *et al*, 2009; Tompkins *et al*., 2010; Jonsson *et al*., 2012). At the same time authors clarify that stakeholders can hold private, sectarian interest and represent local elites, meaning that which voices actually get represented is an important issue (Romero-Lankao, 2012). Studies in Western Nepal have documented obstacles to political inclusion due to social status and caste-based political discrimination where societal elites suppress marginal voices (Jones and Boyd, 2011). Other studies have documented how existing centralized top-down institutions have been complemented and sometimes challenged by public-private partnerships at critical stages in implementation (Juhola and Westerhoff, 2011; Rodima-Taylor *et al*., 2012).

15.5.1.3. Facilitating More Effective Climate Adaptation Planning and Implementation

Although Section15.2 shows that international studies clearly report a large number of ongoing responses to support climate adaptation, which are most commonly incremental responses within existing institutional arrangements (with some rare examples of institutional transformations), there is a large body of evidence of the mainstreaming of climate adaptation resulting in limited implementation. Subsequently most studies on climate adaptation planning and implementation have focused on identifying barriers and challenges. Biesbroek *et al*. (2013) have suggested to move forward in our current context specific and fragmented understanding of barriers, including institutional dimensions, and embrace comparative approaches, synthesizing knowledge and analyzing barriers more systematically. Recent discussions suggest focusing more attention on how to transform barriers to enablers of action and institutional change (Burch *et al*., 2010; Moser and Ekstrom, 2010; Park *et al*., 2012; Biesbroek *et al*., 2013). Dovers and Hezri (2010) have claimed that there is a predominant focus in adaptation research on what should happen rather than how that might be achieved, the latter targeting strengths and weaknesses with different forms of institutional structures, procedures and ways of organizing climate adaptation that supports change. Others have suggested that monitoring and evaluating the effectiveness of strategies adopted and interventions undertaken needs further attention (Mullan *et al*., 2013). Further, it is suggested that propositions for change tend to be driven by theory rather than empirically substantiated and tested and that the adaptation literature would benefit by embracing lessons and experiences of mechanisms for enabling institutional change gained in other policy sectors and past policy interventions (Dovers and Hezri, 2010; Biesbroek *et al*., 2013).

15.5.2. Increasing Capabilities

Governance of adaptation creates the space and conditions for achieving specific goals or collective outputs by aligning principles and norms for regulations, decision making procedures and organizations in providing an overarching system to comprehensively address a challenge (Biermann *et al*., 2009; Young, 2010; DeWulf *et al*., 2011). However, the embryonic stage of adaptation planning and implementation faces challenges to develop governance approaches (Glaas *et al*., 2010; Gupta *et al*., 2010; Tompkins *et al*., 2010; Carmin *et al*., 2012; Huntjens *et al*., 2012; Rodima-Taylor *et al*., 2012; Mukheibir *et al*., 2013). The previous section on the institutional dimensions of adaptation in this chapter stressed the obstacles in current structures of national, subnational, and local governments to address complex and multidimensional problems (Wilson, 2006; Koch *et al*., 2007; Roberts, 2008; Bulkeley *et al*., 2009; Inderberg and Eikeland, 2009; Engle and Lemos, 2010; Glaas *et al*., 2010; Sietz *et al*., 2011; Storbjörk and Hedrén, 2011; van den Brink *et al*., 2011; Huntjens *et al*., 2012; Rodima-Taylor *et al*., 2012; Termeer *et al*., 2012; Vammen Larsen *et al*., 2012; Glaas and Juhola, 2013). Similar fragmented approaches for adaptation planning and implementation also hinder a dynamic and diverse participation of other stakeholders in these processes (Folke *et al*., 2005; Raschky, 2008; Urwin and Jordan, 2008; Coles and Scott, 2009; Dessai *et al*., 2009; Handmer, 2009; Scheffer, 2009; Nath and Behera, 2010; Reid *et al*., 2010; Sissoko *et al*., 2011). Additionally, there have been very few documented changes in forecasts, plans, design criteria, investment decisions, budgets or staffing patterns in response to climate risks (Repetto, 2008; Tompkins *et al*., 2010; Berrang-Ford *et al*., 2011).

Expanding and improving capabilities of stakeholders strengthen operational approaches for adaptation to climate change at different levels. The literature recognizes four areas where improved capabilities can facilitate this creation of governance approaches for adaptation planning and implementation: creating learning processes incorporating various knowledge systems and experiences to facilitate developing a common understanding and policies critical for cross-institutional coordination and multi-stakeholders actions (Engle and Lemos, 2010; Huntjens *et al*., 2012); enhancing monitoring and evaluation of adaptation planning and implementation currently limiting opportunities for learning and improvement of current and future adaptation initiatives (Manuel-Navarrete *et al*., 2009; Preston *et al*., 2011; Nilsson *et al*., 2012); improving cross level coordination within government structures at the national, subnational, and local level (Urwin and Jordan, 2008; Bulkeley *et al*., 2009; Amundsen *et al*., 2010; Robinson and Berkes, 2011; Preston *et al*., 2013); enhancing the participation of stakeholders from the assessment of vulnerability to the design and implementation of operational approaches of adaptation (Moser and Satterthwaite, 2008; Anguelovski and Carmin, 2011; Carmin *et al*., 2012; Dannevig *et al*., 2012).

These interacting aspects strengthen incorporating climate change risks to systems and sectors, and the corresponding response planning and implementation actions occurring at different spatial and temporal scales. The help improving mechanisms to foster and strengthen coordination in the scale of governance together with a clear division of tasks and responsibilities of actors, especially under conflicting timescales of interventions (Koch *et al*., 2007; Amundsen *et al*., 2010; Biesbroek *et al*., 2010; Biesbroek *et al*., 2011). They can also support addressing jurisdictional scales and mandates across sectors, and local, national and sub-national policies, constricting the potential benefits of close dependencies between institutions, institutional systems and organizational units in planning and implementation of adaptation (Dovers and Hezri, 2010).

Creating capabilities to through coordination is reported to expand the adaptive capacity of local actors and enhancing opportunities for policy formulations of larger governance networks and learning opportunities for policy formulations (Keskitalo and Kulyasova, 2009; Owen, 2010). Capturing various perspectives of multiple stakeholders and actors holding different views, power and influence, is pivotal in mutually achieving short-term and long-term adaptation needs to climate change (O'Brien *et al*., 2008; Shaw *et al*., 2009; Bardsley and Sweeney, 2010; IAPAD, 2010; Corfee-Morlot *et al*., 2011). Capabilities to enhance and complement the value of local knowledge through scientific knowledge can become a useful source of community-based adaptation planning and implementation (McLeman *et al*., 2008; Green and Raygorodetsky, 2010; Berrang-Ford *et al*., 2011; Birkmann, 2011; Ford *et al*., 2011; Newsham and Thomas, 2011; Nakashima *et al*., 2012).

Increasing capabilities for adaptation planning and implementation can also benefit from approaches with greater emphasis on nature-based protection strategies or buffers. Related climate change adaptation efforts also improve ecosystem resilience by implementing sustainable forestry management, expanding floodplain setbacks, implementing coastal aforestation, coral reef propagation, restoring degraded lands, maintaining healthy vegetation on slopes, incentivizing development away from coastal areas and bluffs, and removing barriers to the migration of plants and animals, all of which are necessary for the resilience of communities facing climate change impacts (Tobey *et al*., 2010; Sovacool *et al*., 2012).

15.6. Research Needs for Maximizing Opportunities

The following interrelated research needs extracted from the chapter can create and maximize opportunities for adaptation planning and implementation.

The emphasis on impacts and defensive infrastructure has been documented in a number of early adaptation plans (Few *et al*., 2007; Hofstede, 2008; Mitchell *et al*., 2010; Garrelts and Lange, 2011; Harries and Penning-Rowsell, 2011; Rosenzweig *et al*., 2011; Rumbach and Kudva, 2011; Etkin *et al*., 2012; IPCC, 2012). Research on the design and implementation of these plans and the lessons that can be extracted from them can help address concerns in the literature that an impact approach can overshadow the analysis of underlaying stressors of hazards, the drivers of vulnerability, and opportunities for connecting development pressures and climate change (Lemos *et al*., 2007; Sabates-Wheeler *et al*., 2008; Orlove, 2009; Boyd and Juhola, 2009; Hulme *et al*., 2009; Hardee and Mutunga, 2010; Ribot, 2010; Rumbach and Kudva, 2011; Sietz *et al*., 2011). These lessons can help balance the design of adaptation planning including projects for defensive infrastructures needed through flexibility and safety margins and at the same time incorporating other actions seeking to reduce social vulnerability and enhancing adaptation. Relevant in these efforts is building a better understanding of how early adaptation plans can transcend from defensive but fragmented approaches, to multidimensional policy process recognizing adaptation planning and its implementation as learning processes (Hulme *et al*., 2009; Biesbroek *et al*., 2011).

Research on operational strategies and approaches for adaptation can help maximizing available resources for adaptation to climate change. Current contributions in the literature help build a better understanding on diverse dimensions of this complex process, but these contributions have provided little attention to the discussion and suggestion of guidelines to build operational approaches. Some authors stress that few studies show hoWadaptation to climate change is actually being delivered (Arnell, 2010; Tompkins *et al*., 2010; National Research Council, 2011). Key elements in these research efforts are: expanding the understanding the knowledge on the connections between adaptation and development in different context and at different governance levels (Boyd and Juhola, 2009; Dovers, 2009; Hulme *et al*., 2009); the role of multiple stresses - not just climate- in adaptation planning and its implementation (IPCC, 2007; Tompkins *et al*., 2010); the role of low-regret strategies strengthening operational approaches for adaptation (Hallegatte, 2009; UNDP, 2010).

Section 15.5.1 highlights how limitations of current institutional arrangements restrict the mainstreaming of climate adaptation (Roberts, 2008; Burch, 2010; Engle and Lemos, 2010; Glaas *et al*., 2010; Moser and Ekstrom, 2010; Jones and Boyd, 2011; Robinson and Berkes, 2011; Storbjörk and Hedrén, 2011; Dannevig *et al*., 2012; Dovers and Hezri, 2012; Huntjens *et al*., 2012; McNeeley, 2012; Vammen Larsen *et al*., 2012; Glaas and Juhola, 2013; Biesbroek *et al*., 2013). Expanding research on institutional arrangements in at least three key areas can help improve the implementation of adaptation plans in both developed and developing countries, 1) on approaches to improve multilevel institutional coordination between different political and administrative levels in society with a particular emphasis balancing a combination of top-down and bottom-up activities (Urwin and Jordan, 2008; Bulkeley *et al*., 2009; Amundsen *et al*., 2010; Robinson and Berkes, 2011; Preston *et al*., 2013); 2) on approaches to overcome the institutional rigidity limiting the horizontal interplay within local governments where climate adaptation is seen as the isolated task of a singular sector which hindering the mainstreaming and horizontal coordination across professional sectors and departments and constraining the extent to which systems can learn or adapt to climate change (Bulkeley *et al*., 2009; Burch, 2010; Dovers and Hezri, 2010; Glaas *et al*., 2010; Storbjörk, 2010; Juhola and Westerhoff, 2011; Hedensted Lund *et al*., 2012; Runhaar *et al*., 2012; Uittenbroek *et al*., 2012; van den Berg and Coenen, 2012; Wilby and Keenan, 2012); and 3) on approaches improving coordination between formal governmental and administrative agencies and social and private stakeholders in order to create participatory approaches maintaining regard for the highly localized and contextual nature of climate adaptation, and facilitating a collaboration for production of knowledge and interactive learning (Pahl-Wostl, 2009; Engle and Lemos, 2010; Tompkins *et al*., 2010; Preston *et al*., 2011; Jonsson *et al*., 2012; Mees *et al*., 2012).

The literature illustrates a trend to consider planning a problem-free process capable of delivering positive outcomes for adaptation to climate change. Expanding research seeking to build a better understanding of the limitations and strengths of planning can help avoid underestimating the complexity of adaptation as a social process, and creating unrealistic expectations in societies about the capacity of planning to deliver the intended outcome of adaptation. (Repetto, 2008; Biesbroek *et al*., 2009; Blanco and Alberti, 2009; Dovers, 2009; Berrang-Ford *et al*., 2011; Juhola and Westerhoff, 2011; Mozumder *et al*., 2011; Preston *et al*., 2011; Sanchez-Rodriguez, 2012). Research efforts considering adaptation planning and implementation as learning processes can help carrying out periodical adjustments to accommodate changes in climate, socioeconomic conditions and emergent risks in order to strengthen the role of planning as a societal tool for adaptation (Holden, 2008; Frommer, 2009; Hinkel *et al*., 2009; Glaas *et al*., 2010; Hofmann *et al*., 2011). The literature recognizes monitoring and evaluation as important learning tools in adaptation planning but it also acknowledges both as under-researched topic (Adger *et al*., 2009b; Preston *et al*., 2009; Tompkins *et al*., 2010; Wolf *et al*., 2010). Expanding the research on the metrics tocharacterize the success of the goals of adaptation, the trade-offs involved, and recognizing the importance of context can help avoid generalized assessments about the contribution of adaptation to managing the risks posed by climate change, and to identify what builds adaptive capacity and what functions as limits and barriers to adaptation (Barnett and Campbell, 2010; Arnell, 2010; Engle, 2011).

Adaptation planning and implementation can benefit from holistic approaches afforded by linking adaptation to development, by coupling adaptive improvements in infrastructure with ecosystem services, governance and community welfare, improved community resilience by enhancing local ownership, and created organizations able to respond to climate change issues through increased adaptive capacity.

Frequently Asked Questions

FAQ 15.1: What is the present status of climate change adaptation planning and implementation across the globe? *[to remain at the end of the chapter]*

Climate change adaptation has been receiving increasing attention due to recent media coverage and reports. Since the publication of the IPCC Fourth Assessment Report (AR4), a large assortment of adaptive actions has taken place in response to observed climate impacts. These actions mostly address sectoral interests, such as agricultural practices (e.g., altering sowing times, crop cultivars and species, and irrigation and fertilizer control), public health measures for heat-related risks (e.g., early warning systems and air pollution control), disaster risk reduction (e.g., early warning systems), and water resources (e.g., supply and demand management). Some of these are "autonomous" actions in a specific sector.

Another area where progress has been made since AR4 is the development of broad national-level plans and adaptation strategies. These have now been established in developed and developing countries worldwide. Because adaptation policy requires decision-making amid uncertainties about future climate change and its impacts, the major pillars of adaptation plans are iterative assessment, flexible and adaptive planning, and enhancement of adaptive capacity. Adaptation plans are being developed and documented at the national, subnational, and community levels and by the private sector; however, these is still limited evidence of adaptation implementation. Implementation remains challenging because in the transition from planning to implementation the many interested parties must overcome resource, institutional, and capacity barriers. The difference in time scales between medium- and long-term adaptation plans and pressing short-term issues poses a significant problem for prioritizing adaptation.

In parallel with national-level planning, community-based adaptation (CBA) has become an increasingly prevalent practice, particularly in developing counties. It is increasingly apparent that CBA potentially offers ways to address the vulnerability of local communities by connecting climate change adaptation to non-climate local needs. Cities and local governments have also begun active engagement in climate change adaptation. Local governments play an important role in adaptation because they directly communicate with affected communities. For the past several years, leading practices have begun in New York City, Mexico City, Toronto, Albay Province in the Philippines, and elsewhere. These achievements were possible because of elected and local leadership; cooperation among national and local governments, private sectors, and communities; and the participation of boundary organizations, scientists and experts.

FAQ 15.2: What types of approaches are being used in adaptation planning and implementation?
[to remain at the end of the chapter]

Adaptations employ a diverse portfolio of planning and practices that combine subsets of

- Infrastructure and asset development
- Technological process optimization
- Institutional and behavioral change or reinforcement
- Integrated natural resources management (such as for watersheds and coastal zones)
- Financial services, including risk transfer
- Information systems to support early warning and proactive planning

Although approaches vary according to context and the level of government, there are two general approaches observed in adaptation planning and implementation to date: top-down and bottom-up. Top-down approaches are scenario-driven and consist of localizing climate projections, impact and vulnerability assessments, and formulation of strategies and options. National governments often take this approach. National adaptation strategies are increasingly integrated with other policies, such as disaster risk management. These tendencies lead to adaptation mainstreaming, although there are various institutional barriers to this process. As the consideration of the social dimensions of climate change adaptation have attracted more attention, there has been an increased emphasis on addressing the needs of the groups most vulnerable to climate change, such as children, the elderly, disabled, and poor. Bottom-up approaches are needs-driven and include approaches such as community-based adaptation (CBA). CBA is often prominent in developing countries, but communities in developed countries also use this approach. Where a combination of top-down and bottom-up activities have been undertaken, the links between adaptation planning and implementation have been strengthened. In either approach, participation by a broad spectrum of stakeholders and close collaboration between research and management have been emphasized as important mechanisms to undertake and inform adaptation planning and implementation.

Local governments and actors may face difficulties in identifying the most suitable and efficient approaches because of the diversity of possible approaches, from infrastructure development to “softer” approaches such as integrated watershed and coastal zone management. National and subnational governments play coordinating roles in providing support and developing standards and implementation guidance. Therefore, multilevel institutional coordination between different political and administrative levels is a crucial mechanism for promoting adaptation planning and implementation.

Cross-Chapter Box

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

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

Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 24, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012; Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Day et al., 2007; Midgley et al., 2012; Opperman et al., 2009)
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)

- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision; traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach. The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but is should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.]

Box CC-EA References

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Table 15-1: Application of local knowledge in climate change adaptation.

Location	Sector	Approach and Strategy	Adaptive action implemented	Institutions	References
Australia, S. Kimberley	Water Supplies	Define Vulnerabilities Increase Adaptive Capacity	Compile observed changes Increase monitoring Water resource management Review TEK	Universities, NGOs United Nations University	Green *et al*., 2010 Prober *et al*., 2011 Leonard *et al*., 2013
Bolivia Trinidad, North central Bolivia	Ecosystems, Agriculture	Reduce Vulnerability	Revive “camellones” TEK[1] (camellones- earthen platforms) Reduce erosion Document local observations	OXFAM International, NGOs Bolivian Government FAO (Food & Agricultural organization)	Oxfam International, 2009
California, United States Pinoleville Pomo Nation	Infrastructure	Mitigation - Solar Power Increase Adaptive Capacity	Co-design infrastructure Address insufficient capital Address water shortages and energy needs	Universities NGOs Housing &Urban Development	Shelby *et al*., 2012 Redsteer *et al*., 2013 Pinoleville Pomo Nation Housing flyer, 2013
Fiji, South Pacific	Ecosystems And Water Supply	Define Vulnerabilities Increase Adaptive Capacity	Recognition of TEK* Enable adaptive decision-making Enhance community awareness Participation in development	AusAID Fiji Dept. of Environment University of the South Pacific	Dumaru, 2010
E. Africa Kenya Tanzania, Malawi Zimbabwe, S. Zambia	Agriculture	Define Vulnerabilities Increase Technical Capacity Increasing Adaptive Capacity	Drought early warning Application of TEK[1] Development of novel reporting Compile observed changes Rainwater harvesting Change tilling practices Use of appropriate crop varieties	University of Capetown University of Nairobi DFID/IRDC (Department for International Development)	Chang’a *et al*., 2010 Mugabe *et al*., 2010 Kalanda-Joshua *et al*., 2011 Majule *et al*., 2013 Masindel *et al*., 2013
Western United States Reservation lands	Health, Water Supplies, Environment	Define Vulnerability & Impacts - Increasing Adaptive Capacity	Compiled observed changes Utilize environmental legislation Review Indigenous knowledge Analyze local meteorological data Analyze historical/legal context Increase monitoring	Universities & affiliated NGOs Tribal offices federal agency research	Redsteer *et al*., 2010 Doyle *et al*., 2013 Gautam *et al*., 2013

* Traditional Ecological Knowledge: Adaptive ecological knowledge developed through an intimate reciprocal relationship between a group of people and a particular place over time

Table 15-2: Transition from planning to implementation.

Scale	What is being implemented and why?	Transition from planning to implementation	Monitoring and Evaluation
Village of Kaslo (British Columbia) and surrounding unincorporated rural areas (Regional District of Central Kootenay-RDCK Electoral Area D). Implemented 2010 – 2012 (Kaslo/Regional District of Central Koote2010)	The Village of Kaslo and RDCK Electoral Area D developed a Climate Adaptation Action Plan identified water supply as a key community vulnerability related to projected climate change. Action plan noted that current demand for water almost equaled supply and observed the very limited data on water supply for creeks that supply water for the community.	The Village of Kaslo and RDCK Electoral Area D brought in experts in fields related to climate change impacts and involved extensive public outreach and engagement. Adaptation planning process identified projected changes in stream freshet and stream flows associated with climate change could result in insufficient water supply. Community leaders working through the Kaslo and District Community Forest Society sought funds to establish stream flow monitoring stations, developed a monitoring framework on key creeks to track changes in flows providing water to communities within Kaslo and RDCK Area. The Columbia Basin Trust contributed funding to this effort as part of follow-up to its support of the initial climate change planning process.	Monitoring and evaluation performed by Columbia Basin Trust's Communities Adapting to Climate Change Initiative. Area D Advisory Planning Commission monitors the implementation of action recommendations
National Framework on Local Adaptation Plans for Action(LAPA)-Nepal. Implementation began in 2011 (Government of Nepal, 2011)	Nepal adopted the LAPA in 2011, becoming the first country to promote a bottom-up approach to adaptation planning and implementation. The NAPA & the National Climate Change Policy states that at least 80 per cent of the available budget will go towards directly implementing adaptation actions at the local level. To date, 70 LAPAs have been prepared (69 at the village administrative scale and 1 within a municipality) and are under implementation by vulnerable communities.	Policy makers recognised the need to integrate local and context specific adaptation plans into local to national adaptation planning as a way to ensure robust climate change adaptation planning and implementation. The Ministry of Science, Technology and Environment (MoSTE) and the Ministry of Federal Affairs and Local Development (MoFALD) played a leadership role at the central level in coordinating the development and implementation of LAPAs.	Monitoring and evaluation play key roles in supporting iterative planning. Financial arrangements play a key role in integrating local adaptation options into development planning processes. Adaptation investments are being costed and integrated into annual and medium-term budget frameworks and resource mobilisation strategies. Nepal's budget for FY 2013/14 has included Climate Change Financing Code and of the total budget 5.36 percent is directly related to the climate change financing

Local Government-the Albay Province (Philippines) Implementation began in 2008. (Lasco et al, 2009)	"Albay Declaration on Climate Change Adaptation" specified mainstreaming climate change into local and national development policies. AIARP (Albay Integrated Agricultural Rehabilitation Program) though establishing farm clusters to assist farmers and fisher folks in their agricultural needs, food assistance, technological needs and training needs.	Program planning began in December 2006 after Typhoon Reming devastation. Plan prevent scarcity of agricultural commodities and accelerate food production; pump-prime the Agricultural Industry in the Province; and speed up rehabilitation of upland agricultural areas in Albay. The provincial government of Albay established the Center for Initiatives and Research on Climate Adaptation (CIRCA) in 2008, a living research and training institution in collaboration with the Environment Management Bureau (EMB), World Agroforestry Centre (ICRAF), Bicol University (BU) and the University of the Philippines Los Banos (UPLB). Local champions such as the Governor of committed time and resources to put climate change on provincial agenda and also in the national development and policy agenda addressing the needs the farmers and fisher folks	Main mechanism for institutional and stakeholder collaboration is through the Inter-Agency Committee on Climate Change (IACCC) Philippine Senate Resolution No 191 passed during 14th Congress 1st regular session Adopting the Albay Declaration on Climate Change Adaptation as a framework. Mainstreaming of global warming concerns gives a voice to the Albay Declaration in Congress and directly encourages policy makers to mainstream climate change in policy-making; and Indicators measure cleaner environment for the community improvement of infrastructure development plans, land development/ conversion activities institutionalization of pre-planning, enhanced implementation and enhanced monitoring and evaluation .
Pilot Program on Climate Resilience, 2009 (CIF, 2012; PPCR, 2013)	The Pilot Program for Climate Resilience (PPCR) through Climate Investment Funds (CIF) Phase I (planning) , supported by multilateral development bank (MDB) partners, in 2 years developed a strategic plan consistent with national development objectives. Phase II (implementation)Countries define "transformational change" in the context of their national circumstances. Scaling-up potential of successful pilots (e.g. use of good practices in Bangladesh) Addressing basic needs (e.g. food security in Niger) Mobilization of large-scale resources for investments (e.g. coastal highways in Samoa). Country leadership capacity dependant on experience with integrating climate change into	The capacity of countries to take on leadership role depended on their prior experience with integrating climate change considerations into planning activities; institutional and human capacities; and demands to respond to other emergencies. The strategic plans drew on NAPAs, national climate change strategies (if they existed), and national development strategies and plans Lead agency roles assigned to planning or finance ministry (e.g., Zambia, Samoa) or their environment-related ministries (e.g., Bangladesh) Disaster risk management units included Coordinate the work of donors and/or leverage non-PPCR resources. For example, Cambodia and Zambia have leveraged co-financing from the International Fund for Agricultural Development and the Nordic Development Fund, respectively.	Framework includes five core indicators designed to measure outcomes at the country level, aggregated from individual PPCR components. These are: (i) Number of people supported by the PPCR to manage the effects of climate change; (ii) b) Degree of integration of climate change in national, including sector planning; (iii) Extent to which vulnerable households, communities businesses and public sector services use improved PPCR supported tools, instruments, strategies, activities to respond to climate vulnerability and climate change; (iv) Evidence of strengthened government capacity and coordination mechanism to mainstream climate resilience; and (v) Quality of and extent to which climate responsive instruments/ investment models are developed and tested. All of the core indicators address gender issues either directly or indirectly

	planning activities, institutional and human capacities; and need to respond to emergencies.Recent climate-extreme related disasters have affected development.		
United Kingdom National Adaptation Programme. Implementation in 2012 (UK HM Government, 2013)	Pursuant to Climate Change Act 2008, the Climate Change Risk Assessment 2012 (CCRA) for the UK brought together the best available evidence, using a consistent framework to identify the risks and opportunities related to climate change. The assessment distilled approximately 700 potential risks down to more than 100 for detailed review. Recent extreme weather in Britain, such as the flooding in the winter of 2012 and the drought of early 2012 brought into sharp relief the importance of anticipating and managing weather extremes. Costs of rebuilding and impacts on essential public services highlighted the need for implementing preparedness and adaptation.	The Climate Ready Support Service provides direct support and online information to help organisations assess their sensitivity to a changing climate and take steps to manage their climate risks. Through the Service the EA is working with partners in priority sectors to provide tailored tools, guidance and training to enable them to understand and respond to the challenges of a changing climate. Established partnerships are with the Met Office, the Local Government Association, Climate UK and the Climate Change Partnerships. The government is also supporting the building of networks of organisations that may share common risks, for example the Infrastructure Operators Adaptation Forum	Progress indicators provide iterative measures of progress and to develop the next CCRA: • Process-based markers, such as whether planned policies have been implemented. • Quantitative data, such as statistics on trends in factors that influence risks from flooding and water scarcity. These provide a strong foundation for assessing overall adaptation in relevant areas. Discussions about the most appropriate framework are continuing. The Adaptation Sub-Committee (ASC) of the Committee on Climate Change under Climate Change Act assesses progress towards implementation of objectives, proposals and policies highlighted in this report and the Register of Actions, with assessments published in 2015 and every two years hence.

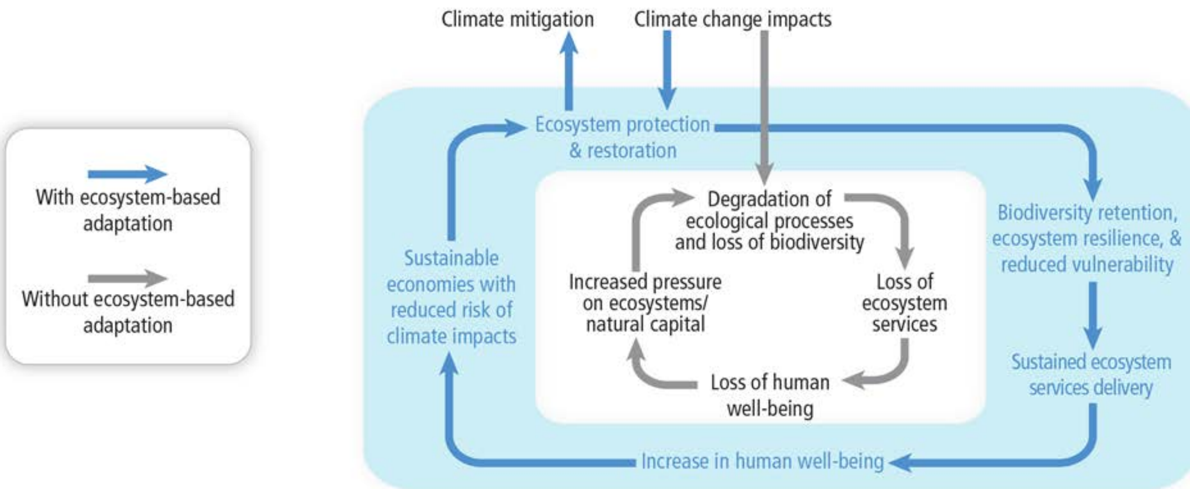

Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

Chapter 16. Adaptation Opportunities, Constraints, and Limits

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Contents

Executive Summary

Risk-based approaches to decision-making provide a useful foundation for assessing the potential opportunities, constraints, and limits associated with adaptation of human and natural systems (*high agreement, medium evidence*). Risk management frames the consequences of climate change and potential adaptation responses in the context of actors' values, objectives, and planning horizons as they make decisions under uncertainty. Adaptation planning and implementation are therefore contingent on actors' perceptions of risk. Some risks may be routine and/or the consequences so minor that they are accepted. Other risks may be judged intolerable because they pose fundamental threats to actors' objectives or the sustainability of natural systems. A key objective of adaptation is to avoid such intolerable risks. Yet, the capacity of societal actors and natural systems to adapt is finite, and thus there are limits to adaptation. [16.2; 16.3.2; 16.4; Box 16-1]

Understanding of how the adaptive capacity of societal actors and natural systems influences the potential for adaptation to effectively manage climate risk has improved since the AR4 (*very high confidence*). Adaptive capacity is influenced by actors' abilities to capitalize on available opportunities that ease the planning and implementation of adaptation as well as constraints that make adaptation processes more difficult for both human and natural systems. Opportunities and constraints are unevenly distributed among global regions, communities, sectors, ecological systems, and species as well as across different time periods. Recent studies have provided greater recognition of the role of private businesses in facilitating adaptation. However, much of current knowledge about adaptation opportunities and constraints is dominated by insights from public institutions and community-based case studies. [16.2; 16.3; 16.4; 16.5; Box 16-1]

Opportunities exist to enable adaptation planning and implementation for actors across all sectors and geographic regions (*very high confidence*). Adaptation guidance, information, and tools are increasingly available to practitioners operating in different sectoral, regional and organizational contexts. Enhancing the awareness of individuals, organizations, and institutions about climate change vulnerability, impacts and adaptation can help build individual and institutional capacity for adaptation planning and implementation. However, addressing knowledge deficits alone is not sufficient to achieve successful adaptation. The development and provision of tools for risk and vulnerability assessment as well as decision-support tools and early warning systems can help actors prioritize adaptation needs and identify options that reduce vulnerability. Opportunities can also arise as actors learn from experience with climate variability and incorporate consideration for long-term climate change into disaster risk reduction efforts. Formal policies regarding infrastructure design standards or spatial planning can trigger adaptation

action. However, many adaptation opportunities arise as ancillary benefits of actions implemented for reasons other than climate change. [16.2 16.3.1; 16.5; Table 16-1; Table 16-3; Box 16-1; Box 16-2; Box CC-EA]

A range of biophysical, institutional, financial, social, and cultural factors constrain the planning and implementation of adaptation options and potentially reduce their effectiveness (*very high confidence*). Adaptation of both human and natural systems is influenced by the rate of climate change as well as rates of economic development, demographic change, ecosystem alteration, and technological innovation. Adaptation planning and implementation may require significant inputs of knowledge as well as human, social, and financial capital. Real or perceived deficiencies in access to such resources can and do constrain adaptation efforts in both developing and developed nations. Public and private institutions influence the distribution of such resources as well as the development of policies, legal instruments, and other measures that facilitate adaptation. Therefore, institutional weaknesses, lack of coordinated governance, and conflicting objectives among different actors can constrain adaptation. Cultural characteristics including age, gender, and sense of place influence risk perception, entitlements to resources, and choices about adaptation. Societal actors and natural systems may experience multiple constraints that interact. [16.2; 16.3.2; 16.5; Table 16-2; Table 16-3; Box 16-1; Box 16-3]

Limits to adaptation can emerge as a result of the interactions among climate change and biophysical and socioeconomic constraints (*high agreement, medium evidence*). An adaptation limit occurs due to the inability to avoid an intolerable risk to an actor's objectives and/or to the sustainability of a natural system. Understanding of limits is informed by historical and recent experience where limits to adaptation have been observed, as well as by limits that are anticipated to arise as a consequence of future global change. Recent studies have provided valuable insights regarding global 'tipping points', 'key vulnerabilities', or 'planetary boundaries' as well as evidence of climate thresholds for agricultural crops, species of fish, forest and coral reef communities, and humans. However, for most regions and sectors, there is a lack of empirical evidence to quantify magnitudes of climate change that would constitute a future adaptation limit. Furthermore, economic development, technology, and cultural norms and values can change over time to enhance or reduce the capacity of systems to avoid limits. As a consequence, some limits may be considered 'soft' in that they may be alleviated over time. Nevertheless, some limits may be 'hard' in that there are no reasonable prospects for avoiding intolerable risks. Recent literature suggests that incremental adaptation may not be sufficient to avoid intolerable risks, and therefore transformational adaptation may be required to sustain some human and natural systems. [16.2; 16.3; 16.4; 16.5; 16.6; 16.7; Table 16-3; Box 16-1; Box 16-4]

Greenhouse gas mitigation can reduce the rate and magnitude of future climate change and therefore the likelihood that limits to adaptation will be exceeded (*high agreement, medium evidence*). Adaptation and greenhouse gas mitigation are complementary risk management strategies. However, residual loss and damage will occur from climate change despite adaptation and mitigation action. Knowledge about limits to adaptation can inform the level and timing of mitigation needed to avoid dangerous anthropogenic interference with the climate system. For example, the level of effort needed to adapt to a 4°C increase in global mean temperature would be significantly greater than that needed to adapt to lower magnitudes of temperature increase. Mitigation can reduce the likelihood of 4°C of warming and therefore the likelihood of exceeding limits to adaptation of natural and human systems. However, the empirical evidence needed to identify limits to adaptation of specific sectors, regions, ecosystems, or species that can be avoided with different greenhouse gas mitigation pathways is lacking. [16.3.2.2; 16.6; Box 16-3]

The selection and implementation of specific adaptation options has ethical implications (*very high confidence*). Adaptation decision-making involves the reconciliation of legitimate differences about how adaptation resources are distributed and the values that adaptation seeks to protect. For example, the costs and benefits of different adaptation options, such as insurance schemes or large-scale infrastructure projects, may be inequitably distributed among different actors and stakeholders. Such inequities may generate ethical questions regarding who is advantaged or disadvantaged by adaptation actions. In addition, awareness that climate change may exceed the capacity of actors to adapt may have ethical implications for decisions regarding mitigation and climate targets as well as investments in greenhouse gas mitigation policies and measures. National and international law as well as decision-making at regional and local scales among both public and private actors will influence distributive and procedural justice in adaptation planning and implementation. [16.3.3.8; 16.6; 16.7; Table 16-4; Box 16-4]

Successful adaptation requires not only identifying adaptation options and assessing their costs and benefits, but also exploiting available mechanisms for expanding the adaptive capacity of human and natural systems (*high agreement, medium evidence*). Since the AR4, a growing body of literature provides guidance on how enabling conditions for adaptation can be developed and how constraints can be reduced. Continued development of this knowledge through research and practice could accelerate more widespread and successful adaptation outcomes. However, seizing opportunities, overcoming constraints, and avoiding limits can involve complex governance challenges and may necessitate new institutions and institutional arrangements to effectively address multi-actor, multi-scale risks. [16.2; 16.3; 16.5; 16.8; Table 16-1; Box CC-EA]

16.1. Introduction and Context

Since the IPCC's *Fourth Assessment Report* (AR4), demand for knowledge regarding the planning and implementation of adaptation as a strategy for climate risk management has increased significantly (Preston *et al.*, 2011a; Park *et al.*, 2012). This chapter assesses recent literature on the opportunities that create enabling conditions for adaptation as well as the ancillary benefits that may arise from adaptive responses. It also assesses the literature on biophysical and socioeconomic constraints on adaptation and the potential for such constraints to pose limits to adaptation. Given the available evidence of observed and anticipated limits to adaptation, the chapter also discusses the ethical implications of adaptation limits and the literature on system transformational adaptation as a response to adaptation limits.

To facilitate this assessment, this chapter provides an explicit framework for conceptualizing opportunities, constraints, and limits (16.2). In this framework, the core concepts including definitions of adaptation, vulnerability, and adaptive capacity are consistent with those used previously in the AR4 (Adger *et al.*, 2007). However, the material in this chapter should be considered in conjunction with that of other complementary AR5 WGII chapters. These include Chapter 14 (*Adaptation Needs and Options*), Chapter 15 (*Adaptation Planning and Implementation*), and Chapter 17 (*Economics of Adaptation*). Material from other WGII chapters is also relevant to informing adaptation opportunities, constraints, and limits, particularly Chapter 2 (*Foundations for Decision-Making*) and Chapter 19 (*Emergent Risks and Key Vulnerabilities*). This chapter also synthesizes relevant material from each of the sectoral and regional chapters (16.5).

In order to enhance its policy relevance, this chapter takes as its entry point the perspective of actors as they consider adaptation response strategies over near, medium, and longer terms (Eisenack and Stecker, 2012; Dow *et al.*, 2013a, b). Actors may be individuals, communities, organizations, corporations, NGOs, governmental agencies, or other entities responding to real or perceived climate-related stresses or opportunities as they pursue their objectives (Patt and Schröter, 2008; Blennow and Persson, 2009; Frank *et al.*, 2011). These actors may seek to navigate near-term constraints to implement adaptation while simultaneously working to alleviate those constraints to enable greater flexibility and adaptive capacity in the future. Therefore, it is necessary to consider diverse timeframes for possible social, institutional, technological and environmental changes. These timeframes also differ in the types of uncertainties that are relevant, ranging from those of climate scenarios and models, possible system thresholds, nonlinear responses or irreversible changes in social or environmental systems, and the anticipated magnitude of impacts associated with higher or lower levels of climate change (Meze-Hausken, 2008; Hallegatte, 2009; Briske *et al.*, 2010).

To provide further background and context, this chapter proceeds by revisiting relevant findings on adaptation opportunities, constraints, and limits within the AR4 and the more recent IPCC *Special Report on Managing the Risks of Extreme Events and. Disasters to Advance Climate Change Adaptation* (SREX) (IPCC, 2012). The chapter then presents a framework for adaptation, opportunities, and limits with an emphasis on explicit definitions of these concepts to facilitate assessment. Key components of this framework are assessed in subsequent chapter sections including the synthesis of how these components are treated among the different sectoral and regional chapters of the AR5 WGII report. The chapter subsequently assesses relationships between mitigation and adaptation opportunities, constraints, and limits as well as their ethical implications. The chapter concludes with discussion of key pathways forward for research and practice to seize opportunities, overcome constraints, and avoid limits.

16.1.1. Summary of Relevant AR4 Findings

The AR4 *Summary for Policymakers* of Working Group II concluded that there are "*formidable environmental, economic, informational, social, attitudinal and behavioural barriers to the implementation of adaptation*" and that "*availability of resources and building adaptive capacity are particularly important*" (IPCC, 2007a, pg. 19). These findings were based primarily on Chapter 17, *Assessment of Adaptation Practices, Options, Constraints and Capacity* (Adger *et al.*, 2007). The key conclusion from Adger *et al.* (2007, pg. 719), as relevant to this chapter, was as follows: "*There are substantial limits and barriers to adaptation (very high confidence)*". The authors go on to discuss biophysical and technological limits to adaptation as well as barriers arising from technological, financial, cognitive and behavioral, and social and cultural factors. The authors also noted both significant knowledge gaps and impediments to the sharing of relevant information to alleviate those gaps.

These findings were further evidenced by the sectoral, and particularly, regional chapters of the AR4 WGII report. For example, the chapters assessing impacts and adaptation in Africa, Asia, and Latin America collectively emphasized the significant constraints on adaptation in developing nations. Meanwhile, the chapter on Small Islands by Mimura *et al.* (2007) identified several constraints to adaptation including limited natural resources and relative isolation. Finally, in the chapter on Polar Regions, Anisimov *et al.* (2007) noted that indigenous groups have developed resilience through sharing resources in kinship networks that link hunters with office workers, and even in the cash sector of the economy. However, they concluded that such responses may be constrained by social, cultural, economic, and political factors. For all of these regions, adaptation constraints are linked to governance systems and the quality of national institutions as well as limited scientific capacity and ongoing development challenges (e.g., poverty, literacy, and civil and political rights).

The AR4 also provided evidence that constraints on adaptation are not limited to the developing world. For example, Hennessy *et al.* (2007) reported that while adaptive capacity in Australia and New Zealand has strengthened over time, a number remain including access to tools and methods for impact assessment as well as appraisal and evaluation of adaptation options. They also note weak linkages among the various strata of government regarding adaptation policy and skepticism among some populations toward climate change science. For North America, Field *et al.* (2007) identify a range of social and cultural barriers, informational and technological barriers, and financial and market barriers. The chapter on Europe mentions the limits faced by species and ecosystems due to lack of migration space, low soil fertility and human alternations of the landscape (Alcamo *et al.*, 2007).

Several other AR4 chapters assessed literature relevant to this chapter. Chapter 18, *Inter-Relationships between Adaptation and Mitigation* (Klein *et al.*, 2007) discussed the possible effect of mitigation on adaptation (an issue also considered by the AR4 Working Group III, in particular by Fisher *et al.* (2007) and Sathaye *et al.* (2007). Finally, Chapter 19, *Assessing Key Vulnerabilities and the Risk from Climate Change* (Schneider *et al.*, 2007) outlined how the presence of adaptation constraints and limits is a contributing factor to vulnerability. Chapters that address similar themes also appear in the AR5, and cross-references are provided in this chapter to this more recent material.

16.1.2. Summary of Relevant SREX Findings

The IPCC's SREX report assesses a broad array of literature on climate change, extreme events, adaptation, and disaster risk reduction. A central framing concept for the SREX was the assertion that (Lavell *et al.*, 2012; pg. 37),

> *" . .while there is a longstanding awareness of the role of development policy and practice in shaping disaster risk, advances in the reduction of the underlying causes – the social, political, economic, and environmental drivers of disaster risk – remain insufficient to reduce hazard, exposure, and vulnerability in many regions (UNISDR, 2009, 2011) (high confidence)."*

This summary of the relevant SREX material focuses on how the key findings of the SREX provide insights relevant to the treatment of opportunities, constraints and limits in this chapter.

With respect to opportunities, the linkages between development and disaster risk reduction provide a number of avenues for enhancing societal resilience to natural disasters and climate change. For example, the SREX highlights the benefits of considering disaster risk in national development planning if strategies to adapt to climate change are adopted (Lal *et al.*, 2012). The observed dependence of disasters upon underlying patterns of development is indicative of the opportunities for increasing societal resilience through sustainable development. In addition, incorporating adaptation into multi-hazard risk management may be an effective strategy for the efficient integrated management of natural hazards and future climate risk (O'Brien *et al.*, 2012).

The SREX report also discussed the constraints associated with enhancing disaster risk reduction and climate adaptation. In particular, ongoing development deficits as well as inequality in coping and adaptive capacities pose fundamental constraints (Cardona *et al.*, 2012). The SREX noted that national systems and institutions are critical for generating the capacity needed to manage the risks associated with climate variability and change (Lal *et al.*, 2012). Yet capacity at one level of governance does not necessarily convey capacity to other levels (Burton *et al.*, 2012). Even in the presence of robust institutions, rates of socioeconomic and climate change can interact to constrain adaptation. For example, O'Brien *et al.* (2012) note that rapid socioeconomic development in vulnerable urban areas can increase societal exposure to natural hazards while simultaneously constraining the capacity of actors to implement policies and measures to reduce vulnerability. Overcoming these constraints to achieve development objectives is constrained by a paucity of disaster data at the local level as well as persistent uncertainties regarding the manifestation of extreme events in future decades (Cutter *et al.*, 2012; Seneviratne *et al.*, 2012).

The SREX report cautioned that natural hazards, climate change and societal vulnerability can pose fundamental limits to sustainable development. Such limits can arise from the exceedance of natural and/or societal thresholds or tipping points (Lal *et al.*, 2012; O'Brien *et al.*, 2012; Seneviratne *et al.*, 2012). Accordingly, the SREX concludes that adaptation options should include not only incremental adjustments to climate variability and climate change, but also transformational changes that alter the fundamental attributes of systems. Though challenging to implement, such transformation may be aided by actors questioning prevailing assumptions, paradigms, and management objectives toward the development of new ways of managing risk and identifying opportunities (O'Brien *et al.*, 2012).

16.2. A Risk-Based Framework for Assessing Adaptation Opportunities, Constraints, and Limits

Risk is an intrinsic element of any understanding of "*dangerous anthropogenic interference with the climate system*" (UNFCCC, 1992) and associated assumptions about the capacity of human and natural systems to adapt to climatic change. The United Nations Framework Convention on Climate Change (UNFCCC) refers specifically to adaptation of ecosystems, threats to food production, and sustainable economic development. While there is evidence of opportunities in natural and human systems to adapt to climate changes, there is also evidence that the potential to adapt is constrained, or more difficult, in some situations, and faces limits in others (e.g. Adger *et al.*, 2009; Dow *et al.*, 2013a, b; 16.3; 16.4; 16.5) (*very high confidence*).

This chapter applies a risk-based framework and a set of linked definitions to the assessment of adaptation opportunities, constraints and limits. This approach is consistent with other risk management approaches to guiding adaptation responses to climate change (IPCC, 2012; 1.3.4; 2.1.2; 14.5; 15.2.3.2). The adaptation literature ascribes a number of different meanings to the terms opportunities, constraints and limits, which may have added confusion to an important scientific and policy debate. The AR4, for example, provided a specific definition of adaptation limits, but used the terms barriers and constraints interchangeably to describe general impediments to adaptation (Adger *et al.*, 2007). Similar ambiguities are apparent within the rapidly expanding literature focused on adaptation constraints (Biesbroek *et al.*, 2013a). The framework and definitions employed here draw on a number of literatures (Dow *et al.*, 2013a, b), in particular vulnerability assessment (Füssel, 2006; Füssel and Klein, 2006) and risk assessment (Jones, 2001; Klinke and Renn, 2002; Renn, 2008; NRC, 2010) as well as climate adaptation (Hulme *et* *al.*, 2007; Adger *et al.*, 2009; Hall *et al.*, 2012). Moving from such general definitions to applications requires specifying who or what is adapting, what they are adapting to, and the process of adaptation (Smit *et al.* 1999). Hence, this chapter explores adaptation opportunities, constraints, and limits from the context of social actors, which includes individuals, businesses, government agencies, or informal social groups.

An explicit focus on risk is particularly useful to understanding climate adaptation (Jones and Preston, 2011; Dow *et al.*, 2012b). Adaptation is intended to reduce the risk to assets or systems of value (Adger *et al.*, 2012b). The concept of risk integrates the dimensions of probability and uncertainty with the material and normative dimensions that shape societal responses to threats (Renn, 2008). Figure 16-1 relates judgements about risk and the ability to maintain risks at a tolerable level to the concept of adaptation and adaptation opportunities, constraints, and limits (Box 16-1). Drawing on the work of Klinke and Renn (2002), actors evaluate risks based on one of three categories – acceptable, tolerable, and intolerable. Acceptable risks are those deemed so low that additional efforts at risk reduction, in this case climate adaptation efforts, are not justified. Tolerable risks relate to situations where adaptive, risk management efforts are required and effective for risks to be kept within reasonable levels. The scope of risks that fall within the tolerable area is influenced by adaptation opportunities and constraints. Therefore, the categorization of risks varies across spatial, jurisdictional, and temporal. As discussed further later in this chapter, opportunities and constraints may be physical, technological, economic, institutional, legal, cultural, or environmental in nature [16.3; 16.5; 16.5; 16.6; 16.7]. Constraints may limit the range of available adaptation options creating the potential for residual damages for actors, species or ecosystems associated with specific regions or sectors. Under some circumstances, the risk of residual damage may be viewed as an acceptable or tolerable trade-off (Stern *et al.*, 2006; de Bruin *et al.*, 2009a).

[INSERT FIGURE 16-1 HERE
Figure 16-1: Conceptual model of the determinants of acceptable, tolerable, and intolerable risks and their implications for limits to adaptation (Dow *et al.*, 2013b, based on Klinke and Renn, 2002; also see Renn and Klinke 2013). In this conceptual diagram, adaptation efforts are seen as keeping risks to objectives within the tolerable risk space. Opportunities and constraints influence the capacity of actors to maintain risks within a tolerable range. The dotted lines indicate that individual or collective views on risk tolerance with respect to the frequency and intensity of climate-related risks are not fixed, but may vary and change over time. In addition, the shape or angle of the lines and the relative area in each section of the diagram are illustrative and may themselves change as capacities and attitudes change. The shaded areas represent the potential differences in perspective among actors.]

Intolerable risks may be related to threats to core social objectives associated with health, welfare, security or sustainability (Klinke and Renn 2002; Renn 2008; Dow *et al.*, 2013a, b). Risks become intolerable when practicable or affordable adaptation options to avoid escalating risks to such valued objectives or biophysical needs become unavailable. Therefore, a limit is a point when an intolerable risk must be accepted; the objective itself must be relinquished; or some adaptive transformation must take place to avoid intolerable risk. Such a discontinuity may take several forms such as individual's decision to relocate, an insurance company's decision to withdraw coverage, or a species' extinction. The alternative to such discontinuities is an escalating and unmediated risk of losses (Moser and Ekstrom 2010; 16.4.2). While individuals have their own perspectives about what are acceptable, tolerable or intolerable risks, collective judgements about risk are also codified through mechanisms such as engineering design standards, air and water quality standards, and legislation that establishes goals for regulatory action. There are also international agreements that establish norms and rights relevant to climate change risks (Knox, 2009; OHCHR, 2009; Crowley, 2011), such as the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights, and the International Covenant on Economic, Social and Cultural Rights. Further, these high level responses often shape the constraints and opportunities to adaptation and responses to risk at lower levels through the distribution of resources, institutional design, and support of capacity development (16.2; 16.3; 16.4.1). If these risks and discontinuities have global-scale consequences, they can be linked to 'key vulnerabilities' to climate change (19.6). Consistent with our framing of adaptation limits, such key vulnerabilities would need to be assessed in terms of the limits they imply for specific social actors, species and ecosystems.

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Box 16-1. Definitions of Adaptation Opportunities, Constraints, and Limits

Adaptation Opportunities: *Factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.* These factors enhance the ability of an actor(s) to secure their existing objectives, or for a natural system to retain productivity or functioning. For instance, increased public awareness and support for adaptation, availability of additional resources from actors at other levels of governance to overcome constraints and soft limits, and interest in acquiring co-benefits arising from adaptation strategies can all facilitate adaptation planning and implementation. Private sector efforts in research and development that can improve affordability, flexibility, or ease of implementation could also create opportunities (14.4.8). Such adaptation opportunities, sometimes also referred to as adaptation enablers, are distinct from opportunities arising from climate change (e.g., longer growing seasons), which are commonly referred to as potential benefits of climate change or adaptation options.

Adaptation Constraints: *factors that make it harder to plan and implement adaptation actions.* Adaptation constraints restrict the variety and effectiveness of options for an actor to secure their existing objectives, or for a natural system to change in ways that maintain productivity or functioning. These constraints commonly include lack of resources (e.g., funding, technology or knowledge) (16.3.2), institutional characteristics that impede action (16.3.2.8), or lack of connectivity and environmental quality for ecosystems (4.4). The terms 'barriers' and 'obstacles' are frequently used as synonyms. Constraints, alone or in combination, can drive an actor or natural system to an adaptation limit.

Adaptation Limit: *The point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions* (Adger *et al., 2*009; Moser and Ekstrom 2010; Dow *et al.*, 2013a, b; Islam *et al.*, 2014).

> *Hard Adaptation Limit: No adaptive actions are possible to avoid intolerable risks.*
> *Soft Adaptation Limit: Options are currently not available to avoid intolerable risks through adaptive action*

A limit to adaptation means that, for a particular actor, system, and planning horizon of interest, no adaptation options exist, or an unacceptable measure of adaptive effort is required, to maintain societal objectives or the sustainability of a natural system. Objectives include, for example, maintaining safety standards such as those codified in laws, regulations, or engineering design standards (*e.g.*, 1 in 500 year levees); security of air or water quality; as well as equity, cultural cohesion, and preservation of livelihoods. Requirements for sustaining natural systems might include temperature ranges or moisture availability. In the case of hard limits, no adaptation options are foreseeable, even when looking beyond the current planning horizon. For soft limits, however, adaptation options could become available in the future due to changing attitudes or values or as a result of innovation or other resources becoming available to an actor. For example, 31 Native Alaskan villages are facing "imminent threats" due to coastal erosion and at least 12 of the 31 have begun to explore relocation or have decided to partially or totally relocate (US GAO, 2009). In the case of these communities with minimum local revenue, the ability to relocate depends on the political and financial support of the U.S. federal government (Huntingon *et al.,* 2012). Therefore, limits are strongly influenced by relationships among public and private actors and institutions across different spatial, temporal, and jurisdictional scales (Cash *et al.*, 2006; 16.4.1).

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It is essential to evaluate opportunities, constraints, and limits with respect to both the rate and magnitude of climate change and the relevant time horizon for an actor, a species, or an ecosystem. Opportunities, constraints and limits to adaptation develop along a dynamic continuum (i.e., the dotted lines in Figure 16-1 can shift), together conditioning the capacity of natural and human systems to adapt to climate change. New opportunities for adaptation may emerge through time, constraints may be loosened, and some, although not all, limits that arise in the present may eventually be shifted or removed altogether. For a given social actor, the time horizon for adaptation decisions usefully bounds an analysis of opportunities, constraints and limits. For natural systems, the rate of species responses relative to changes in environmental conditions is a limit to the capacity to adapt (4.3.2.5; 4.4; 16.3.2.3; 16.4.1). The observed rate of evolutionary and other species responses ranges from rapid to inadequate to allow persistence (Hoffmann and Sgro, 2011).

Because adaptation limits relate to adaptation resources and attitudes to risk that may change over time, some limits may be viewed as 'soft' or time sensitive (16.4.1). While a given adaptation option may not be available today or require impracticable levels of effort, it may become available through innovation or changes in attitudes in time. Soft limits may be shifted by investments in research and development, changes in regulatory rules or funding arrangements, or by changing social or political attitudes (Park *et al., 2*012; Adger *et al., 2*013). Other limits are 'hard' or time insensitive in that there is no known process to change them (16.4.1). Examples of hard limits include water supply in fossil aquifers, limits to retreat on islands, and loss of genetic diversity.

16.3. Adaptation Opportunities and Constraints

Different actors, sectors, and geographic regions have differential capacities to adapt to climate variability and change (Adger *et al.*, 2007; IPCC, 2012) (*very high confidence*), although those capacities can be difficult to measure (Tol *et al.*, 2008; Hinkel, 2011). Since the AR4 (Adger *et al.*, 2007), the literature on the factors that contribute to adaptive capacity has deepened (Adger *et al.*, 2009; Moser and Ekstrom, 2010). This literature has evolved along two different pathways. One focuses on the range of opportunities that exist to facilitate adaptation planning and implementation. The other, which is also more extensive, focuses on describing the constraints that inhibit adaptation. Although they are sometimes treated in the literature as distinct, opportunities and constraints are complementary in that adaptive capacity is influenced jointly by the extent to which actors take advantage of available opportunities to pursue adaptation responses and the extent to which those actors or natural, unmanaged systems experience constraints. In addition, factors that are identified as constraints may also reveal valuable opportunities for adaptation interventions to build adaptive capacity.

While some level of generalization regarding opportunities and constraints that are common to different regions, sectors, communities, and actors is possible, the manner in which they manifest is context-dependent (Adger *et al.*, 2007; Orlove, 2009; Kasperson and Berberian, 2011; Weichselgartner and Breviere, 2011; IPCC, 2012) (*very high confidence*). For example, actors that frame adaptation as a process of capacity building or sustainable development may pursue different adaptation options with different opportunities and constraints compared with those that frame adaptation as largely addressing climate change impacts (McGray *et al.*, 2007; Fünfgeld and McEvoy, 2011). Adaptation researchers apply their own frameworks and heuristics that influence understanding of adaptation processes (Biesbroek *et al.*, 2013b; Preston *et al.*, 2013b). Therefore, one must be cautious in applying generic assumptions regarding adaptation opportunities and constraints in assessments of vulnerability and adaptive capacity or in the identification of appropriate adaptation responses (Adger and Barnett, 2009; Barnett and Campbell, 2009; Mortreux and Barnett, 2009). The recent adaptation literature suggests significant work remains in understanding such context-specific determinants of vulnerability and adaptive capacity and in effectively using the knowledge gained from available case studies to facilitate adaptation more broadly (Tol and Yohe, 2007; Klein, 2009; Smith *et al.*, 2010; Hinkel, 2011; Preston *et al.*, 2011b; Biesbroek *et al.*, 2013a). Therefore, the discussion of opportunities and constraints here should be considered in the context of the sectoral and regional synthesis (16.5) as well as the sector- and region-specific material on constraints and opportunities in other WGII chapters.

16.3.1. Adaptation Opportunities

16.3.1.1. Enabling Conditions for Adaptation

Adaptation opportunities represent enabling factors that enhance the potential for an actor to plan and implement actions to achieve their adaptation objective(s) or facilitate adaptive responses by natural systems to climate risk (Box 16-1). Therefore, an opportunity is distinct from an adaptation option, which is a specific means of achieving an adaptation objective (such as an early warning system as a means of reducing vulnerability to tropical cyclones) or a strategy for the conservation of an ecological system (14.3; Table 14-2). Adaptation opportunities described here also do not consider the potential beneficial consequences of climate change (Box 16-1), an issue addressed to varying degrees among the various sectoral and regional chapters.

[INSERT TABLE 16-1 HERE]
Table 16-1: Identification of key adaptation opportunities considered in this chapter. Each general type of opportunities is represented by multiple illustrative examples as well as supporting key references.*]*

Opportunities for adaptation range from increasing awareness of climate change, its consequences, and the potential costs and benefits of adaptation options to the implementation of specific policies that create conditions that are conducive to adaptation implementation. For example, rice is a key food crop, particularly in Asia in which 90% of rice is produced and subsequently consumed (Timmer, 2010). Multiple studies have identified rice as being particularly vulnerable to the effects of climate change including both temperature and water availability impacts (Papademetriou *et al.*, 2000). Therefore, planning and implementation of adaptive responses will be an important component of managing the risk of climate change to rice production (Howden *et al.*, 2007; Lobell *et al.*, 2008; Tilman *et al.*, 2011; Anwar *et al.*, 2013). A range of opportunities are available to support adaptation (Table 16-1; Table 16-3) (*very high confidence*). Hypothetically, these could include the use of analysis tools to better understand vulnerabilities and thresholds in rice and develop scenarios of future consequences. That information could then be communicated to farmers, national governments, and international agencies to increase awareness of potential risks. Policies can be used to incentivize adaptation including investments in biotechnology research to breed more resistant strains as well as field studies to identify potential new regions that might be appropriate for rice cultivation in the future.

Such opportunities exist for other agricultural commodities as well as other sectors and regions at risk from climate change (Box 16-2). For example, there is growing recognition of the potential for using disaster response and recovery processes as a means of increasing resilience to future extreme events (Lavell *et al.*, 2012). Meanwhile, case studies of Australian local governments as well as Inuit communities in the Arctic have identified a range of opportunities for building adaptive capacity and overcoming constraints (Smith *et al.*, 2008; Ford, 2009; Ford *et al.*, 2010). These include risk assessment, partnerships, establishment of monitoring and evaluation frameworks, developing finance mechanisms, and formal adaptation policy development.

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Box 16-2. A Case Study of Opportunities for Adaptation and Disaster Risk Reduction

Bangladesh has been identified as a region of South Asia that is particularly vulnerable to tropical cyclones (Ali, 1999; Mallick and Rahman, 2013), and this vulnerability is projected to increase due to climate change (Karim and Mimura, 2008; Dasgupta *et al.*, 2010). The nation’s response to this vulnerability illustrates the manner in which multiple opportunities can converge to facilitate adaptation and disaster risk reduction. The Cyclone Preparedness Program (CPP) was launched in the 1960s to establish a warning system in coastal regions (Habib *et al.*, 2012). The CPP has been continually improved in subsequent years with assistance from the International Federation of Red Cross and Red Crescent Societies and the International Foundation (Mallick and Rahman, 2013). A coastal reforestation program was also established in the 1960s to enhance natural buffers to storm surge (Mallick and Rahman, 2013; Box CC-EA). The Bangladesh Government initiated construction of cyclone shelters in the late 1980s, yet a cyclone in 1991 revealed that too few shelters were available (Bern *et al.*, 1991; Chowdhury *et al.*, 1993). This prompted collaboration between the government of Bangladesh, the United Nations Development Programme, and the World Bank to launch the Multipurpose Cyclone Shelter Program. That program characterized shelter needs along the coast and provided resources for their construction. In addition, shelter construction, which was concentrated around primary and secondary schools, coincided with national legislation requiring compulsory attendance in primary school, which required the construction of new schools. This created the opportunity for multi-purpose construction of buildings, reflecting the potential ancillary benefits that can arise from integrated planning (16.3.1.2).

More recently, Bangladesh has begun to focus on increasing the resilience of the built environment. This effort has focused on the development of disaster resilient habitat (Mallick and Rahman, 2007), where communities participate in the design and construction of resilient housing with support from international donors (Mallick *et al.*, 2008; Mallick and Rahman, 2013). This may be a more cost-effective strategy for both reducing mortality and property damage (Mallick *et al.*, 2008). The observed progress in reducing vulnerability to tropical cyclones is a function of various opportunities (awareness, assessment, policies, innovation, and capacity building) that have emerged over the past several decades that created conditions that enabled the implementation of specific policies, projects, and programs. Nevertheless, the additional risk posed by future climate change may necessitate further future investments (Dasgupta *et al.*, 2010).

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Sustainable economic development is a critical foundation for the creation of adaptation opportunities (20.2; 20.6), because it has the potential to build the capacity of individuals and organizations to adapt (*very high confidence*). Sustainable development is associated with increasing opportunities for research, training and education as well as for enhancing access to expertise and tools for assessment activities and decision-support. It also increases access to technologies that can enhance efficiencies. For example, water use in the United States has remained relatively constant since the mid-1980s, despite population growth, increases in agricultural yields, and expansion of electricity generation (Kenny *et al.*, 2009). Improvements in technology and management practice stimulated by innovation, education and learning have increased water use efficiency. This phenomenon may increase the resilience of U.S. water resources to climate change. Yet, these advances are a function of broader national and regional economic development trends. Therefore, future development pathways may have a significant influence on the opportunities for adaptation and therefore the adaptive capacity of adaptation actors (16.3.2.10; 20.6; Box 16-3).

16.3.1.2. Ancillary Benefits of Adaptation

Some adaptation options may offer ancillary benefits (or co-benefits) independent of their direct benefits with respect to reducing vulnerability to climate change (17.4) (*very high confidence*). The potential for ancillary benefits has two important implications for adaptation planning and implementation. First, their consideration may result in a more favorable assessment of the cost-effectiveness of a specific adaptation option (Hallegatte, 2009). Second, consideration of the ancillary benefits of adaptation may help in efficiently integrating adaptation into existing management and decision-making processes (Ahmed and Fajber, 2009; Dovers, 2010).

Such ancillary benefits may arise from adaptation responses in three ways:

- *Stimulating adaptation to current climate variability*: While it is generally assumed that physical, ecological and social systems are well-adapted to current climatic conditions; this is frequently not the case (Heyd and Brooks, 2009; Dugmore *et al.*, 2009). Increased awareness of the potential impacts of future climate change may, in some instances, lead to the implementation of adaptation options in order to reduce vulnerability or capitalize on opportunities (16.3.2.1) (*high agreement, medium evidence*). These options may have near-term ancillary benefits with respect to reducing vulnerability to current climate variability and extreme weather events (Füssel, 2008; Hallegatte, 2009; Ford *et al.*, 2010). On the other hand, future reductions in vulnerability to climate change can be perceived as ancillary benefits of near-term responses to current climate variability and natural disasters (Ziervogel *et al.*, 2010a, b). Hence, there may be some ambiguity with respect to what actors perceive as the primary versus ancillary benefit of a particular policy or measure.
- *Generation of climate adaptation goods and services*: Adaptation planning and implementation often may require additional knowledge and investment of resources. Adaptation therefore represents a potential economic opportunity for producers of goods and services used to satisfy adaptation needs (EBI, 2013) (*medium agreement, limited evidence*). Such services range from vulnerability assessment and risk analysis to the implementation of technology and engineering solutions. The Stern Review indicated that the market opportunities for new infrastructure and buildings resilient to climate change in OECD countries could be quite significant (Stern *et al.*, 2006). For example, the market for snow machines will be influenced by growing concerns about snow cover in more marginal ski resorts (Scott *et al.*, 2006). Higher elevation regions may see new opportunities as a result of snow resort shifts (Bark *et al.*, 2010). Likewise, increased risks associated with track buckling caused by higher summer temperatures may trigger innovation and

investment in new railway track and drainage systems (Bark *et al.*, 2010). Rising damage caused by climate change could provide new markets for innovative insurance products and other risk-based financial services (Botzen *et al.*, 2009; Botzen *et al.*, 2010) (*medium agreement, limited evidence*). However, these ancillary benefits must be weighed against the adverse impacts that create the market for such services.

- *Advancement of sustainable development*: As part of a larger portfolio of policies and measures, adaptation can assist in addressing existing development deficits while also meeting long-term sustainable development objectives (20.2, 20.6) (*very high confidence*). For example, policy options related to management of water and natural resources under a changing climate; the development of water, transportation, and communication infrastructure; and the promotion of credit and insurance services can promote economic development, increase adaptive capacity and reduce the impacts of climate change on the poor (Hertel and Rosch, 2010). Therefore, effective adaptation and climate risk management may be important enablers of sustainable economic development.

16.3.2. Adaptation Constraints

As discussed in the AR4 (Adger *et al.*, 2007), a number of factors constrain planning and implementation of adaptation options (*very high confidence*). More recent studies have documented an expanded range of constraints in a diverse array of contexts, but Biesbroek *et al.* (2013a) note that there is no consensus definition of constraints or a consistent framework for their assessment. Although constraints are often discussed in the literature as discrete determinants of adaptive capacity, they rarely act in isolation (Dryden-Cripton *et al.*, 2007; Smith *et al.*, 2008; Moser and Ekstrom, 2010; Shen *et al.*, 2011). Rather actors are challenged to navigate multiple, interacting constraints in order to achieve a given adaptation objective (Adger *et al.*, 2007; Dryden-Cripton *et al.*, 2007; Smith *et al.*, 2008; Shen *et al.*, 2008; Adger *et al.*, 2009; Jantarasami *et al.*, 2010; Moser and Ekstrom, 2010; Shen *et al.*, 2011; 16.3.2.10) (*very high confidence*). Multiple constraints can significantly reduce the range of adaptation options and opportunities available to actors and therefore may pose fundamental limits to adaptation (16.4) (*very high confidence*), and/or drive actors toward responses that may be maladaptive (Barnett and O'Neill, 2010; Eriksen *et al.*, 2011) (*medium agreement, limited evidence*).

16.3.2.1. Knowledge, Awareness, and Technology Constraints

The AR4 concluded that there are significant knowledge gaps and impediments to flows of information that can constrain adaptation, but knowledge in itself is not sufficient to drive adaptive responses (Adger *et al.*, 2007). These conclusions are echoed by more recent literature. Adaptation practitioners and stakeholders in both developed (Tribbia and Moser, 2008; Jantarasami *et al.*, 2010; Gardner *et al.*, 2010; Ford *et al.*, 2011; Milfont, 2012) and developing nations (Bryan *et al.*, 2009; Deressa *et al.*, 2009; Begum and Pereira, 2013; Pasquini *et al.*, 2013) continue to identify knowledge deficits as an adaptation constraint (*very high confidence*). Often this demand for more information is linked to concerns regarding decision-making under uncertainty about the future (Tribbia and Moser, 2008; Moser, 2010a; Whitmarsh, 2011; Stoutenborough and Vedlitz, 2013) (*medium agreement, medium evidence*). A broad range of guidance on adaptation planning and implementation continues to emerge as a means of empowering actors to pursue adaptation efforts (Clar *et al.*, 2013; EU, 2013; FAO, 2013; USCTI, 2013; Webb and Beh, 2013), and the World Meteorological Organization have emphasized the importance of climate services for vulnerability and disaster risk reduction (WMO, 2011).

A number of recent studies have investigated the extent to which education and knowledge about climate change influences perceptions of risk (Hamilton, 2011; McCright and Dunlap, 2011; Milfont, 2012). For example, studies suggest over-confidence in the ability of actors to manage risk (Wolf *et al.*, 2010; Kuruppu and Liverman, 2011) or differences in the perception of climate risk between actors and governing institutions (Patt and Schröter, 2008a) can constrain adaptation (*medium agreement, medium evidence*). Therefore, capacity building through education, training, and information access represents a valuable opportunity for adaptation (16.3.1.1).

Nevertheless, numerous recent studies caution that addressing knowledge deficits may not necessarily lead to adaptive responses (Tribbia and Moser, 2008; Kellstedt *et al.*, 2008; Adger *et al.*, 2009; Malka and Krosnick, 2009;

Moser, 2010b; Preston *et al.*, 2011b; Kahan *et al.*, 2012; Lemos *et al.*, 2012) (*very high confidence*). Research from the United States indicates that those most informed about science and climate change are not necessarily the most concerned about its potential consequences (Kellstedt *et al.*, 2008; Kahan *et al.*, 2012), although these findings run counter to research from New Zealand where increased knowledge translated into increased public concern and efficacy (Milfont, 2012). Recent research also indicates that multiple factors influence how knowledge is perceived including political affiliation (Hamilton, 2011; McCright and Dunlap, 2011), educational attainment (McCright and Dunlap, 2011), and the confidence placed on different information sources (Sundblad *et al.*, 2009). Various studies have questioned a common assumption in the climate change literature that improvements in climate information are needed to facilitate adaptation (Dessai *et al.*, 2009; Hulme *et al.*, 2009; Wilby and Dessai, 2010; Verdon-Kidd *et al.*, 2012; 2.3). Similarly, multiple authors have questioned the utility and robustness of vulnerability metrics and indices for informing adaptation decision-making (Barnett *et al.*, 2009; Klein, 2009; Hinkel, 2011; Preston *et al.*, 2011b).

Similar tensions arise with respect to the role of traditional knowledge in adaptation. For example, cultural preferences regarding the value of traditional versus more formal scientific forms of knowledge influence what types of knowledge, and therefore adaptation options, are considered legitimate (Jones and Boyd, 2011). In the Arctic, Inuit traditional knowledge (*Inuit Qaujimajatuqangit*, IQ) encompasses all aspects of traditional Inuit culture including values, world-view, language, life skills, perceptions and expectations (Nunavut Social Development Council, 1999; Wenzel, 2004). Inuit IQ includes, for example, weather forecasting, sea ice safety, navigation, hunting and animal preparation skills that are may have value for managing climate risk. Yet, as noted in the AR4 and more recent studies, these skills are declining among youth (Adger *et al.*, 2007; Pearce *et al.*, 2011) (*medium agreement, medium evidence*). Increasing reliance on non-traditional forecasting (national weather office forecasts) and other technologies (GPS) in Arctic communities is in part responsible for increased risk taking when travelling on the land and sea ice (Aporta and Higgs, 2005; Ford *et al.*, 2006; Pearce *et al.*, 2011) (*medium agreement, medium evidence*). Collectively, the recent literature suggests the extent to which knowledge acts to constrain or enable adaptation is dependent upon how that knowledge is generated, shared, and used to achieve desired adaptation objectives (Patt *et al.*, 2007; Nelson *et al.*, 2008; Tribbia and Moser, 2008; Moser, 2010a, b) (*very high confidence*).

Individual, institutional, and societal knowledge influences the capacity to develop and use technologies to achieve adaptation objectives (*very high confidence*) (UNFCCC, 2006; Adger *et al.*, 2007). The AR4 noted the role of technology in contributing to spatial and temporal heterogeneity in adaptive capacity and the potential for technology to constrain adaptation or create opportunities (Adger *et al.*, 2007). Key considerations with respect to technology as an adaptation constraint include a) availability; b) access (including the capacity to finance, operate and maintain); c) acceptability to users and affected stakeholders; and d) effectiveness in managing climate risk (Adger *et al.*, 2007; Dryden-Cripton *et al.*, 2007; van Aalst *et al.* 2008; 9.4.4; 11.7; 14.2.4; 15.3.2). Although technology has implications for regional adaptive capacity (e.g., 22.4.5.7; 27.3.6.2; 29.6.2), in-depth exploration of technology in the adaptation literature is often associated with specific sectors (Howden *et al.*, 2007; Bates *et al.*, 2008; van Koningsveld *et al.*, 2008; Parry *et al.*, 2009; US EPA, 2009; Zhu *et al.*, 2010). For example, Howden *et al.* (2007) note the importance of technology options for facilitating adaptation including applications of existing management strategies as well as introduction of innovative solutions such as bio- and nanotechnology (see also Hillie and Hlophe, 2007; Bates *et al.*, 2008; Fleischer *et al.*, 2011). Several studies from Africa have explored how different factors drive awareness, uptake and use of adaptation technologies for agriculture (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa *et al.*, 2009, 2011). While such literature identifies specific adaptation technology options, and in some cases the costs associated with their implementation, quantitative understanding of the extent to which improving technology will enhance adaptive capacity or reduce climate change impacts remains limited (Piao *et al.*, 2010).

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Box 16-3. Rates of Change as a Cross-Cutting Constraint

Future rates of global change will have a significant influence on the demand for, and costs of, adaptation (*very high confidence*). Since, the AR4, new research has confirmed the commitment of the Earth system to future warming (Lowe *et al.*, 2009; Armour and Roe, 2011; AR5 WGI 12.5) and elucidated a broad range of tipping points or ‘key vulnerabilities’ that would result in significant adverse consequences should they be exceeded (Lenton *et al.*, 2008;

Rockstrom *et al.*, 2009; Chapter 19). While the specific rate of climate change to which different ecological communities or individual species can adapt remains uncertain (16.3.2.3; 16.4.1), more rapid rates of change can constrain adaptation of natural systems (Hoegh-Guldberg, 2008; Gilman *et al.*, 2008; Maynard *et al.*, 2008; Allen *et al.*, 2009; Hallegatte, 2009; Malhi *et al.*, 2009a; Malhi *et al.*, 2009b; Thackeray *et al.*, 2010; Lemieux *et al.*, 2011; Fankhauser and Soare, 2013; 4.3.2.5; 5.5.5), particularly in the presence of other environmental pressures (Brook *et al.*, 2008) (*very high confidence*). Literature suggests that the near-term economic costs of societal adaptation may be substantial, and those costs increase incrementally over time as the climate changes (17.6.3). Therefore, higher rates or magnitudes of climate change may reduce the effectiveness of some adaptation options, and higher costs for adaptation may be incurred (New *et al.*, 2011; Stafford Smith *et al.*, 2011; Peters *et al.*, 2013; 16.6). However, more rapid rates of change may also create greater incentives for adaptation resulting in a faster pace of implementation (Travis and Huisenga, 2013).

Although rapid socioeconomic change, including economic development and technological innovation and diffusion, can enhance adaptive capacity (16.3.1), it can also pose constraints (20.3.2) (*very high confidence*). Globally, economic losses from climate extremes are doubling approximately every one to two decades due to increasing economic exposure (Pielke Jr. *et al.*, 2008; Baldassarre *et al.*, 2010; Bouwer, 2011; Gall *et al.*, 2011; Munich Re, 2011; IPCC, 2012; Preston, 2013). Such losses are associated with high interannual variability (Preston, 2013), but current trends are projected to continue in future decades (Pielke Jr., 2007; Montgomery, 2008; O'Neill *et al.*, 2010; UN, 2011; Preston, 2013; 10.7.3), although losses may decline relative to growth in GDP (IPCC, 2012). In addition, population growth and economic development can lead to greater resource consumption and ecological degradation (Alberti, 2010; Chen *et al.*, 2010; Raudsepp-Hearne *et al.*, 2010; Liu *et al.*, 2012), which can constrain adaptation in regions that where livelihoods are closely linked to ecosystem goods and services (Badjeck *et al.*, 2010; Marshall, 2010; Warner *et al.*, 2010; 16.3.2.3; CC-EA) (*very high confidence*). The adaptation literature also suggests that successful adaptation will be dependent in part upon the rate at which institutions can learn to adjust to the challenges and risks posed by climate change and implement effective responses (Adger *et al.*, 2009; Moser and Ekstrom, 2010; Stafford Smith *et al.*, 2011) (*very high confidence*).

_____ END BOX 16-3 HERE _____

16.3.2.2. Physical Constraints

The capacity of human and natural systems to adapt to a changing climate is linked to characteristics of the physical environment including the climate itself. Recent studies have suggested that the effort required to adapt to an increase in global mean temperature of 4°C by 2100 may be significantly greater than adapting to lower magnitudes of change (Fung *et al.*, 2011; Gemenne, 2011; New *et al.*, 2011; Nicholls *et al.*, 2011; Stafford Smith *et al.*, 2011; Thornton *et al.*, 2011; Zelazowski *et al.*, 2011; 19.5.1) (*very high confidence*). This challenge arises from the magnitude of climate change, as well as the rate (Box 16-3).

A variety of non-climatic physical factors also can constrain adaptation efforts of natural systems (*very high confidence*). For example, migration can be constrained by geographical features such as lack of sufficient altitude to migrate vertically or barriers posed by coastlines or rivers (Clark *et al.*, 2011). Alternatively, Lafleur *et al.* (2010) identify soil conditions as a factor that may influence the migration of North American forests in response to climate change. Such physical barriers to migration can also arise from human activities. Feeley and Silman (2010) note that anthropogenic land use change can constrain the migration of Andean plant species to higher altitudes. Meanwhile, Titus *et al.* (2009) analyze state and local land use plans along the U.S. Atlantic coast and conclude that approximately 60% of coastal land below 1 meter in elevation is anticipated to be developed in the future, posing a physical barrier to inland migration of wetlands (see also Bulleri and Chapman, 2010; Jackson and McIlvenny, 2011). Collectively, such physical constraints can reduce available migration corridors and the distances over which migration is a feasible adaptive response.

Physical constraints have important implications for human adaptation as well (*high agreement, medium evidence*). For example, the distribution and abundance of water is a feature of the physical environment that is influenced by climate. Human consumption of freshwater increasingly is approaching the sustainable yield of surface and groundwater systems in a number of global regions (Shah, 2009; Pfister *et al.*, 2009, 2011a, b; 3.3.2; 3.5). Water-dependent enterprises in such regions may therefore have reduced flexibility to cope with transient or long-term reductions in water supply. This in turn influences the portfolio of adaptation actions that can be implemented effectively to manage risk to water security and, subsequently, agriculture and food security (Hanjra and Qureshi, 2010) as well as energy security (Voinov and Cardwell, 2009; Dale *et al.*, 2011). Similarly, water quality and soil quality can constrain agricultural activities and therefore the capacity of agricultural systems to adapt to a changing climate (Delgado *et al.*, 2011; Kato *et al.*, 2011; Lobell *et al.*, 2011; Olesen *et al.*, 2011).

It is important to note, however, that these physical characteristics of the environment are often amenable to management (*very high confidence*). The AR4 presented case studies where adaptive capacity was linked to the ability of human populations or communities to access physical capital (Adger *et al.*, 2007), such as machinery or infrastructure, to manage the environment and associated risks. Similar findings have appeared in more recent studies (Paavola, 2008; Thornton *et al.*, 2008; Iwasaki *et al.*, 2009; Badjeck *et al.*, 2010; Nelson *et al.*, 2010a, b). Human modification of the physical environment is particularly apparent in urban areas, where the location and design of buildings and infrastructure influence vulnerability to climate variability and change (8.2.2.2). However, past decisions regarding the built environment and its need for continual maintenance can constrain future adaptation options and/or their costs of implementation (16.3.2.10).

16.3.2.3. Biological Constraints

Since the AR4, the literature on biological (including behavioural, physiological, and genetic) tolerances of individuals, populations, and communities to climate change and extremes has continued to expand (4.4; 5.5.5; 6.2). This has resulted in a significant increase in the number of studies describing mechanisms by which biological factors can constrain the adaptation options for humans, non-human species, and ecological systems more broadly. In particular, biological characteristics influence the capacity of organisms to cope with increasing climate stress in situ through acclimation, adaptation, or behavior (Jensen *et al.*, 2008; Somero, 2010; Tomanek, 2010; Aitken *et al.*, 2011; Gale *et al.*, 2011; Sorte *et al.*, 2011; Donelson *et al.*, 2011) as well as the rate at which organisms can migrate to occupy suitable bioclimatic regions (Hill *et al.*, 2011; Morin and Thuiller, 2009; Feeley *et al.*, 2012) (*very high confidence*). Studies of humans also find age and geographic variation among populations with respect to perceptions of thermal comfort in indoor and outdoor space, which in turn influences the use of technologies (e.g., air conditioning, vegetation) and behaviour to adjust to the thermal environment (Indraganti, 2010; Chen and Chang, 2012;Yang *et al.*, 2012; Fuller and Bulkeley, 2013; Müller *et al.*, 2013).

The biological capacity for migration among non-human species is linked to characteristics such as fecundity, phenotypic and genotypic variation, dispersal rates, and interspecific interactions (Aitken *et al.*, 2008; Engler *et al.*, 2009; Hellmann *et al.*, 2012). For example, Aitken *et al.* (2008) argue that migration rates of tree species necessary to track a changing climate are higher than what has been observed since the last glaciation. However, Kremer *et al.* (2012) note that long-distance gene flow of tree species can span distances in one generation that are greater than habitat shifts predicted under climate change. Additional research is needed to clarify the capacity of species and communities to migrate in response to a changing climate.

The degradation of environmental quality is another source of constraints (Côté and Darling, 2010) (*very high confidence*), with multiple studies including natural capital as a foundation for sustainable livelihoods (Paavola, 2008; Thornton *et al.*, 2008; Iwasaki *et al.*, 2009; Badjeck *et al.*, 2010; Nelson *et al.*, 2010a, b). Non-climatic stresses to ecological systems can reduce their resilience to climate change as evidenced by studies on coral reefs and marine ecosystems, tropical forests, and coastal wetlands (Malhi *et al.*, 2009a, b; Diaz and Rosenberg, 2008; Kapos and Miles, 2008; Afreen *et al.*, 2011) (*very high confidence;* 4.2.4; CC-CR). For example, several studies have noted interactions between anthropogenic land use change and species migration rates on the risk of extirpation (Feeley *et al.*, 2010; Yates *et al.*, 2010; Cabral *et al.*, 2013; Svenning and Sandel, 2013).

Ecological degradation also reduces the availability of ecosystem goods and services for human populations (Nkem *et al*, 2010; Tobey *et al.*, 2010; 4.4.3; 6.4.1; (*very high confidence*). For example, degradation of coastal wetlands and coral reef systems may reduce their capacity to buffer coastal systems from the effects of tropical cyclones (Das and Vincent, 2009; Tobey *et al.*, 2010; Gedan *et al.*, 2011; Keryn *et al.*, 2011; Box CC-EA). Similarly, soil degradation and desertification can reduce crop yields and the resilience of agricultural and pastoral livelihoods to climate stress (Iglesias *et al.*, 2011; Lal, 2011).

Ecosystem constraints can also arise from non-native species, including pests and disease, that compete with endemic species (Hellman *et al.*, 2008; Dukes, *et al.*, 2009; Moser *et al.*, 2011; Ziska *et al.*, 2011; Pautasso *et al.*, 2012; Svobodová *et al.*, 2013) (4.2.4.6). Climate change could reduce the effectiveness of current control mechanisms for invasive species (Hellmann *et al.*, 2008) (*very low confidence*). However, studies also indicate that uncertainty associated with predictions of future pests, disease, and invasive species remains high (Dukes *et al.*, 2009).

16.3.2.4. Economic Constraints

The AR4 concluded that adaptive capacity is influenced by the entitlements of actors to economic resources and by larger macro-level driving forces such as economic development and trends in globalization (Adger *et al.*, 2007). More recent literature continues to identify economic constraints associated with adaptation. However, such constraints are often associated with the financing of discrete adaptation options (e.g., Matasci *et al.*, 2013; Islam *et al.*, 2014). This chapter draws a distinction between such financial constraints (16.3.2.5) and economic constraints, which are associated with broader macroeconomic considerations.

Long-term trends in economic development as well as short-term dynamics in economic systems can have a significant influence on the capacity of actors to adapt to climate change (*very high confidence*) (16.3.1.1). Multiple authors, for example, discuss the concept of 'double exposure' where actors are subjected to stresses associated with climate change as well as those associated with economic disruptions such as the recent global financial crisis or other stresses (Leichenko *et al.*, 2010; Silva *et al.*, 2010; Leichenko, 2012; Jeffers, 2013; McKune and Silva, 2013). Similarly, Kiem and Austin (2013) argue that prevailing economic conditions have an important influence on the capacity of Australian farmers to cope with drought.

The implications of economic constraints vary among different sectors that have differential vulnerability to climate change. Economies that are disproportionately comprised of climate-sensitive sectors such as agriculture, forestry and fisheries, may be particularly vulnerable to the effects of climate change and may encounter greater constraints on their capacity to adapt (*very high confidence*). Such economies occur disproportionately in the developing world (Thornton *et al.*, 2008; Allison *et al.*, 2009; Feng *et al.*, 2010; Füssel, 2010), although multiple studies have explored climate-sensitive regional economies in developed nations as well (Edwards *et al.*, 2009; Aaheim *et al.*, 2012; Leichenko *et al.*, 2010; Kiem and Austin, 2013). Poverty and development deficits that are linked to economic conditions also exist in urban areas (8.1.3; 8.3.2.1).

While economic development and diversification are generally seen as factors that can ameliorate resource deficits (20.2.1.2; 20.3.2), certain economic enterprises can constrain adaptation. For example, the AR4 noted that activities such as shrimp farming and conversion of coastal mangroves, while profitable in an economic sense, can exacerbate vulnerability to sea-level rise (Agrawala *et al.*, 2005 in Adger *et al.*, 2007). More recent studies have demonstrated that economic development and urbanization of hazardous landscapes may increase human exposure to extreme weather events and climate change resulting in greater economic losses and risks to public health and safety (Baldassare *et al.*, 2010; IPCC, 2012; Preston, 2013). Economic development also can put pressure on natural resources and ecosystems that can constrain their capacity to adapt (Titus *et al.*, 2009; Sydneysmith *et al.*, 2010; 16.3.2.3; 20.3.2). The extent to which economic development creates opportunities or constrains adaptation is dependent on the development pathway (17.4.3; 20.6). Low resource-intensive economic growth can enhance adaptive capacity while minimizing externalities of development that can increase vulnerability of human and natural systems (20.6).

16.3.2.5. Financial Constraints

In addition to broader macroeconomic constraints on adaptation (16.3.2.4), the implementation of specific adaptation strategies and options can be constrained by access to financial capital (*very high confidence*). Financial capital can manifest in a variety of forms including credit, insurance, tax revenues, as well as earnings of individual households or private entities. The AR4 concluded that the global costs of adaptation could be quite substantial over the next several decades (Adger *et al.*, 2007). More recent studies suggest costs on the order of $75 to $100 billion per year by 2050 (17.6; Table 17-2). In the context of the UNFCCC, mechanisms have been established to help meet these costs. The Least Developed Country Fund was established to assist developing nations in developing National Adaptation Plans of Action (14.5.4; 15.2.2.1; 15.2.2.2). The Adaptation Fund was established within the context of the UNFCCC to finance adaptation in developing nations through the sale of certified emissions reductions credits (CERs) under the Clean Development Mechanism (14.3.2; 15.2.2.1). Nevertheless, declines in CER prices since early 2011 have reduced the flow of revenue to the Adaptation Fund (Adaptation Fund Board, 2013), and the demand for adaptation finance in general is larger than the current availability of resources represented through these funds (Bouwer and Aerts, 2006; Flåm and Skjærseth, 2009; Hof *et al.*, 2009). Furthermore, developing a framework for the equitable and effective allocation of adaptation funds to developing nations is a non-trivial challenge (Barr *et al.*, 2010; Smith *et al.*, 2009a).

Overseas development assistance (ODA) represents another mechanism for channeling financial capital into adaptation programs and projects. However, multiple authors have identified potential constraints associated with the use of ODA for financing adaptation including concerns among donors for the effectiveness of ODA (Kalirajan *et al.*, 2011), lack of incentives among donors to allocate ODA to adaptation (Buob and Stephan, 2013), and potential for allocation of ODA to adaptation to reduce the availability of funds for achieving development goals (Ayers and Huq, 2009).

The potential for finance to constrain adaptation also emerges from a broad range of recent case studies exploring adaptive capacity in different sector and regional contexts, although finance is often identified as just one of a broad range of resource constraints (Paavola, 2008; Jantarasami *et al.*, 2010; Moser and Ekstrom, 2010; Osbahr *et al.*, 2010; Biesbroek *et al.*, 2013a). Investigations of farming communities in Africa have identified finance as a key determinant of vulnerability and adaptive capacity of farmers to climate variability and change (Nhemachena and Hassan, 2007; Hassan and Nhemachena, 2008; Deressa *et al.*, 2009, 2011). Islam *et al.* (2014) cite access to credit as a key constraint on adaptation among fishing communities in Bangladesh, and financial constraints have also been documented in municipal governments in South Africa (Pasquini *et al.*, 2013). Huntington *et al.* (2012) question whether relocating the 184 Alaskan Native villages threatened by coastal erosion and inundation is politically feasible given the high costs, estimated at up to $1 million per person or $100 million per village on average.

Institutions in developed nations face constraints in funding adaptation options despite their comparatively high adaptive capacity. For example, Jantarasami *et al.* (2010) report that staff from U.S. federal land management agencies identified resource constraints as a key barrier to adaptation. Similarly, surveys and interviews with state and local government representatives in Australia indicate that the costs of investigating and responding to climate change are perceived to be significant constraints on adaptation at these levels of governance (Smith *et al.*, 2008b; Gardner *et al.*, 2010; Measham *et al.*, 2011). However, Burch (2010) argues that financial constraints on adaptation reported by local governments in Canada are secondary to other institutional practices and cultures (16.3.2.8).

Insurance represents a cross-cutting financial instrument that is relevant to a range of public and private institutions in both developing and developed nations. While insurance can represent an opportunity to influence decision-making regarding climate risk management (Næss *et al.*, 2005; Herweijer *et al.*, 2009; 10.7), reduced accessibility and/or increased costs of insurance can constrain the utility of insurance as an adaptation option (Herwijer *et al.*, 2009; Islam *et al.*, 2014; 10.7).

16.3.2.6. Human Resource Constraints

The effectiveness of societal efforts to adapt to climate change is dependent upon humans who are the primary agents of change (*very high confidence*). Human resources provide the foundation for intelligence gathering, the uptake and use of technology, as well as leadership regarding the prioritization of adaptation policies and measures and their implementation. Although the AR4 and subsequent adaptation literature identify human resources as one of the factors influencing adaptive capacity (Adger *et al.*, 2007), there has been little attention given specifically to human resources as a constraint on adaptation by adaptation researchers. Rather the literature mentions human resources in two principle contexts. First, it highlights the linkages between the development of human resources and adaptive capacity more broadly. For example, Ebi and Semenza (2008) treat human resources as part of the portfolio of resources that can be harnessed to facilitate adaptation in the public health arena. Similarly, Nelson *et al.* (2010a, b) use human capital as one indicator of the capacity of rural communities to cope with climate impacts. In addition, a number of recent studies call attention to the role of leadership in enabling or constraining organisational adaptation (Gupta *et al.*, 2010; Tompkins *et al.*, 2010; Termeer *et al.*, 2012; van der Berg *et al.*, 2010). Murphy *et al.* (2009) discuss the emergence of institutions to build human resources in the climate change arena, including expanded higher education opportunities to build climate expertise as well as professional societies. Second, the literature highlights the finite nature of human resources as a need to prioritize adaptation efforts including the extent of engagement in participatory processes (van Aalst *et al.*, 2008) as well as the selection of adaptation actions for implementation (Millar *et al.*, 2007).

16.3.2.7. Social and Cultural Constraints

Adaptation can be constrained by social and cultural factors that are linked to societal values, world views, and cultural norms and behaviors (O'Brien, 2009; Moser and Ekstrom, 2010; O'Brien and Wolf, 2010; Hartzell-Nichols, 2011) (*very high confidence*). These social and cultural factors can influence perceptions of risk, what adaptation options are considered useful and by whom, as well as the distribution of vulnerability and adaptive capacity among different elements of society (Grothmann and Patt, 2005; Weber, 2006; Patt and Schröter, 2008; Kuruppu, 2009; Adger *et al.*, 2009; O'Brien, 2009; Nielsen and Reenberg, 2010; Wolf and Moser, 2011; Wolf *et al.*, 2013). Although the AR4 noted that social and cultural constraints on adaptation have not been well researched, more recent literature has significantly expanded their understanding. As a case-in-point, the erosion of traditional knowledge among the Arctic Inuit is the consequence of a long-term process of changing livelihoods, technology, and sources of knowledge (Pearce *et al.*, 2011; 16.3.2.1). Studies from the United States indicate that increasing demand for amenity lifestyles is resulting in the settlement of individuals in locations where there is little experience or oral history regarding natural hazards – a phenomenon that subsequently influences risk perception and engagement in risk management (Heyd and Brooks, 2009; Gordon *et al.*, 2013).

Different actors within and among societies experience different constraints, which result in differential adaptive capacities and preferences for adaptation options (Wolf *et al.*, 2013). As discussed in the AR4, for example, gender can be a factor that constrains adaptation. Recent studies from Nepal and India report that adaptation decisions among women, in particular, can be constrained by cultural and institutional pressures that favor male land ownership (Jones and Boyd, 2011) and constrain access to hazard information (Ahmed and Fajber, 2009), respectively. Studies of evacuation during hurricane Katrina suggest that females were more likely to evacuate New Orleans than males (Brunsma *et al.*, 2010), as were individuals without sufficient resources and access to transportation (Cutter and Emrich, 2006). Studies from both the United States and United Kingdom find that the elderly do not necessarily perceive themselves as vulnerable to extreme heat events (Sheridan, 2007; Wolf *et al.*, 2009), which may create disincentives to react to such events (Chapter 11).

Barriers to taking action have also been attributed to sense of place, which shapes individual identity (Adger *et al.* 2011; 2012; Fresque-Baxter and Armitage, 2012). Foresight (2011) notes that processes that constrain migration could be maladaptive, resulting in the abandonment of livelihoods or geographic locations. For example, Park *et al.* (2012) find that sense of place attachment among some wine grape growers in Australia precludes consideration for migration to other growing areas in response to a changing climate.

Case studies from multiple developing countries report that some actors view natural phenomena as being controlled by God, supernatural forces, or ancestral spirits which are not amenable to human management (Sehring, 2007; Schipper, 2008; Byg and Salick, 2009; Mustelin *et al.*, 2010; Kuruppu and Liverman, 2011; Artur and Hilhorst, 2012). Such perspectives are not confined to the developing world. Surveys conducted after Hurricane Katrina also indicated that religious beliefs were a factor influencing the decision to remain rather than evacuate (Brunsma *et al.*, 2010).Yet, religion was also identified as a factor that enabled affected individuals to cope with the stress of the event.

16.3.2.8. Governance and Institutional Constraints

Research conducted since the AR4 has expanded understanding of adaptation constraints associated with governance, institutional arrangements, and legal and regulatory issues. Adaptation to climate change will necessitate the mobilization of resources, decision-making, and the implementation of specific policies by societal institutions (Huang *et al.*, 2011). Yet, these processes may be most effective when they are aligned to the given context and group of actors (Berkhout, 2012; Garschagen, 2013). The adaptation literature provides extensive evidence that institutional capacity is a key factor that can potentially constrain the adaptation process (Berkhout, 2012) (*very high confidence*). Lesnikowski *et al.* (2013), for example, find that planned adaptation by the public health sector among different nations is significantly associated with national GDP. Similarly, it's been argued that U.S. institutions across different levels of governance lack the mandate, information, and/or professional capacity to select and implement adaptation options (NRC, 2009). Institutional capacity may be linked to the level of priority assigned to adaptation (Keskitalo *et al.*, 2010; Westerhoff *et al.*, 2010; Measham *et al.*, 2011; Sowers *et al.*, 2011; Maibach *et al.*, 2011). For example, Ebi *et al.* (2009) argue that U.S. public health agencies allocate less than US$3 million per year to address climate change, yet a budget greater than US$200 million is needed to adequately address the problem. Keskitalo (2010) and Lesnikowski *et al.* (2013) find that adaptation efforts are associated with the extent to which institutions prioritize environmental management more broadly. Corruption within institutions may also undermine adaptation efforts, as evidenced by empirical studies among multiple nations (Lesnikowski *et al.*, 2013), as well as case studies within nations (Schilling *et al.*, 2012)

A key role that institutions play in facilitating adaptation is through legal and regulatory responsibilities and authorities (*very high confidence*). Multiple studies have documented the adaptation constraints affecting institutions in Australia engaged in the development of local and regional planning policy (Pini *et al.*, 2007; Measham *et al.*, 2011; Matthews, 2013). Similar capacity constraints have been observed within institutions governing Canada's Inuit population (Ford *et al.*, 2010). Li and Huntsinger (2011) observe how increasing land privatization and the institutionalization of rigid land tenure in the Inner Mongolia region of China have reduced the resilience of pastoralists to cope with drought, although the lack of secure land tenure has been found to constrain adaptation in other contexts (Almansi, 2009; Ebi *et al.*, 2011; Hisali *et al.*, 2011; Larson, 2011; 8.4.2.2; 9.3.5.2.3). In addition to such capacity issues, multiple studies from both developed and developing nations suggest that the current structure of institutions and regulatory policies may be poorly aligned to achieve adaptation objectives (Craig, 2010; Spies, 2010; Stillwell *et al.*, 2010; Stuart-Hill and Schulze, 2011; Eisenack and Stecker; 2012; Huntjens *et al.*, 2012; Herrfahrdt-Pähle, 2013), Changing legal principles to accommodate more forward-looking adaptation responses as opposed to basing them on historical precedent and practice may be a difficult process (Craig, 2010; McDonald, 2011).

Adaptation can also be constrained due to the complexities of governance networks that often comprise multiple actors and institutions such as government agencies, market actors, non-governmental organizations, as well as informal community organizations and social networks (Rosenau, 2005; Adger *et al.*, 2009; Juhola and Westerhoff, 2011; Carlsson-Kanyama *et al.*, 2013; Sosa-Rodriguez, 2013) (*very high confidence*). Coordination among these different actors is important for facilitating adaptation decision-making and implementation (Young, 2006; van Nieuwaal *et al.*, 2009; Grothmann, 2011). Yet, different actors may have different objectives, jurisdictional authority, as well as levels of power or resources. Adaptation efforts may recognize these constraints, but don't necessarily articulate institutional arrangements that facilitate their coordination and reconciliation to achieve common adaptation objectives (Zinn, 2007; Preston, 2009; Birkmann *et al.*, 2010; 15.3.1). This may arise, in part, from the dominant focus of the adaptation discourse on formal, public institutions of governance (Eisenack *et al.*, 2012), although work examining the role of private institutions has emerged recently (Tompkins *et al.*, 2010; CDP, 2012; Mees *et al.*, 2012; Taylor *et al.*, 2012; Tompkins and Eakin, 2012; EBI, 2013; 14.4.8).

Actors and institutions associated with different scales may have different perceptions of the need for adaptation as well as the factors that constrain or enable adaptation (Biesbroek *et al.*, 2011) (*very high confidence*). In this context, scale refers to analytical dimensions used to study adaptation (including spatial, temporal, institutional or jurisdictional), and each scale can be comprised of multiple levels (e.g., local to global in the context of spatial scales or household to central government in the context of jurisdictions of governance) (Cash *et al.*, 2006; Adger *et al.*, 2009). A large number of studies have emerged since the AR4 that focus on how local adaptation efforts are constrained by higher levels of governance, such as state or federal governments or private companies (Urwin and Jordan, 2008; Huntjens *et al.*, 2010; Abel *et al.*, 2011; Measham *et al.*, 2011; Pittock, 2011; Westerhoff *et al.*, 2011; Amaru and Chhetri, 2013; Carlsson-Kanyama *et al.*, 2013; Mukheibir *et al.*, 2013; Sosa-Rodriguez, 2013). This has led some to question whether it is appropriate to consider adaptation as an exclusively local process (Burton *et al.*, 2008; Preston *et al.*, 2013b). For example, a study of adaptation policy initiatives in EU member countries concluded that central governments can play a significant role in supporting local adaptation policies. However, in cases where there is weak top down leadership on adaptation, it may be useful to have less centralized mechanisms for supporting local adaptation efforts (Keskitalo, 2010). In addition, EU funding has enabled local adaptation even in the absence of funding from the relevant EU member state (Keskitalo, 2010), suggesting opportunities exist for trans-national governance to overcome adaptation constraints. Other authors have also noted that informal social institutions may help to extend the reach of formal government actors (Wolf *et al.*, 2010; Juhola and Westerhoff, 2011) or drive adaptation processes when formal actors are unable to do so (Measham and Preston, 2012). Adaptation planning and implementation thus creates new governance challenges, and new institutions and bridging organizations may be needed to facilitate integration of complex planning processes across scales (Preston, 2009; NRC, 2010; UKCIP, 2011) (*high agreement, medium evidence*).

16.3.2.9. Constraints and Competing Values

A number of the aforementioned types of adaptation constraints arise from a common cause – the differential values of societal actors and the trade-offs associated with prioritizing and implementing adaptation options (Haddad, 2005; UNEP, 2011; 2.3.3; Table 16-2) (*very high confidence*). At the international level, for example, agreements such as the Bali Action Plan (UNFCCC, 2007a) and Cancun Adaptation Framework (UNFCCC, 2011) indicate that deliberation over how the adaptation needs of least developed countries will be financed has become central to the UNFCCC policy agenda (see also UNFCCC, 2007b; Ayers and Huq, 2009; Dellink *et al.*, 2009; Flåm and Skjærseth, 2009; Denton, 2010; Patt *et al.*, 2010a). Yet the extent to which the developed world bears responsibility for compensating the developing world for climate impacts has been a contentious issue (Hartzell-Nichols, 2011). Rayner and Jordan (2010) and Brouwer *et al.* (2013) report concern among EU water policy-makers that adaptation may undermine efforts to maintain water quality. For example, technological solutions to enhance water supply in a changing climate may occur at the expense of water quality. Alternatively, placing adaptation on the policy agenda may create the perception that climate change will eventually necessitate the acceptance of reduced water quality. At the local level, Measham *et al.* (2011) report that some local governments in Australia find it difficult to pursue adaptation efforts due to perceived conflicts between potential adaptation options and the values and preferences of individuals and stakeholder groups within the community.

Such potential differences among stakeholders regarding adaptation options may result in some actions being simultaneously perceived as adaptive and maladaptive (Bardsley and Hugo, 2010) (*medium agreement, limited evidence*). Maladaptation arises from the implementation of adaptation options that increase the vulnerability of individuals, institutions, sectors, or regions (Barnett and O'Neill, 2010). Individuals or institutions may have specific management objectives or values that they seek to achieve or maintain through adaptation (16.2, Table 16-2). For every objective, however, there may be multiple adaptation options, each of which is associated with a particular set of costs, benefits, and externalities. For example, biotechnology may contribute to the development of drought and pest resistant cultivars that can maintain or enhance yields despite more challenging climate conditions. Yet, ecological and public health concerns over the use of biotechnology and genetically modified crops, in particular, can constrain the use of such technologies (Table 16-2). Agricultural producers may view biotechnology as an adaptive response, while some consumers may view it as a maladaptation that increases risks to ecosystems and food security. Similar types of trade-offs can be identified across different sectors (Table 16-2), and thus a challenge in adaptation planning and implementation is determining who decides what options are adaptive or maladaptive and successful or unsuccessful. The potential for maladaptation or for some adaptation options to undermine sustainability (Eriksen *et al.*, 2011), suggests that actors may choose to regulate adaptation and deliberately constrain possible options to avoid adverse externalities (*very low confidence*).

Recognizing the potential for values conflicts to constrain adaptation, researchers and practitioners have advocated for so-called ‘no regrets’ or ‘low regrets’ adaptation strategies that create net benefits under the current climate as well as a range of future potential climates (Hallegatte, 2009; Heltberg *et al.*, 2009). Such strategies can focus adaptation efforts on options where there are fewer perceived trade-offs (Preston *et al.*, 2013b). However, identifying options that are perceived as having no regrets across all potential stakeholders may be quite difficult (Merz *et al.*, 2010; Preston *et al.*, 2013b), and it has been suggested such strategies may reduce the perceived need for more substantive adaptations necessary to protect highly vulnerable systems or avoid irreversible consequences (Preston *et al.*, 2013b). Reconciling such trade-offs may necessitate deliberation among decision-makers and other stakeholders regarding adaptation objectives and the manner in which competing or conflicting values can be reconciled to achieve outcomes (McNamara and Gibson, 2009; de Bruin *et al.*, 2009b; McNamara *et al.*, 2011; UNEP, 2011).

[INSERT TABLE 16-2 HERE
Table 16-2: Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.]

16.3.2.10. Consideration of Cross-Scale Dynamics

The AR4 noted that adaptation processes can be constrained by interactions and dynamics within or among different scales (Adger *et al.*, 2007). Recent literature since the AR4 has expanded understanding of vulnerability and adaptive capacity as a cross-scale and multi-level process (16.3.2.8). The vulnerability of different communities, regions, and sectors are linked through processes and feedbacks that span multiple scales and levels (*high agreement, medium evidence*). Adger *et al.* (2008) and Eakin *et al.* (2009) refer to this phenomenon as “nested and teleconnected vulnerability.”

A number of recent studies focused on agriculture and global commodities provide evidence of this phenomenon, (see also 16.3.2.8). Adger *et al.* (2008) and Eakin *et al.* (2009) illustrate such teleconnected vulnerability with case studies of coffee production. Although coffee is a global commodity, the majority of production occurs in developing nations among small-scale farmers. As such, household vulnerability and adaptive capacity among coffee farmers is linked to global markets and coffee prices as well as local environmental conditions and policies. Such interactions were also apparent in 2006–2008 and again in 2010–2011 when global food commodity prices increased sharply in part due to the impacts of extreme weather events on food producing regions (FAO, 2011). The resulting increase in food prices benefited producers that were unaffected by the drought who were able to capitalize on higher prices, but higher prices adversely affected consumer welfare and food security (Abbott and de Battisti, 2009; Woden and Zaman, 2009; FAO, 2011). Similar constraints on adaptation arise in the context of transboundary water resources where river management is influenced by processes occurring at different jurisdictional levels (i.e., local, regional, national, and international water policies and management practice) as well as different spatial levels (e.g., linkages between global climate change and climate trends at more regional or local levels) (Iglesias *et al.*, 2007; Goulden *et al.*, 2009; Krysanova *et al.*, 2010; Huntjens *et al.*, 2010; Timmerman *et al.*, 2011; Wilby and Keenan, 2012; Milman *et al.*, 2013).

Constraints on adaptation are also associated with temporal scaling. A key factor constraining future adaptation options and costs is path dependence (*very high confidence),* which Preston (2013, pg. 719) defines as “*the dependence of future societal decision processes and/or socio-ecological outcomes on those that have occurred in the past*.” Libecap (2010) suggests that water infrastructure developed in the U.S. West in the late-19th and early 20th centuries has constrained management choice regarding water allocation in the present. Chhetri *et al.* (2010) suggest similar constraints may exist for the U.S. agricultural industry in the future due to constraints on farmers' capacity to alter management practices and technology in response to a changing climate. Major development of water management and allocation systems in watersheds of Australia and the U.S. Southeast over the latter half of the 20th century occurred during periods of favorable rainfall relative to long-term instrumental and paleo records (Jones and Pittock, 2002; Jones, 2010; Chiew *et al.*, 2011; Pederson *et al.*, 2012), and thus those systems were adapted to conditions that were not representative of the long-term risk of extensive drought (Jones and Pittock, 2002; Jones, 2010; Connell and Grafton, 2011; Pederson *et al.*, 2012).

Adjusting large-scale, complex systems and institutional behavior established by past decision-making can be costly. The Australian Government, for example, has engaged in a water management reform process since the 1980s (Connell and Grafton, 2011), and in recent years has committed more than AUS$12.9 billion for a number of initiatives to address historical resource over-allocation and support sustainable water management practices in the Murray-Darling Basin (Commonwealth of Australia, 2010). In order to avoid adverse outcomes associated with path dependence, the literature on flexible adaptation pathways emphasizes the implementation of reversible and flexible options that allow for ongoing adjustment (Stafford Smith *et al.*, 2011; Haasnoot *et al.*, 2013). In addition, the literature on 'real options' suggests that, under certain circumstances, there may be value in such flexible adaptation strategies or in delaying investments in certain adaptation options until new information or management options are available (Hertzler, 2007; Dobes, 2008; Jeuland and Whittington, 2013).

16.4. Limits to Adaptation

The various constraints discussed previously (16.3.2) can, if sufficiently severe, pose limits to the ability of actors to adapt to climate change (Meze-Hausken, 2008; O'Brien, 2009; Adger *et al.*, 2009; Moser and Ekstrom, 2010; Dow *et al.*, 2013a, b) (*high agreement, medium evidence*). A limit is reached when adaptation efforts are unable to provide an acceptable level of security from risks to the existing objectives and values and prevent the loss of the key attributes, components or services of ecosystems (Box 16-1). For example, one of the key messages from the WGII chapter on Africa (Chapter 22) is, "*Progress is being achieved on managing risks to food production from current climate variability but these will likely not be sufficient to address long-term risks from climate change (high confidence)*."

There are a variety of circumstances and terminology in the literature that imply adaptation limits including 'thresholds' (Meze-Hausken, 2008; Briske *et al.*, 2010; Washington-Allen *et al.*, 2010); 'regime shifts' (Washington-Allen *et al.*, 2010); 'tipping points' (Lenton *et al.*, 2008; Kriegler *et al.*, 2009); 'dangerous climate change' (Mastrandrea and Schneider, 2004; Ford, 2009a); 'reasons for concern' (Smith *et al.*, 2009a); 'planetary boundaries' (Rockström *et al.*, 2009); or 'key vulnerabilities' (Schneider *et al.*, 2007; Johannessen and Miles, 2011; Hare *et al.*, 2011; 19.6). In addition, terms such as barriers, constraints, and limits are sometimes used interchangeably. Due to this diversity in language, this discussion builds on recent efforts to develop a common lexicon to facilitate research and practice (Hulme *et al.*, 2007; Adger *et al.*, 2009; Dow *et al.*, 2013a, b; 16.2; Box 16-1).

_____ START BOX 16-4 HERE _____

Box 16-4. Historical Perspectives on Limits to Adaptation

Does human history provide insights into societal resilience and vulnerability under conditions of environmental change? Archeological and environmental reconstruction provides useful perspectives on the role of environmental change in cases of significant societal change – sometimes termed 'collapse' (Diamond, 2005). These may help to illuminate how adaptation limits were either exceeded, or where collapse was avoided to a greater or lesser degree. Great care is necessary to avoid over-simplifying cause and effect, or over-emphasizing the role of environmental change, in triggering significant societal change, and the societal response itself. Coincidence does not demonstrate causality, such as in the instance of matching climatic events with social crises through the use of simple statistical tests (Zhang *et al.*, 2011), or through derivative compilations of historical data (deMenocal, 2001; Thompson *et al.*, 2002; Drysdale *et al.*, 2006; Butzer, 2012). Application of social theories may not explain specific cases of human behavior and community decision-making, especially because of the singular importance of the roles of leaders, elites and ideology (Hunt, 2007; McAnany and Yoffee, 2010; Butzer and Endfield, 2012; Butzer, 2012).

There are now roughly a dozen case studies of historical societies under stress, from different time ranges and several parts of the world, that are sufficiently detailed (based on field, archival, or other primary sources) for relevant analysis (Butzer and Endfield, 2012). These include Medieval Greenland and Iceland (Dugmore *et al.*, 2012; Streeter *et al.*, 2012); Ancient Egypt (Butzer, 2012); Colonial Cyprus (Harris, 2012); the prehistoric Levant (Rosen and Rivera-Collazo, 2012); Islamic Mesopotamia and Ethiopia (Butzer, 2012); the Classic Maya (Dunning *et al.*, 2012; Luzzadder-Beach *et al.*, 2012); and Colonial Mexico (Endfield, 2012). Seven such civilizations underwent drastic transformation in the wake of multiple inputs, triggers, and feedbacks, with unpredictable outcomes. These can be seen to have exceeded adaptation limits. Five other examples showed successful adaptation through the interplay of environmental, political and socio-cultural resilience, which responded to multiple stressors (e.g., insecurity, environmental or economic crises, epidemics, famine). In these cases, climatic perturbations are identified as only one of many ‘triggers’ of potential crisis, with preconditions necessary for such triggers to stimulate transformational change. These preconditions include human-induced environmental decline mainly through over-exploitation.

Avoidance of limits to adaptation requires buffering feedbacks that encompass social and environmental resilience. Exceedance of limits occurred through cascading feedbacks that were characterized by social polarization and conflict that ultimately result in societal disruption. Political simplification undermined traditional structures of authority to favor militarism, while breakdown was accompanied or followed by demographic decline. Although climatic perturbations and environmental degradation did contribute to triggering many cases of breakdown, the most prominent driver at an early stage was institutional failure, which refers to the inability of societal institutions to address collective-action problems (Acheson, 2006). In these cases, collapse was neither abrupt nor inevitable, often playing out over centuries. Lessons from the implementation of adaptation responses over historical time periods in Mexico City suggest that some responses may create new and even more significant risks (Sosa-Rodriguez, 2010).

Recent work on resilience and adaptation synthesizes lessons from extreme event impacts and responses in Australia (Kiem *et al.*, 2010). This further emphasizes an institutional basis for resilience, finding that government intervention through the provision of frameworks to enable adaptation is beneficial. Furthermore, it was found that a strong government role may be necessary to absorb a portion of the costs associated with natural disasters. On the other hand, community awareness and recognition of novel conditions were also found to be critical elements of effective responses. It would be useful to consider how lessons learned from historical experience may relate to the perceived multiple environmental changes characterized by the “Anthropocene” era (Crutzen, 2002).

16.4.1. Hard and Soft Limits

Although limits to adaptation are at times described in the literature as fixed thresholds (Adger *et al.*, 2009), recent studies have emphasized the need to consider the perspective of actors in defining adaptation limits (Adger *et al.*, 2009; Dow *et al.*, 2013 a, b; 16.1; 16.2) as well as the dynamic nature of both biophysical and socioeconomic processes that influence adaptation decision-making and implementation (Park *et al.*, 2012; Preston *et al.*, 2013a; Islam *et al.*, 2014). Informed by the distinctions drawn in the work of Meze-Hausken (2008), Adger *et al.* (2009), and Moser and Ekstrom (2010), one can distinguish between ‘hard’ limits, those that will not change, and ‘soft’ limits, which could change over time. For human actors, whether a limit is hard or soft is usefully evaluated at a given point in time by asking whether an adaptation response to manage an intolerable risk could emerge in the future. For example, projected climate change impacts in Europe indicate that increasing irrigation needs will be constrained by reduced runoff, demand from other sectors, and economic costs. As a consequence, by the 2050s farmers will be limited by their inability to use irrigation to prevent damage from heat waves to crops (23.4.1; 23.4.3). For natural systems, whether a limit is hard or soft is defined by the rate and capacity of species and ecosystem responses relative to environmental changes (Shaw and Etterson, 2012).

Discussions of hard limits in the literature are often associated with thresholds in physical systems that, if exceeded, would lead to irreversible changes or the loss of critical structure or function (Lenton *et al.*, 2008; Adger *et al.*, 2009; IPCC, 2012). Such limits arise from the magnitude and/or rate of climate change (Box 16-3). For example, a number of physical thresholds in the Earth system have been proposed as posing potential limits to adaptation, particularly large-scale events such as irreversible melting of the Greenland or Antarctic Ice Sheets (Schneider and Lane, 2006a; Sheehan *et al.*, 2008; Travis, 2010). Such physical thresholds, however, though relevant to understanding adaptation limits, are not necessarily limits in themselves as they neglect consideration for the adaptive capacity of natural and human systems (Leary *et al.*, 2009; Adger *et al.*, 2009; Dow *et al.*, 2013a, b; Klein and Juhola, 2013; Preston *et al.*, 2013a).

For species and ecosystems, hard limits to adaptation are often associated with exceedance of the physiological capacity of individual organisms or communities to adapt to changes in the climate (i.e., temperature, rainfall, and/or disturbance regimes (Peck *et al.*, 2009); or to climate-induced changes in the abiotic environment (e.g., ocean circulation and stratification, (Harley *et al.*, 2006; Doney *et al.*, 2012) (16.3.2.2; 16.3.2.3). Such systems tend to be those that persist at the upper limit of their climate tolerances (Sheehan *et al.*, 2008; Dirnböck *et al.*, 2011; Benito *et al.*, 2011); those for which sustainability is closely tied to vulnerable physical systems (Johannessen and Miles, 2011); or those that are under significant pressure from non-climatic forces (Jenkins *et al.*, 2011). For example, many species, including humans (11.8.1) and key food crops (e.g., wheat, maize, and rice; 7.3.2; 11.8.2) are known to have thermal limits to survival. Similarly, increased ocean acidity is expected to reduce the ability of some marine organisms such as corals to grow, posing threats of significant ecosystem damage (CC-OA; CC-CR). Nevertheless, defining those limits remains challenging due to system complexity and lack of information regarding responses across different levels of biological organization (Steffen *et al.*, 2009; Wookey *et al.*, 2009; Lavergne *et al.*, 2010; Preston *et al.*, 2013a). Furthermore, species have mechanisms for coping with climate change including phenotypic plasticity (Charmantier *et al.*, 2008; Matesanz *et al.*, 2010) genetic (evolutionary) responses (Gienapp *et al.*, 2008; Bradshaw and Holzapfel, 2006; Visser, 2008; Wang *et al.*, 2013), and range shifts (Colwell *et al.*, 2008; Thomas, 2010; Chen *et al.*, 2011; 16.3.2.3). Such mechanisms influence adaptation limits by extending the range of climate conditions with which individual organisms can cope in situ and/or enabling species to migrate over time to more suitable climates. Yet, more comprehensive assessments of such adaptive mechanisms are needed to develop robust understanding of ecological limits.

While human systems may also experience hard limits, such systems are influenced by exogenous climate change as well as endogenous processes such as societal choices and preferences (Adger *et al.*, 2009). This creates the potential for limits encountered by actors to be soft. Although they may limit adaptation for the current planning horizon, they may be ameliorated in the future by changing circumstances. Various authors have noted that adaptation limits are socially-constructed by human agency in that economics, technology, infrastructure, laws and regulations, or broader social and cultural considerations can limit adaptation (Flåm and Skjærseth, 2009; O'Brien, 2009; Adger *et al.*, 2009; de Bruin *et al.*, 2009b; Wilbanks and Kates, 2010; McNamara *et al.*, 2011; Morrison and Pickering, 2012; 16.3) (*high agreement*, *medium evidence*). Cost-benefit analyses and associated discount rates, for example, reflect a social value on investment returns (17.3.7.2). Yet, Morgan (2011) notes that adaptation planning based on cost-benefit analysis can pose limits to adaptation by discounting the future economic benefits of adaptation actions and excluding non-market benefits. Meanwhile, increasing loss and damage from societal exposure and climate change may pose financial limits to the insurability of disaster risks (10.7.3), which ultimately influences what activities can occur in certain locations. All of these factors are dynamic and can change over time. The Shared Socioeconomic Pathways, which have been designed to facilitate comparison of findings across modeling teams, reflect different perspectives on future changes in the capacity of actors to adapt (Kriegler *et al.*, 2012; Ebi *et al.*, 2013; Schweizer and O'Neill, 2013; van Ruijven *et al.*, 2013). Given rising incomes and advances in knowledge and technology, a greater number of adaptation options may become available to a greater number of actors over time. In contrast, impediments to development, constraints on investments in adaptation, or rapid escalations in risk may increase the likelihood of experiencing a limit.

Societal assessments of risk and willingness to invest in risk management are subject to many influences (Renn, 2008; IPCC, 2012; 14.3.1.1), such as experience of a recent disaster, some of which can result in rapid changes (Ho *et al.*, 2008; Breakwell, 2010; Renn, 2011). Adger *et al.* (2009; pg. 338), argue that many limits to adaptation are dependent on the changing goals, values, risk tolerances and social choices of society which make them "*mutable,* *subjective, and socially constructed*." Similarly, Meze- Hausken (2008) views adaptation as being triggered in part by subjective thresholds including perceptions of change; choices, needs, and values; and expectations about the future (see also O'Brien, 2009). For instance, the distribution of grape suitability will change in response to climate change, but the potential for relocation as an adaptation is limited by the concept of 'terroir', which reflects biophysical traits and local knowledge and wine making traditions to a cultural landscape (Box 23-1). However, terroir could become a soft limit if the rigid, regionally defined regulatory frameworks and concepts of regional identity that prescribe what grapes can be grown where were to become more geographically flexible and tied to the culture and history of the winemakers rather than regional climate and grape suitability (Box 23-1).

Limits also have scale-dependent properties (see also 16.3.2.10) (*high agreement, limited evidence*). Adaptation finance and capacity building activities more broadly, for example, enable resources for adaptation to be transferred from a variety of governmental and non-governmental entities to developing nations in order to overcome soft limits to adaptation (16.3.2.5). For example, a local community may not have the necessary resources to adapt, but these constraints may be overcome by drawing in resources, such as technical expertise, from regional, national, or international authorities as well as from NGOs, other civil society organizations, or the private sector (16.3.2.5). Scale-dependence also manifests among different actors within sectoral supply chains. For example, climate change that poses limits to the sustainability of an individual farm enterprise may have less impact on a national or international agribusiness (Park *et al.*, 2012).

16.4.2. Limits and Transformational Adaptation

Adaptation has traditionally been viewed as a process of incremental adjustments to climate variability and change to maintain existing objectives and values despite changes in climate conditions (Smit *et al.*, 2001). As evidenced by the examples in 16.4.1, however, future changes in climate could exceed the capacity of human actors and/or natural systems to successfully adapt using incremental adjustments (*high agreement, medium evidence*). Since the AR4, the adaptation and resilience literature has suggested that climate change or other factors may drive actors toward the deliberate pursuit of transformational adaptation as a mechanism for managing the discontinuities associated with experiencing an adaptation limit (Pelling, 2010; Kates *et al.*, 2012; O'Brien, 2012; O'Brien *et al.*, 2012; O'Neill and Handmer, 2012; Dow *et al.*, 2013a, b; 20.3). In addition, some studies have discussed the interactions between incremental and transformational adaptation and the pathways by which actors can transition from one to the other (Pelling, 2010; Park *et al.*, 2012).

As a relatively new concept in the adaptation literature, clear operational definitions of what constitutes transformational adaptation remain elusive. Several authors have offered criteria that include a significant increase in the magnitude of a management effort; introduction of new technologies or practices; formation of new structures or systems of governance; or geographic shifts in the location of activities (Pelling, 2010; Stafford Smith *et al.*, 2011; Kates *et al.*, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012; 20.2.3). However, the concept has also been identified as having normative elements involving changes in desired values, objectives, and perceptions of problems (Pelling, 2010; O'Neill and Handmer, 2012; Park *et al.*, 2012; O'Brien *et al.*, 2012). The current complexity and ambiguity in the definition of transformational adaptation may constrain its effective operationalization in policy environments (*very low confidence*). However, this matter has not been investigated.

In the context of limits to adaptation, transformational adaptation represents options and strategies that human actors can exploit to reorganize systems when incremental adaptation has reached its limits. As with incremental adaptation, these changes can be reactions to what has been experienced in the past or decisions made in anticipation of the future (Kates *et al.*, 2012). As a fundamental change in a system, transformation may involve changes in actors' objectives and associated values. Therefore, transformational adaptation isn't without risks or costs (Orlove, 2009; Kates *et al.*, 2012; O'Brien, 2012). For example, the level of investment needed to relocate a community or economic enterprise to reduce the risk of system failure (Kates *et al.*, 2012; O'Neill *et al.*, 2012) and/or to take advantage of changing climatic conditions (Park *et al.*, 2012) may be quite substantial.

Furthermore, transformational adaptation may be associated with various externalities. Strategies such as migration, for example, may involve the loss of sense of place and cultural identity, particularly if migration is involuntary

(Adger *et al.*, 2009). The feasibility of transformational adaptation may therefore be dependent in part upon whether it results in outcomes that are perceived to be positive versus negative (Preston and Stafford Smith, 2009). This suggests that the factors that constrain incremental adaptation (e.g., 16.3.2) also can constrain transformation, but the greater level of investment and/or shift in fundamental values and expectations required for transformational change may create greater resistance (Pelling, 2010; O'Brien, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012) (*medium agreement, limited evidence*).

16.5. Sectoral and Regional Synthesis

The adaptation literature since the AR4 indicates that despite a range of opportunities to enable adaptation, multiple factors will constrain adaptation planning and implementation (16.3) (*very high confidence*), and, in some cases, such constraints may limit adaptation (16.4) (*high agreement*, *medium evidence*). However, adaptation opportunities, constraints, and limits for adaptation vary significantly among different sectors and regional contexts (Adger *et al.*, 2007; 16.3; 16.4; Table 16-3) (*very high confidence*). This heterogeneity arises from a range of sources including regional differences with respect to the rate and magnitude of climate change that is experienced, differential exposure and sensitivity of sectors or ecological systems, and differential capacity to adapt. Given this diversity, it is important that opportunities, constraints and limits are evaluated in the specific context in which they arise. Therefore, this section draws on the various assessments of adaptation presented in the sectoral (Chapters 3‒13) and regional (Chapters 22‒30) chapters of the AR5 Working Group II report to synthesize knowledge regarding opportunities, constraints, and limits across these contexts.

16.5.1. Sectoral Synthesis

Each of the sectoral chapters in the Working Group II report addresses the opportunities for, and constraints associated with, the pursuit of adaptation (Table 16-3). Collectively, this represents a rich body of knowledge regarding how adaptation processes are evolving among different human and natural systems. Although each sectoral chapter assesses the relevant literature on adaptation independently, common themes emerge in opportunities, constraints and limits to adaptation (Table 16-3). Opportunities most often cited include building awareness, strengthening adaptive capacity, developing tools for improving vulnerability and risk assessments, and adopting favorable policies to improve governance. Likewise, common constraints arise among different sectors, but the bulk of the evidence for adaptation constraints is focused on inadequate governance and institutional structures at the scale of the challenge, lack of access to financial resources or relevant information for adaptation, and social and cultural norms that prevent adoption of viable adaptation options.

There are a number of emerging, integrated approaches to adaptation planning, governance and implementation identified by many sectoral and regional chapters. For example, Integrated Water Resource Management (IWRM), Integrated Coastal Zone Management (ICZM), Community-Based Adaptation, and Ecosystem-Based Adaptation (EBA) are identified as cross-sectoral adaptation options, which are viewed as more effective than standalone efforts to reduce climate-related risks (Bijlsma *et al.*, 1996; 5.5.1.4; 14.4.5; CC-EA). Such integration is important as many sectors experience threats not from by climate change, but also from a range of existing or emerging threats. The sectoral chapters also reflect on the distinction between autonomous adaptation, which is particularly important for natural systems such as freshwater, coastal, terrestrial, and ocean ecosystems (e.g., WGII Chapters 3‒6), and planned adaptation, which features strongly in the literature associated with human-managed systems (WGII Chapters 5, 7‒13).

While the sectoral chapters offer few explicit definitions of adaptation limits, they reflect the potential for hard limits to be reached and the potential for them to be persistent due to interactions among multiple constraints (16.3.5). For example, the sustainability of individual species or ecosystems may experience hard limits in a changing climate, as may ecosystem services for humans such as food crop and fisheries production. While significantly more attention is given to sectoral adaptation opportunities, constraints, and limits than in the AR4, the AR5 chapters suggest that literature relevant to the coastal (Chapter 5), food systems (Chapter 7), and urban sectors

(Chapter 8) has expanded more rapidly, perhaps because of the experience within these sectors with risk reduction planning associated with extreme weather events.

[INSERT TABLE 16-3 HERE
Table 16-3: Sectoral and regional synthesis of adaptation opportunities, constraints, and limits. Each icon represents types of opportunities, constraints and limits (described below). The size of the icon represents when there is relatively little (small icon) or relatively ample (large icon) information in the sectoral and regional chapters to describe each type of opportunity, constraint, or limit. If no information was presented, the table cell is blank.

Opportunities are defined *as factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.* Types of opportunities include (1) **Awareness -** communication, education and awareness raising; (2) **Capacity -** human and institutional capacity building including preparedness, resource provision, and development of human and social capital; (3) **Tools -** decision-making, vulnerability and risk analysis, decision support and early warning tools; (4) **Policy -** integration and mainstreaming of policy, governance and planning processes including sustainable development, resource and infrastructure planning, and design standards; (5) **Learning -** mutual experiential learning and knowledge management of climate vulnerability, adaptation options, disaster risk response, monitoring and evaluation; and (6) **Innovation -** development and dissemination of new information, technology development, and technology application.

Constraints *are defined as factors that make it harder to plan and implement adaptation actions*. Types of constraints include (1) **Economic -** existing livelihoods, economic structures and economic mobility; (2) **Social** and cultural **-** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) **Human capacity -** individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, skill development; (4) **Governance,** Institutions & Policy - existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) **Financial -** lack of financial resources; (6) **Information**/ Awareness/ Technology - lack of awareness or access to information or technology; (7) **Physical -** presence of physical barriers; and (8) **Biological -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind**.**

*A **Limit** is defined* as the *point at which actor's objectives or natural system's needs cannot be secured from intolerable risks through adaptive actions*. Types of limits include (1) **Biophysical -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind, (2) **Economic -** existing livelihoods, economic structures and economic mobility; and (3) **Social/cultural -** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support.]

16.5.2. Regional Synthesis

While the regional chapters assess the relevant literature on key sectors affected by climate change, those discussions are specific to the various regional contexts (Table 16-3). Mainstreaming adaptation to climate change into national development policies, regional and local planning, and economic development has emerged as an opportunity across all regions for addressing multiple, interacting, stresses (Dovers and Hezri, 2010; Tompkins *et al.*, 2010; Table 16-3). Most regional chapters reveal there are significant spatial and temporal mismatches between national adaptation planning on adaptation and local implementation to achieve substantive reductions in vulnerability. Adaptation interventions largely emphasize short-term risk management over long-term transformative strategic planning to reduce long-term risk, which potentially increases vulnerability and therefore the costs associated with future adaption efforts. Such short-sighted decision-making can also create the potential for maladaptation (Barnett and O'Neill, 2010; Berrang-Ford *et al.*, 2011; Preston *et al.*, 2013b).

Effective governance and institutions for facilitating adaptation planning and implementation across multiple sectors within regions was by far the dominant opportunity and constraint. Both a shift to risk-based approaches to adaptation and to the multi-sector planning for adaptation mentioned above (EBA, IRWM and ICZM) offer opportunities for the development of approaches, tools and guidelines for the construction of adaptation plans at a regional scale with a long-term focus. Developing and developed nations alike identified opportunities for building adaptive capacity and access to better information at the scale of decision-making as important to making this happen. Compared with sectoral chapters, the regional chapters identified limits to adaptation less frequently (Figure 16-3). This reflects the tendency for the literature to focus on limits for specific sectors, species, or ecosystems (16.5).

16.6. Effects of Mitigation on Adaptation Opportunities, Constraints, and Limits

The AR4 identified four ways in which adaptation and mitigation can inter-relate, one of which is mitigation actions that have consequences for adaptation (Klein *et al.*, 2007). It follows that mitigation actions could have consequences for adaptation constraints and limits. Klein *et al.* (2007) concluded that without mitigation, a magnitude of climate change could be reached that makes adaptation impossible for some natural systems, while for most human systems such high magnitudes of change would involve very high social and economic costs. Adaptation constraints and limits therefore have implications for the definition of dangerous anthropogenic interference under Article II of the UNFCCC (UNFCCC, 1992; see also Travis, 2010; Hoegh-Guldberg, 2011; Tao *et al.*, 2011; Preston *et al.*, 2013a). A number of studies published since the AR4, for example, demonstrate that constraining future greenhouse gas emissions would lower the magnitude of climate change experienced over the 20^{th} century and constrain the magnitude of future adverse impacts or the likelihood of exceeding system thresholds (Stern *et al.*, 2006; Meinshausen *et al.*, 2009; Preston and Jones, 2008; Sheehan *et al.*, 2008; O'Neill *et al.*, 2010; Garnaut, 2011; Arnell *et al.*, 2011; Rogelj *et al.*, 2011; Webster *et al.*; 2011; see also discussion of mitigation in the AR5 WGII sectoral and regional chapters) (*very high confidence*). Therefore, mitigation can potentially reduce the magnitude of climate change to which human and natural systems must adapt.

Understanding the relationship between damages avoided by mitigation and adaptation limits requires information regarding what magnitude of climate change and associated damages would constitute an intolerable risk. The WGI contribution to AR5 quantifies the cumulative CO_2 emissions below which – with probabilities of >33%, >50%, and >66% – global mean warming would be limited to less than 2°C since the period 1861–1880 (see WGI AR5 12.5.4). Warming beyond 2°C is considered to give rise to 'reasons for concern' (Smith *et al.*, 2009a; see also 19.6), in part because adaptation to impacts associated with such warming would be constrained or limited (16.3.2.2; 16.4.1; Box 16-3). Uncertainty about the location of both hard and soft limits is due to the fact that these limits are determined not only by the degree and rate of climate change (as a function of mitigation pathways), but also by the degree and rate of non-climatic stresses affecting the resilience or adaptive capacity of natural and human systems (16.4). Little empirical information is available on the functional relationships between climate change, non-climatic stresses and the emergence of limits to adaptation. The literature aiming to establish at which degree and rate of climate change, or at which levels of mitigation, such adaptation constraints and limits emerge is sparse and refers primarily to natural systems (16.4) (*medium agreement, limited evidence*).

Nevertheless, studies indicating that limits to adaptation have already been reached for some systems suggest the climate change observed to date has been sufficient to threaten the sustainability of human communities, ecosystem services, or ecological systems (16.4) (*medium agreement, limited evidence*). Nevertheless, for many valued human and natural systems, the complex spatial and temporal dynamics of impacts, adaptive capacity, and adaptation make it difficult to quantitatively project with any degree of accuracy and confidence when and where limits to adaptation will be encountered. Furthermore, although constraints and limits have been demonstrated to have cross-scale and cross-level interactions (16.3.2.10; 16.4.1), there is little evidence that indicates how limits to adaptation experienced by actors, species, or ecosystems in individual regions or sectors scale to a global aggregate limit. Therefore, there is little evidence to either substantiate or refute the idea that global mean warming beyond 2°C represents a global adaptation limit.

Analysis by Christensen *et al.* (2011) (see also WGI AR5 12.4.1) shows that all emission scenarios – whether aggressive mitigation scenarios consistent with a 2°C stabilization pathway or medium-high emission scenarios such as SRES A1B and A1Fi, or RCP6.0 and RCP8.5 – are very similar in terms of projected climate up to 2040 (i.e. the 'era of climate responsibility'). The effects of mitigation on overall adaptation potential will therefore arise in the medium to long term, during the 'era of climate options'. Integrated assessment models (IAMs) can assess the relative damage-reducing effect of mitigation and adaptation, based on the assumption that the two strategies are substitutes. In reality, however, mitigation and adaptation are hardly substitutable: they create benefits on different spatial, institutional and temporal scales and involve different actors with different interests. Substitutability of mitigation and adaptation in IAMs requires the reconciliation of welfare impacts on people living in different places and at different points in time into an aggregate measure of well-being (Klein *et al.*, 2007). Moreover, defining the costs and benefits of adaptation is particularly difficult, limited by data, and depends on value judgments (chapter 17).

Since AR4 the literature on tipping elements (Lenton *et al.*, 2008; Kriegler *et al.*, 2009; Levermann *et al.*, 2012) has provided a greater separation of mitigation and adaptation, because only mitigation can avoid these discontinuities. While there could be potential for mitigation and adaptation substitutability under scenarios where catastrophic climate change is avoided, the thresholds for the onset of any tipping elements (anticipated to drive some systems to the limits of adaptation) are not known. These concerns have been picked up in the economic literature, in relation to the plausible, if unknown, probability of catastrophic climate change as well as 'fat tails', where uncertainty is so large that the tails of the probability distribution tend to dominate (Weitzman, 2009). Against this background, mitigation can prevent or delay catastrophic climate change and the reaching of adaptation limits.

Several studies using IAMs have investigated tradeoffs between mitigation and adaptation (de Bruin *et al.*, 2009a; Bosello *et al.*, 2010), treating the two strategies as substitutes in order to find a balance or even an optimal mix. De Bruin *et al.* (2009a) report that short-term optimal policies need to consist of a mixture of substantial investments in adaptation measures, coupled with investments in mitigation, even though the latter will only decrease damages in the longer term. They also find that the relative mix of the two depends critically on the assumptions, notably in relation to the discount rate and the parameterization of damages. Felgenhauer and de Bruin (2009) examine the role that uncertainty over climate sensitivity has on optimal mitigation and adaptation policy levels over time. They find that optimal levels of both mitigation and adaptation are lower under uncertainty than under certainty, and that the optimal mitigation level is more dependent on adaptation costs than vice versa.

Such findings are all preliminary, because the current representation of adaptation in IAMs is generally very simple (Ackerman *et al.*, 2009; Patt *et al.*, 2010b). The models adopt a highly aggregated and theoretical approach without considering any real-world constraints on adaptation (Ackerman *et al.*, 2009; Patt *et al.*, 2010b). They also often assume perfect foresight, no uncertainty and no maladaptation (see also Watkiss, 2011; Berkhout, 2012). More recent models have attempted to address some of these issues. De Bruin and Dellink (2011), for example, model different types of constraints of adaptation over time. Also the PAGE09 model assumes adaptation to be about half as effective as it was inPAGE02 (Hope, 2011). Along with other factors, the reduced effectiveness of adaptation in the model leads to a strong increase in the economic costs of climate change (Hope, 2011).

16.7. Ethical Dimensions of Adaptation Opportunities, Constraints, and Limits

Hartzell-Nichols (2011, pg. 690) argues that, in general terms, "*Adaptation is fundamentally an ethical issue because the aim of adaptation is to protect that which we value.*" More specifically, ethical issues concern the distribution of costs and benefits of prevention measures and adaptation activities, compensation for residual damages, and participation in the related decision processes (Grasso, 2009). These distributive and procedural justice-related issues can be diverse and contextually specific (Paavola, 2011). Brisley *et al.* (2012) argue that ensuring social justice in adaptation requires both an understanding of which groups are most vulnerable to climate change impacts, as well as social choice processes about adaptation responses that are seen to meet the needs of the vulnerable fairly. The key ethical issues raised by adaptation opportunities, constraints and limits as they are discussed here are summarized in Table 16-4, together with the public policy questions they raise.

[INSERT TABLE 16-4 HERE
Table 16-4. Ethical dimensions of adaptation opportunities, constraints and limits and their policy implications.]

Defining general moral principles to clarify how to handle risks to objectives, values and needs, including where they are unavoidable and catastrophic, is difficult. According to Gardiner (2006, pg. 407),

> "*Even our best theories face basic and often severe difficulties addressing basic issues … such as scientific uncertainty, intergenerational equity, contingent persons, nonhuman animals, and nature. But climate change involves all of these matters and more*".

Complicating this picture further is the observation that social and personal values are not universal or static (O'Brien, 2009; O'Brien and Wolf, 2010). There may be different, but equally legitimate, values that are fostered or put at risk by climate change (Adger *et al.*, 2012). These are not limited to instrumental or economic values, but include cultural values as well. Berkes (2008, pg. 163), for instance, documents that in Inuit culture, the loss of sea ice in summer months leaves some people "*lonely for the ice*." Whether the risk of irreversible cultural losses would be seen as intolerable remains a complicated question, but has been noted to manifest in a psychological response termed "solastalgia" (Albrecht *et al.*, 2007). The loss of traditional ways of experiencing and seeing the world is a common occurrence throughout human history. The ethical question is whether such losses should be acknowledged in considering adaptation opportunities, constraints and limits (as well as in human responses to climate change more generally).

One ethical principle that is widely applied in ethical discussions of climate is 'equity' (Gardiner, 2010). It is now well-established that nations, peoples and ecosystems are differentially vulnerable to current and future projected climate change impacts, which themselves are unequally distributed across world regions (IPCC, 2007b; Füssel, 2009; Füssel, 2010) (*very high confidence*). This inequity is exacerbated by the fact that exposure to adverse impacts is involuntary for many societies (Paavola and Adger, 2006; Patz *et al.*, 2007; Dellink *et al.*, 2009; Füssel, 2010). Therefore, adaptation constraints have the potential to create or exacerbate inequitable consequences due to climate change (*very high confidence*). Where limits to adaptation lead to catastrophic losses there is often a need for humanitarian responses, as well as more structural adaptations at the societal level (Bardsley and Hugo, 2010) (*high agreement, medium evidence*). Linked to this is the complex question of the attribution of risks to anthropogenic forcing of climate change and whether there could be grounds for redress or compensation (Verheyen, 2005). In this regard, different ethical positions taken by countries such as through 'equity weighting' would result in very different compensation outcomes (Anthoff and Tol, 2010)

Inequity resulting from adaptation constraints and limits emerge across several dimensions; namely inter-country equity, inter-generational equity, inter-species equity (Schneider and Lane, 2006b), and intra-country or sub-national equity (Thomas and Twyman, 2005). Climate change, and the need for adaptation, unfairly shifts burdens onto future generations, contradicting the principle of intergenerational equity. This raises ethical and justice questions since benefits are extracted from the global environment by those who do not bear the burden of that extraction (UNEP, 2007). Policy debates about inter-generational equity considerations have been dominated by the need to treat the time discount rate consistently across cases (Nordhaus, 2001; Stern *et al.*, 2006; Beckerman and Hepburn, 2007). But this debate largely ignores the challenge of irreversible damages associated with limits to adaptation, especially those that may result from non-linear damage functions (Hanemann, 2008). Inter-species equity is the subject of an evolving ethics debate (e.g., Jolibert *et al.*, 2011), but adaptation interventions involving ecosystems and wild species increasingly invoke human and societal benefits as a primary motivation (CBD, 2009; CC-EA).

Law codifies the social values and objectives influenced by opportunities, constraints and limits to adaptation, and sets norms and procedures for dealing with problems of risk and loss, including the intolerable losses experienced at adaptation limits (16.3.2.8). Changing such values and objectives, including the shifting and sharing of risks this may involve, will often involve complex and time-consuming governance effort. National and international law will play a role in managing and sharing climate-related risks. The Cancun Adaptation Framework (UNFCCC, 2011) adopted at COP16 of the UNFCCC sets out principles for international cooperation on adaptation "*…to enable and support the implementation of adaptation actions*" (UNFCCC, 2010, p. 4). Nevertheless, the complexity of international law comprises a significant constraint to making the case for addressing the breaching of adaptation limits (Koivurova, 2007). At national and sub-national levels, cultural attitudes can contribute to stakeholder marginalization from adaptation processes (16.3.2.7), thus preventing some constraints and limits from being identified (such as gender issues and patriarchal conventions).

16.8. Seizing Opportunities, Overcoming Constraints, and Avoiding Limits

As discussed in this chapter, researchers and practitioners now have a richer understanding of how constraints and limits influence adaptation (16.3; 16.4; 16.5; 16.6; 16.7). Based on the available literature, however, less attention has been paid to understanding the range of opportunities that exist and how they create enabling conditions for adaptation (16.3.1; Table 16-1). Focused research on facilitating such enabling conditions and how these lead to the minimization or avoidance of adaptation constraints would support capacity building of individuals and institutions (Smith *et al.*, 2008; Ford, 2009; Burch, 2010; Ford *et al.*, 2010; Eisenack, 2012; Biesbroek *et al.*, 2013a) (*very high confidence*). Translating knowledge of potential opportunities into adaptation responses requires that they be recognized and then exploited by actors. Such opportunities are being created through policies, tools and guidelines that are emerging throughout the developed and developing world (15.2; 16.3.2.1). It is not yet clear if these efforts are translating into effective adaptation actions for the benefit of human and natural systems including the avoidance of limits. As adaptation practice has focused on what adaptation efforts can achieve in terms of avoided damages rather than on the residual damages that adaptation cannot avoid (Jenkins *et al.*, 2011; McNamara *et al.*, 2011), this question remains largely unexplored.

Adaptation constraints have contributed to uneven adaptation planning and implementation with some sectoral and regional actors progressing more rapidly than others (Urwin *et al.*, 2008; Biesbroek *et al.*, 2010; Tompkins *et al.*, 2010; Bichard and Kazmierczak, 2012; Bierbaum *et al.*, 2012; Carmin *et al.*, 2012; (*very high confidence*). Multiple studies have concluded that adaptation is largely proceeding autonomously and incrementally, often in response to perceived climate change trends and impacts that have been experienced (Ford, 2009; Ford *et al.*, 2010; Berrang-Ford *et al.*, 2011; Ford *et al.*, 2011; Preston *et al.*, 2011a; Lesnikowski *et al.*, 2013) (*high agreement, medium evidence*). In so doing, however, actors may not adequately invest in adaptation responses that will address future long-term risks associated with higher levels of climate change (Preston *et al.*, 2013b; 16.3.2.2) (*medium agreement, limited evidence*). The suggestion that incremental approaches to mitigation and adaptation may be inadequate to avoid intolerable risks has led to a growing discourse regarding transformational adaptation (Pelling, 2010; Kates *et al.*, 2012; O'Brien, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012). While various practical examples of transformational adaptation appear in the literature (Kates *et al.*, 2012; O'Neill and Handmer, 2012; Park *et al.*, 2012; 16.4.2), the extent to which transformational adaptation can be operationalized within adaptation policy remains unclear. Unresolved issues including which actors, sectors, and regions should be considering transformational adaptations, when, and what constitutes appropriate adaptation actions under such circumstances would benefit from focused investigation.

Better understanding and quantification of how future greenhouse gas emissions trajectories and climate change translates into impacts would improve understanding of limits to adaptation. Fundamental understanding of the vulnerability of different regions and sectors to climate change suggest that adaptive capacity is finite and thus, in general, limits to adaptation can be anticipated to arise as a consequence of future global change (16.3.2; 16.4; 16.5; 16.6) (*high agreement, medium evidence*). Yet, at present, understanding of limits to adaptation is largely qualitative, and it is unclear whether current approaches to assessing climate change impacts and adaptation sufficiently explore the range of potential future climates and adaptive capacities of human and natural systems in a manner that is sufficient to identify limits. The parallel process for scenario development may provide a coherent framework for internally consistent analyses of climate change impacts that address uncertainty among climate models, emissions scenarios, and socioeconomic scenarios (Moss *et al.*, 2010; van Vuuren *et al.*, 2012; Ebi *et al.*, 2013). Such knowledge could subsequently provide early warning of systems at risk of experiencing intolerable risks (Dow *et al.*, 2013a, b) while also providing guidance regarding greenhouse gas mitigation targets.

Finally, recent literature questions whether existing institutions and systems of governance are adequate to effectively manage climate change risk. This includes not only institutions engaging in adaptation planning and implementation (Berkes and Armitage, 2010; Chapin *et al.*, 2010; NRC, 2010; UKCIP, 2011; Kates *et al.*, 2012; Biesbroek *et al.*, 2013a), but also those associated with adaptation research (Meyer, 2011; Kates *et al.*, 2012). New institutions and institutional arrangements have in fact emerged including adaptation research institutions with boundary spanning functions (Preston *et al.*, 2013c; 14.2.4), as well as those designed to facilitate adaptation and improve environmental and risk management (NRC, 2009; Biesbroek *et al.*, 2011; Jäger and Moll, 2011; Lemos *et al.*, 2013) (*high agreement, medium evidence*). However, others have cautioned that the complexity of modern governance systems poses significant constraints on institutional change (Adger *et al.*, 2009; 16.3.2.8), and new institutions do not necessarily resolve complex governance challenges (Lebel *et al.*, 2013). Additional research is therefore needed regarding the extent to which new institutions will be required to effectively govern adaptation.

Frequently Asked Questions

FAQ 16.1: What is the difference between an adaptation barrier, constraint, obstacle, and limit?
[to be insert in Section 16.2]
An adaptation constraint represents a factor or process that makes adaptation planning and implementation more difficult. This could include reductions in the range of adaptation options that can be implemented, increases in the costs of implementation, or reduced efficacy of selected options with respect to achieving adaptation objectives. In this context, a constraint is synonymous with the terms adaptation barrier or obstacle that also appear in the adaptation literature. However, the existence of a constraint alone doesn't mean that adaptation is not possible or that one's objectives can't be achieved. In contrast, an adaptation limit is more restrictive in that it means there are no adaptation options that can be implemented over a given time horizon to achieve one or more management objectives, maintain values, or sustain natural systems. This implies that certain objectives, practices, or livelihoods as well as natural systems may not be sustainable in a changing climate, resulting in deliberate or involuntary system transformations.

FAQ 16.2: What opportunities are available to facilitate adaptation? *[to be inserted in Section 16.3.1.1]*
Although an extensive literature now exists regarding factors that can constrain adaptation, there is *very high confidence* that a broad range of opportunities exist for actors in different regions and sectors that can ease adaptation planning and implementation. Generally, sustainable economic development is an over-arching process that can facilitate adaptation, and therefore represents a key opportunity to reduce adaptation constraints and limits. More specifically, those actions or processes that enhance the awareness of adaptation actors and relevant stakeholders and/or enhance their entitlements to resources can expand the range of adaptation options that can be implemented and help overcome constraints. The development and application of tools to support assessment, planning, and implementation can aid actors in weighing different options and their costs and benefits. Policies, whether formal policies of government institutions, initiatives of informal actors, or corporate policies and standards, can direct resources to adaptation and/or reduce vulnerability to current and future climate. Finally, the ability for humans to learn from experience and to develop new practices and technologies through innovation can significantly expand adaptive capacity in the future.

FAQ 16.3: How does greenhouse gas mitigation influence the risk of exceeding adaptation limits?
[to be insert in Section 16.6]
There is *very high confidence* that higher rates and/or magnitudes of climate change contribute to higher adaptation costs and/or the reduced effectiveness of certain adaptation options. For example, increases in global mean temperature of 4°C or more would necessitate greater investment in adaptation than a temperature increase of 2°C or less. As future climate change is dependent upon emissions of greenhouse gases, efforts to mitigate those emissions can reduce the likelihood that human or natural systems will experience a limit to adaptation. However, uncertainties regarding how future emissions translate into climate change at global and regional levels remain significant, and therefore it is difficult to draw robust conclusions regarding whether a particular greenhouse gas stabilization pathway would or would not allow residual risk to be successfully managed through adaptation. For example, evidence regarding limits to adaptation does not substantiate or refute the idea that an increase in global mean temperature beyond 2°C represents an adaptation limit or, subsequently "dangerous anthropogenic interference" as defined by the UNFCCC's Article II.

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

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

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection and appealing environments for tourism (Wild *et al*., 2011). About 275 million people live within 30 km of a coral reef (Burke *et al*., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling) and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5) and more than half of the world's reefs are under medium or high risk of degradation (Burke *et al*., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see 6.3.1. for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs towards net dissolution (*medium confidence*; 5.4.2.4). Ocean warming and acidification have synergistic effects in several reef-builders (5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg *et al*., 2007). The abundance of reef building corals is in rapid decline in many Pacific and SE Asian regions (*very high confidence*, 1-2% per year for 1968-2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner *et al*., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski *et al*., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones *et al*., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the RCP3-PD scenario (Frieler *et al*., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan *et al*., 2013). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

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

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton *et al*. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the SRES A2 emissions scenario (Bell *et al*., 2013).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard *et al*., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke *et al*., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the Global Domestic Product but their economic importance can be high at the country and regional scales (Pratchett *et al*., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001-2011; Laurans *et al*., 2013). At the local scale, these two services provided in 2009-2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans *et al*., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour *et al*., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod *et al*., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig *et al*., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau *et al*., 2012; Billé *et* *al*., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm *et al*. 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod *et al*., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann *et al*., 2012) and coastal pollutants enriched with fertilizers can increase acidification (Kelly *et al.*, 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; 5.2.4.4, 30.5).

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

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

Ecosystem-based adaptation (EBA) integrates the use of biodiversity and ecosystem services into climate change adaptation strategies (e.g., CBD, 2009; Munroe et al., 2011; see Chapters 3, 4, 5, 8, 9, 13, 14, 15, 16, 19, 22, 24, 25, and 27). EBA is implemented through the sustainable management of natural resources and conservation and restoration of ecosystems, to provide and sustain services that facilitate adaptation both to climate variability and change (Colls et al., 2009). It also sets out to take into account the multiple social, economic, and cultural co-benefits for local communities (CBD COP 10 Decision X/33).

EBA can be combined with, or even a substitute for, the use of engineered infrastructure or other technological approaches. Engineered defenses such as dams, sea walls and levees adversely affect biodiversity, potentially resulting in maladaptation due to damage to ecosystem regulating services (Campbell et al., 2009; Munroe et al., 2011). There is some evidence that the restoration and use of ecosystem services may reduce or delay the need for these engineering solutions (CBD, 2009). EBA offers lower risk of maladaptation than engineering solutions in that their application is more flexible and responsive to unanticipated environmental changes. Well-integrated EBA can be more cost effective and sustainable than non-integrated physical engineering approaches (Jones et al., 2012), and may contribute to achieving sustainable development goals (e.g., poverty reduction, sustainable environmental management, and even mitigation objectives), especially when they are integrated with sound ecosystem management approaches. In addition, EBA yields economic, social, and environmental co-benefits in the form of ecosystem goods and services (World Bank, 2009).

EBA is applicable in both developed and developing countries. In developing countries where economies depend more directly on the provision of ecosystem services (Vignola et al., 2009), EBA may be a highly useful approach to reduce risks to climate change impacts and ensure that development proceeds on a pathways that are resilient to climate change (Munang et al., 2013). EBA projects may be developed by enhancing existing initiatives, such as community-based adaptation and natural resource management approaches (e.g., Khan et al., 2012; Midgley et al., 2012; Roberts et al., 2012).

Examples of ecosystem based approaches to adaptation include:

- Sustainable water management, where river basins, aquifers, flood plains, and their associated vegetation are managed or restored to provide resilient water storage and enhanced baseflows, flood regulation services, reduction of erosion/siltation rates, and more ecosystem goods (e.g., Day et al., 2007; Midgley et al., 2012; Opperman et al., 2009)
- Disaster risk reduction through the restoration of coastal habitats (e.g., mangroves, wetlands, and deltas) to provide effective measure against storm-surges, saline intrusion, and coastal erosion (Jonkman et al., 2013)
- Sustainable management of grasslands and rangelands to enhance pastoral livelihoods and increase resilience to drought and flooding
- Establishment of diverse and resilient agricultural systems, and adapting crop and livestock variety mixes to secure food provision; traditional knowledge may contribute in this area through, for example, identifying indigenous crop and livestock genetic diversity, and water conservation techniques
- Management of fire-prone ecosystems to achieve safer fire regimes while ensuring the maintenance of natural processes.

Application of EBA, like other approaches, is not without risk, and risk/benefit assessments will allow better assessment of opportunities offered by the approach. The examples of EBA are too few and too recent to assess either the risks or the benefits comprehensively at this stage. EBA is still a developing concept but is should be considered alongside adaptation options based more on engineering works or social change, and existing and new cases used to build understanding of when and where its use is appropriate.

[INSERT FIGURE EA-1 HERE
Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.]

Box CC-EA References

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Box CC-OA. Ocean Acidification

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

Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence*, *high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Fig. CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30.8, 30.9). Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts
Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several metaanalyses (6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea-floor calcifiers (*medium agreement, robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves and gastropods reducing the competitiveness with non-calcifiers (5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; 6.1.2).

Projections of ocean acidification effects at ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (5.4.2.2).

Due to an incomplete understanding of species-specific responses and trophic interactions the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts and Costs
The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, 5.4.2.4) and the goods and services that they provide such as fisheries, tourism and coastal protection (*limited evidence, high agreement*; Box CC-CR, 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially-exploited shelled mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global GDP, it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e. reduce anthropogenic emissions of CO_2), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (6.4.2.1).

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Table 16-1: Identification of key adaptation opportunities. Each type of opportunity is represented by multiple illustrative examples as well as supporting references.

Opportunity	Examples	References
Awareness raising	Positive stakeholder engagement	Kahan (2010); O'Neill and Chicholson-Cole (2009)
	Communication of risk and uncertainty	Berry *et al.* (2011); Pidgeon and FIschhoff (2011); Pidgeon (2012); Lieske *et al.* (2013)
	Participatory research	Pearce *et al.* (2009) ; McNamara and McNamara (2011); Sheppard *et al.* (2011); Duru *et al.* (2012); Faysse *et al.* (2012)
Capacity building	Research, data, education, and training	PCAST (2011); WMO (2011); Bangay and Blum (2012); Lemos *et al.* (2013)
	Extensions services for agriculture	Deressa *et al.* (2009); Fosu-Mensah *et al.* (2012)
	Resource provision	Ayers (2009); Ayers and Huq (2009); Grasso (2010); Klein (2010); Rübbelke (2011)
	Development of human capital	Bowen *et al.* (2012); Lemos *et al.* (2013)
	Development of social capital	Deressa *et al.* (2009); Adger *et al.* (2010); Engle and Lemos (2010); Huang *et al.* (2011)
Tools	Risk analysis	van Aalst *et al.* (2008); Pidgeon and Butler (2009); Chin *et al.* (2010); Zhou *et al.* (2012); Wade *et al.* (2013)
	Vulnerability assessment	Allison *et al.* (2009); Moreno and Becken (2009); Nelson *et al.* (2010b); Romieu *et al.* (2010); Koh (2011); Preston *et al.* (2011b)
	Multi-criteria analysis	de Bruin *et al.* (2009b); Garfi *et al.* (2011); Yang *et al.* (2012); Kyung-Soo *et al.* (2013)
	Cost/benefit analysis	Hallegatte (2009); Mechler and Islam (2013); Tol *et al.* (2008);Weitzman (2009)
	Decision support systems	Norman *et al.* (2010); Wenkel *et al.* (2013)
	Early warning systems	Lowe *et al.* (2011); Marvin *et al.* (2013); Lenton (2013)
Policy	Integrated resource and infrastructure planning	Rosenberg *et al.* (2010); Becker *et al.* (2012); Heeres *et al.* (2012)
	Spatial planning	Brown (2011); Wheeler (2012); Pinto *et al.* (2013)
	Design/planning standards	Hamin and Gurran (2009); Mailhot and Duchesn (2009); Kwok and Rajkovich (2010); Ren *et al.* (2011); Nassopoulos *et al.* (2012)
Learning	Experience with climate vulnerability and disaster risk	Fiksel (2006) ; Crespo Cuaresma *et al.* (2008); Cuttter *et al.* (2012)
	Learning-by-doing	Berkhout *et al.* (2006); Roberts *et al.* (2012); Bulkeley and Castán Broto (2012)
	Monitoring and evaluation	GIZ, 2011a,b; Preston *et al.* (2011a), Adaptation Sub-Committee (2012)
Innovation	Technological change	Hanjra and Qureshi (2010); Chhetri *et al.* (2012); Lybbert and Sumner (2012); Rodima-Taylor *et al.* (2012); Vermeulen *et al.* (2012)
	Infrastructure efficiencies	Beard *et al.* (2009); Newton (2013)
	Digital/mobile telecommunications	Ospina and Heeks (2010a, b); Meera *et al.* (2012)

Table 16-2: Examples of potential trade-offs associated with an illustrative set of adaptation options that could be implemented by actors to achieve specific management objectives.

Sector	Actor's Adaptation Objective	Adaptation Option	Real or Perceived Trade-Off	References
Agriculture	Enhance drought and pest resistance; enhance yields	Biotechnology and genetically modified crops	Perceived risk to public health and safety; ecological risks associated with introduction of new genetic variants to natural environments	Howden *et al.* (2007); Nisbet and Scheufele (2009); Fedoroff *et al.* (2010)
	Provide financial safety net for farmers to ensure continuation of farming enterprises	Subsidized drought assistance; crop insurance	Creates moral hazard and distributional inequalities if not appropriately administered	Productivity Commission (2009); Pray *et al.* (2011); Trærup (2011); O'Hara (2012); Vermeulen *et al.* (2012)
	Maintain or enhance crop yields; suppress opportunistic agricultural pests and invasive species	Increased use of chemical fertilizer and pesticides	Increased discharge of nutrients and chemical pollution to the environment; adverse impacts of pesticide use on non-target species; increased emissions of greenhouse gases; increased human exposure to pollutants	Gregory *et al.* (2005); Howden *et al.* (2007); Boxall *et al.* (2009)
Biodiversity	Enhance capacity for natural adaptation and migration to changing climatic conditions	Migration corridors; expansion of conservation areas	Unknown efficacy; concerns over property rights regarding land acquisition; governance challenges	Hodgson *et al.* (2009); West *et al.* (2009); Krosby *et al.* (2010); Levin and Petersen (2011)
	Enhance regulatory protections for species potentially at-risk due to climate and non-climatic changes	Protection of critical habitat for vulnerable species	Addresses secondary rather than primary pressures on species; concerns over property rights; regulatory barriers to regional economic development	Clark *et al.* (2008); Ragen *et al.* (2008); Bernanzzani *et al.* (2012)
	Facilitate conservation of valued species by shifting populations to alternative areas as the climate changes	Assisted migration	Ultimate success of assisted migration is difficult to predict; introduction of species into new ecological regions could have adverse impacts on indigenous flora and fauna	Lovejoy (2005, 2006); McLachlan *et al.* (2007); Dunlop and Brown (2008)
Coasts	Provide near-term protection to financial assets from inundation and/or erosion	Sea walls	High direct and opportunity costs; equity concerns; ecological impacts to coastal wetlands	Nicholls (2007); Hayward (2008); Hallegatte (2009); Zhu *et al.*, (2010)
	Allow natural coastal and ecological processes to proceed; reduce long-term risk to property and assets	Managed retreat	Undermines private property rights; significant governance challenges associated with implementation	Rupp-Armstrong and Nicholls (2007); Hayward (2008); Abel *et al.* (2011); Titus (2011)
	Preserve public health and safety; minimize property damage and risk of stranded assets	Migration out of low-lying areas	Loss of sense of place and cultural identify; erosion of kinship and familial ties; impacts to receiving communities	Hess *et al.* (2008); Heltberg *et al.* (2009); McNamara and Gibson (2009); Adger *et al.* (2011)

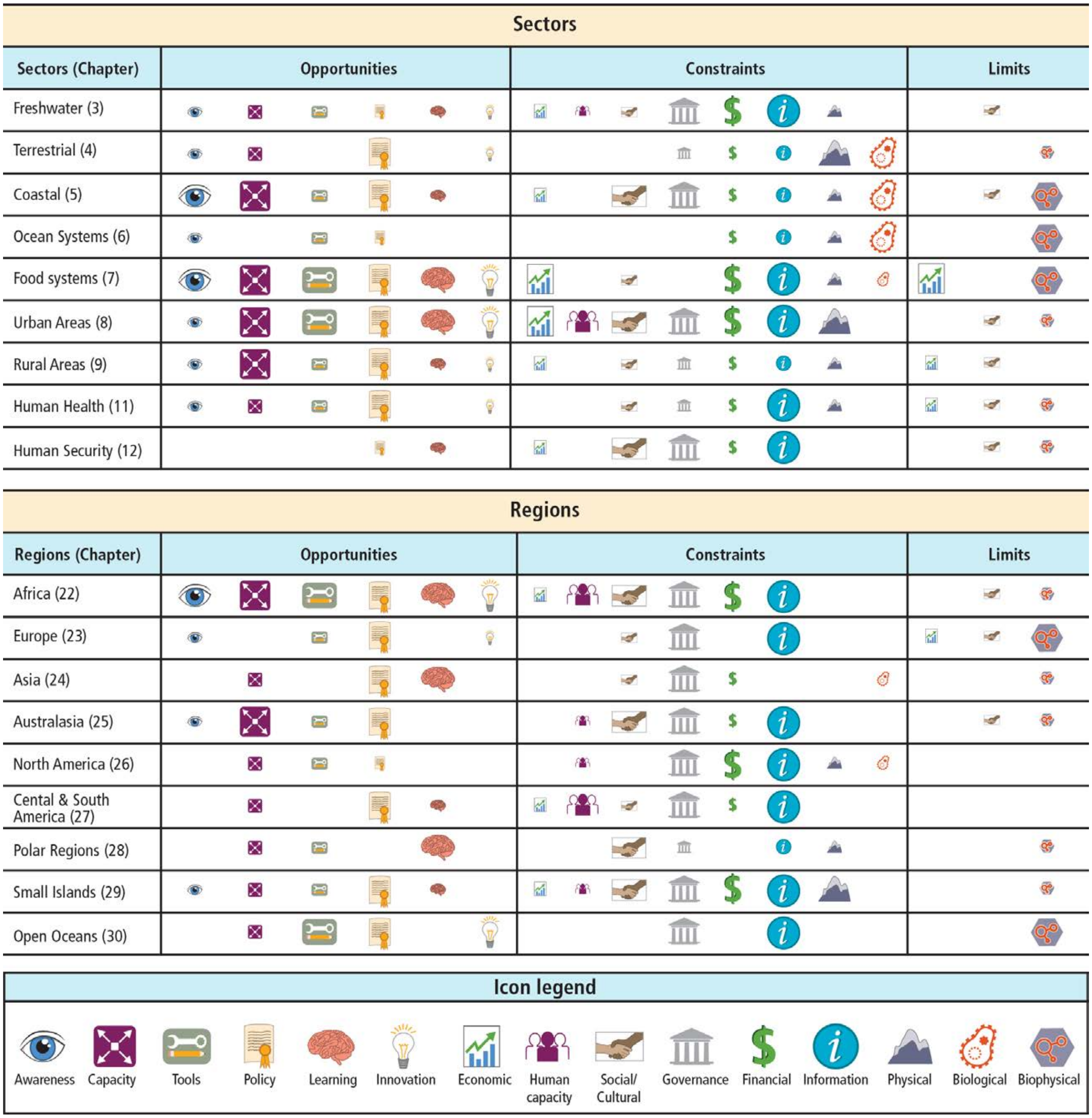
Water resources management	Increase water resource reliability and drought resilience	Desalination	Ecological risk of saline discharge; high energy demand and associated carbon emissions; creates disincentives for conservation	Adger and Barnett (2009); Barnett and O'Neill (2010); Becker *et al.* (2010, 2012); Rygaard *et al.* (2011); Tal *et al.* (2011)
	Maximize efficiency of water management and use; increases flexibility	Water trading	Undermines public good/social aspects of water	Alston and Mason (2008); Bourgeon *et al.* (2008); Donohew (2008); Mooney and Tan (2012); Tan *et al.* (2012)
	Enhance efficiency of available water resources	Water recycling/reuse	Perceived risk to public health and safety	Hartley (2006); Dolcinar *et al.* (2011)

Table 16-3. Sectoral and regional synthesis of adaptation opportunities, constraints, and limits. Each icon represents types of opportunities, constraints and limits (described below). The size of the icon represents when there is relatively little (small icon) or relatively ample (large icon) information in the sectoral and regional chapters to describe each type of opportunity, constraint, or limit. If no information was presented, the table cell is blank.

Opportunities are defined *as factors that make it easier to plan and implement adaptation actions, that expand adaptation options, or that provide ancillary co-benefits.* Types of opportunities include (1) **Awareness -** communication, education and awareness raising; (2) **Capacity -** human and institutional capacity building including preparedness, resource provision, and development of human and social capital; (3) **Tools -** decision-making, vulnerability and risk analysis, decision support and early warning tools; (4) **Policy -** integration and mainstreaming of policy, governance and planning processes including sustainable development, resource and infrastructure planning, and design standards; (5) **Learning -** mutual experiential learning and knowledge management of climate vulnerability, adaptation options, disaster risk response, monitoring and evaluation; and (6) **Innovation -** development and dissemination of new information, technology development, and technology application.

Constraints *are defined as factors that make it harder to plan and implement adaptation actions*. Types of constraints include (1) **Economic -** existing livelihoods, economic structures and economic mobility; (2) **Social** and cultural **-** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support; (3) **Human capacity -** individual, organizational, and societal capabilities to set and achieve adaptation objectives over time including training, education, skill development; (4) **Governance,** Institutions & Policy - existing laws, regulations, procedural requirements, governance scope, effectiveness, institutional arrangements, adaptive capacity, and absorption capacity; (5) **Financial -** lack of financial resources; (6) **Information**/ Awareness/ Technology - lack of awareness or access to information or technology; (7) **Physical -** presence of physical barriers; and (8) **Biological -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind**.**

*A **Limit** is defined* as the *point at which an actor's objectives or system's needs cannot be secured from intolerable risks through adaptive actions*. Types of limits include (1) **Biophysical -** temperature, precipitation, salinity, acidity, intensity and frequency of extreme events including storms, drought and wind, (2) **Economic -** existing livelihoods, economic structures and economic mobility; and (3) **Social/cultural -** social norms, identity, place attachment, beliefs, worldviews, values, awareness, education, social justice, and social support.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Sectors (Chapter)
Opportunities
Constraints
Limits
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Terrestrial (4)
Coastal (5)
Ocean Systems (6)
Food systems (7)
Urban Areas (8)
Rural Areas (9)
Human Health (11)
Human Security (12)
Regions
Regions (Chapter)
Opportunities
Constraints
Limits
Africa (22)
Europe (23)
Asia (24)
Australasia (25)
North America (26)
Cental & South America (27)
Polar Regions (28)
Small Islands (29)
Open Oceans (30)
Icon legend
Awareness
Capacity
Tools
Policy
Learning
Innovation
Economic
Human capacity
Social/ Cultural
Governance
Financial
Information
Physical
Biological
Biophysical

16-4: Ethical dimensions of adaptation opportunities, constraints, and limits and their policy implications.

Ethical dimensions	Commentary	Public policy issues	References
Adaptation opportunities			
Access to opportunities	Inequitable access to the factors making it easier to adapt and achieve adaptation objectives	Whether national or international policy should support more equitable access to adaptation opportunities	Thomas and Twyman (2005); Paavola and Adger (2006); Paavola, (2008); Füssel (2010); Rübbelke (2011); Klinsky *et al.* (2012)
Adaptation constraints			
Distribution of constraints	Inequitable distribution of factors that make it harder to plan and implement adaptation actions	Whether national or international policy should reduce or remove constraints to adaptation	Paavola and Adger, (2006); Klein and Möhner (2009); Grasso (2010)
Adaptation limits			
Differing attitudes to risk	What is deemed an acceptable, tolerable and intolerable risk will vary across cultures, social groups and individuals	Risk governance is concerned with balancing differentiated and dynamic attitudes to risk in allocating resources to managing risks	Bisaro *et al.* (2010); Juhola *et al.* (2011); Lata and Nunn (2012); Sovacool (2012); Fatti and Patel (2013); Ward *et al.* (2013)
Rights and potentials of people to secure particular valued objectives	Limits are related to given valued objectives, but such objectives vary between individuals and collectives	Risk governance related to adaptation limits is concerned with setting priorities between different (and conflicting) valued objectives	Foale (2008); Devine-Wright (2009); Gorman-Murray (2010); Jacob *et al.* (2010); Brown *et al.* (2011); Adger *et al.* (2012)
Differing rates at which limits are reached	Limits will be reached earlier by some groups and regions (Arctic, unprotected coastal zones) than others	Risk governance at different scales will be confronted with choices about adaptation limits emerging through time	Baum and Easterling (2010); Edvardsson-Bjornberg and Hansson (2011); Dow *et al.* (2013a)
Trade-offs in securing valued objectives	Adaptive responses will involve choices between valued objectives at adaptation limits (i.e. between river water quality and water demand from irrigation)	As adaptation limits affecting multiple valued objectives are reached, private and public choices will be made about which values have priority over others	Steenberg *et al.* (2011); Towler *et al.* (2012); Seidl and Lexer (2013); Pittock (2013)
Intergenerational and interspecies equity and adaptation limits	Valued objectives may be irrecoverably lost at adaptation limits, denying them to future generations	Species extinctions, and loss cultural heritage, place or identity may call for extraordinary public policy interventions	Albrecht *et al.* (2013)

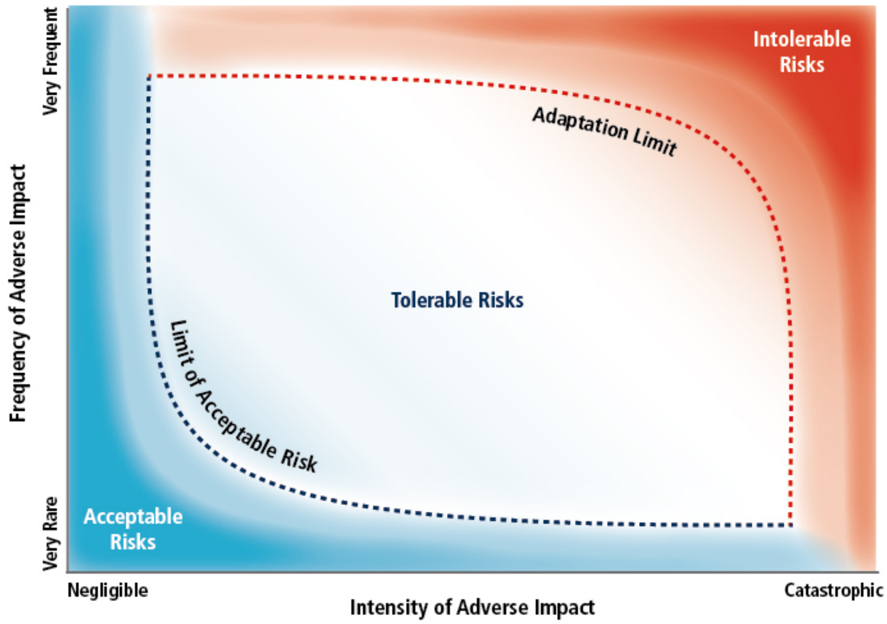

Figure 16-1: Conceptual model of the determinants of acceptable, tolerable and intolerable risks and their implications for limits to adaptation (Dow *et al.*, 2013b; based on Klinke and Renn, 2002; also see Renn and Klinke 2013). In this conceptual diagram, adaptation efforts are seen as keeping risks to objectives within the tolerable risk space. Opportunities and constraints influence the capacity of actors to maintain risks within a tolerable range. The lines are dotted to indicate that individual or collective views on risk tolerability with respect to the frequency and intensity of climate-related risks are not fixed, but may vary and change over time. In addition, the shape or angle of the lines and the relative area in each section of the diagram are illustrative and may themselves change as capacities and attitudes change. The shaded areas represent the potential differences in perspective among actors.

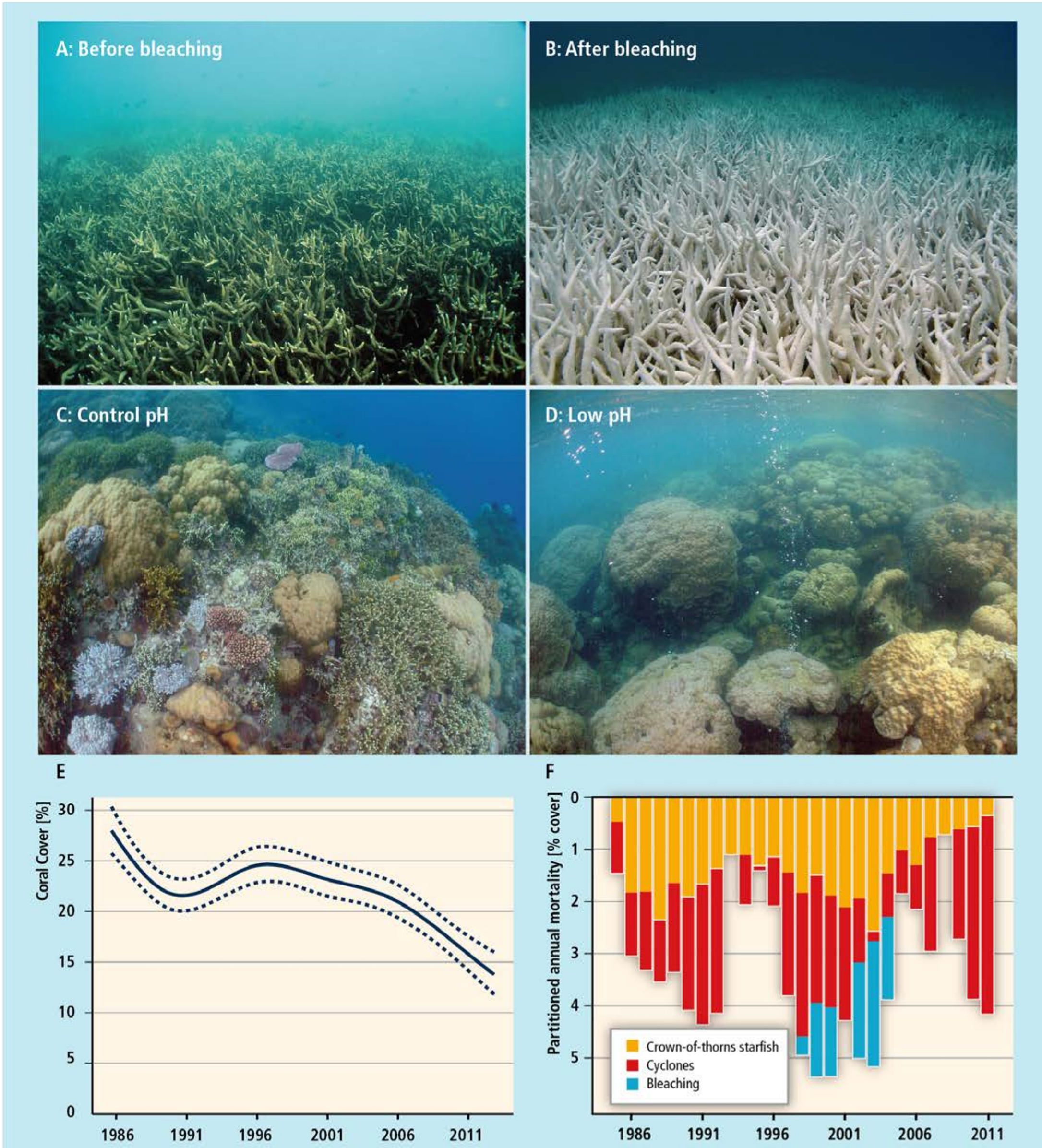

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

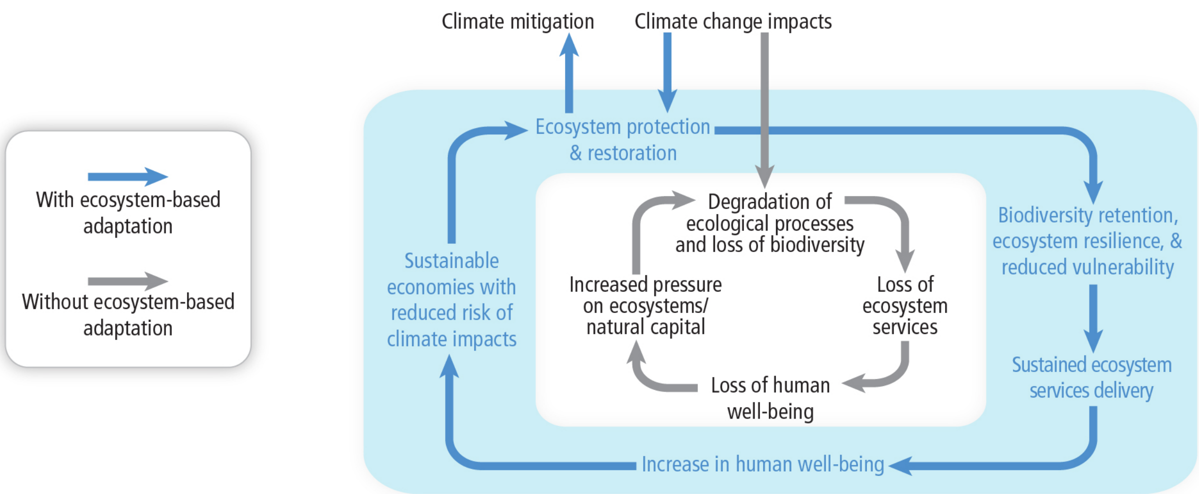

Figure EA-1: Adapted from Munang et al. (2013). Ecosystem based adaptation (EBA) uses the capacity of nature to buffer human systems from the adverse impacts of climate change. Without EBA, climate change may cause degradation of ecological processes (central white panel) leading to losses in human well-being. Implementing EBA (outer blue panel) may reduce or offset these adverse impacts resulting in a virtuous cycle that reduces climate-related risks to human communities, and may provide mitigation benefits.

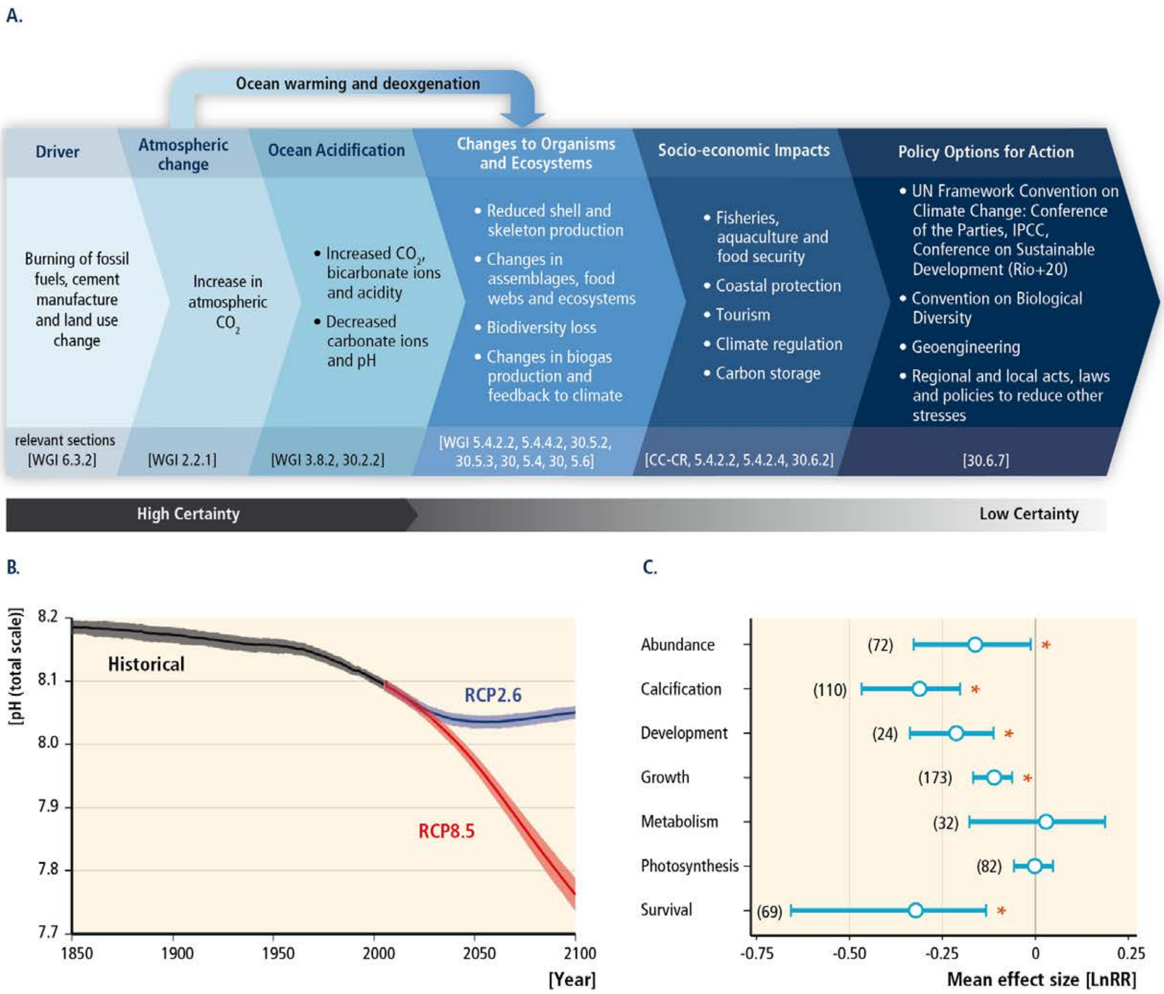

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.

Chapter 17. Economics of Adaptation

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Contents

Executive Summary

In the presence of limited resources and a range of objectives, adaptation strategy choices involve trade-offs among multiple policy goals *(high confidence)*. The alternative policy goals include development and climate change mitigation. Economics offers valuable insights into these trade-offs and into the wider consequences of adaptation. It also helps to explain the differences between the potential of adaptation and its achievement as a function of costs, barriers, behavioral biases, and resources available. [17.2.7.1, 17.2.7.2, 17.3.1]

Economic thinking on adaptation has evolved from a focus on cost benefit analysis and identification of "best economic" adaptations to the development of multi-metric evaluations including the risk and uncertainty dimensions in order to provide support to decision makers (*high confidence*). Economic analysis is moving away from a unique emphasis on efficiency, market solutions, and benefit/cost analysis of adaptation to include consideration of non-monetary and non-market measures; risks; inequities; behavioral biases; barriers and limits and consideration of ancillary benefits and costs. One role of economics is to contribute information to decision makers on the benefits and costs, including a number of non-monetary items, and on the equity impacts of alternative actions. It does not provide a final ranking for policy makers. A narrow focus on quantifiable costs and benefits can bias decisions against the poor and against ecosystems and those in the future whose values can be excluded or are understated. Sufficiently-broad-based approaches, however, can help avoid such maladaptation. Indeed the evidence shows that maladaptation is a possibility if the evaluation approaches taken are not comprehensive enough in this sense. [17.2.3, 17.3.2]

The theoretical basis for economic evaluation of adaptation options is clear, and can be and has been applied to support decisions in practical contexts *(medium confidence)*. There is extensive experience of applying the concepts and methods underlying the economic framework in non-adaptation contexts, which is useful for designing climate adaptation policies. The limited empirical evidence available shows a number of cases where desirable adaptation strategies have been identified based on these economic tools. The findings show that adaptation is highly regional and context specific. Thus the results do not readily permit widespread generalizations about the nature of attractive adaptation actions. [17.2, 17.4.1, 17.4.2, 17.4.4].

Both private and public sectors have a role to play in the development and implementation of adaptation measures *(high confidence)*. Economic theory and empirical results show that a degree of adaptation will be autonomously carried out by private parties in response to climate change. However the private sector alone will often not provide the desirable level of adaptation with some types of actions not undertaken due to costs, incentives, nature of beneficiaries and resource requirements. This implies the public sector will need to play a strong role. There are also other reasons for public action such as overcoming barriers, developing technologies, representing current and future equity concerns and other items. [17.2.1, 17.3.1]

The theory and the evidence indicate that adaptation cannot generally overcome all climate change effects (*high confidence*). In addition to there being biophysical limits to adaptation, such as the inability to restore outdoor comfort under high temperatures, some adaptation options will simply be too costly or resource intensive or will be cost ineffective until climate change effects grow to merit investment costs. Thus the desirability of adaptation options will vary with time and climate change realization. [17.2.2, 17.2.5]

Adaptation generally needs to be seen in the frame of the overall development path of the country, particularly for developing countries *(high confidence)*. Development and adaptation can be complementary or competitive. Also development can yield positive ancillary adaptation effects or co-benefits, provided it takes into account climate change in its design. Adaptation actions can provide significant co benefits such as alleviating poverty or enhancing development**.** Many aspects of economic development also facilitate adaptation to a changing climate, such as better education and health, and there are adaptation strategies that can yield welfare benefits even in the event of a constant climate, such as more efficient use of water and more robust crop varieties. Maximizing these synergies requires a close integration of adaptation actions with existing policies, referred to as “mainstreaming”. [17.2.7, 17.2.3.1, 17.2.3.2]

Not all adaptation actions are investment-based. Policy actions are also important tools for adaptation (*medium confidence*). These include direct R&D funding, environmental regulation, economic instruments, and education. Economic instruments have high potential as flexible tools because they directly and indirectly provide incentives for anticipating and reducing impacts and can have lower costs to the public budget. These instruments are currently not well explored in an adaptation context apart from risk financing instruments. Existing incentives will lead to a set of private adaptation actions. They include risk sharing and transfer mechanisms (insurance), loans, public private finance partnerships, payment for environmental services, improved resource pricing (water markets), charges and subsidies including taxes, norms and regulations, and behavioral modification approaches. These instruments offer some useful possibilities for addressing climate change but they also have problems of effective implementation that need to be addressed. The problems can be particularly severe in developing countries. [17.4, 17.5]

Risk financing mechanisms at local, national, regional, and global scales contribute to increasing resilience to climate extremes and climate variability, but involve major design challenges so as to avoid providing disincentives, causing market failure and worsening equity situations (*medium confidence*). Mechanisms include insurance, reinsurance, micro insurance, and national, regional and global risk pools. The public sector often plays a key role as regulator, provider or insurer of last resort. Risk financing can directly promote adaptation through providing claim payments after an event, and allow for improved decisions under risk pre-event (strong evidence). It can also directly provide incentives for reducing risk, yet the evidence is weak and the presence of many counteracting factors often leads to disincentives, which is known as moral hazard.[17.5.1]

Global adaptation cost estimates are substantially greater than current adaptation funding and investment, particularly in developing countries, suggesting a funding gap and a growing adaptation deficit (limited evidence, *medium confidence*). The most recent global adaptation cost estimates suggest a range from $70 billion to $100 billion per year globally by 2050, but there is little confidence in these numbers. The evidence base is limited and there is strong evidence of important omissions and shortcomings in data and methods rendering these estimates highly preliminary (*high confidence*). Comparison of the global cost estimates with the current level of adaptation funding shows the projected global needs to be orders of magnitude greater than current investment levels particularly in developing countries**(***limited evidence***)**. [17.4.1, 17.4.2, 17.4.4].

Economics offers a range of techniques appropriate for conducting analysis in the face of uncertainties, and the choice of the most appropriate technique depends on the nature of the problem and the nature and level of uncertainty (*high confidence*).Uncertainty is unavoidable in analyses of adaptation to climate change because of lack of data, the efficacy of adaptation actions and because of uncertainties inherent in forecasting climate change. Approximate approaches are often necessary. There is a strong case for the use of economic decision-making under uncertainty, working with tools such as cost-benefit and related approaches that include a time dimensions (real options techniques), multi-metrics approaches and non-probabilistic methodologies. There are methodologies that are able to capture non-monetary effects and distributional impacts, and to reflect ethical considerations. [17.3.2.1, 17.3.2.2, 17.3.2.3]

Selected regional and sectoral studies suggest some core considerations and characteristics that should be included in the economic analyses of adaptation (*medium confidence*). These desirable characteristics include: a broad representation of relevant climate stressors to ensure robust economic evaluation; consideration of multiple alternatives and/or conditional groupings of adaptation options; rigorous economic analysis of costs and benefits across the broadest possible market and nonmarket scope; and a strong focus on support of practical decision-making that incorporates consideration of sources of uncertainty. Few current studies manage to include all of these considerations [17.4.3].

17.1. Background

This chapter assesses the literature on the economics of climate change adaptation, building on the Fourth Assessment Report (AR4) and the increasing role that economic considerations are playing in adaptation decision-making and policy. AR4 provided a limited assessment of the costs and benefits of adaptation, based on narrow and fragmented sectoral and regional literature (Adger *et al*, 2007). Substantial advances have been made in the economics of climate change adaptation after AR4.

What are the Objectives of Adaptation?

The specific objectives involved in an adaptation effort can be diverse. One may try to cancel all impacts (negative and positive), maintaining the status quo. Alternatively one can try to cancel adverse impacts and capture positive opportunities, so that the welfare gain (or loss) is maximized (or minimized).

Part of the literature presents adaptation as a continuous, flexible process, based on learning and adjustments (IPCC SREX, Ch 8). Adaptation projects informed by this approach emphasize learning and experimenting, plus the value of using reversible and adjustable strategies (Berkhout *et al.*, 2006; Pelling *et al.*, 2007; Leary et al., 2008; McGray et al., 2007; Hallegatte, 2009; Hallegatte et al., 2011c).

Adaptation action and policy has also advanced since AR4, and the literature on the economics of adaptation has reflected this. This chapter builds on other chapters in this assessment, in particular Chapter 2, which sets the basis for decision-making, recognizing economics as a decision support tool for both public and private actors. The type of economic approach used depends on factors discussed in Chapter 2 among others, including the agent making the decision, the nature or type of decision, the information used to make the decision, who implements the decision, others affected by the outcomes and the values attached to those outcomes. While realizing the linkages between adaptation and mitigation, the starting point of this chapter is that adaptation is a given need.

This chapter assesses the scientific literature covering: the economic aspects of adaptation; decision making and economic context of adaptation, including economic barriers to adaptation decision making, and uncertainty; costing adaptation; and the economic and related instruments to provide incentives for adaptation.

17.2. Economic Aspects of Adaptation

When considering adaptation, economic studies give insight into issues regarding the roles of various actors in society, the character of adaptation strategies, the types of benefits and costs involved, the role of time and a number of other factors that we discuss in this section.

17.2.1. Public and Private Actors in Adaptation Implementation

Previous IPCC reports (TAR and FAR) indicate adaptation actions can be autonomous, planned or natural through ecological systems. Autonomous actions are mostly undertaken by private parties while planned can be undertaken by private or public actors. Natural adaptation is that occurring within the ecosystem in reaction to climate change but may be subject to human intervention (See discussion in chapter 14 section 14.1).

In terms of human actions there are important economic distinctions regarding the roles of private and public actors. Some adaptation actions create public goods that benefit many and in such cases the implementing party cannot typically capture all the gains. For example if an individual pays to protect a coastline or develop an improved irrigation system the gains generally go to many others. Classical economic theory (Samuelson, 1954) and experience plus observations regarding adaptation (Mendelsohn, 2000, Osberghaus et al 2010, Wing and Fisher-Vanden. 2013) indicate that such actions will not receive appropriate levels of private investment (creating a market failure). In turn, this calls for public action by elements of broader society (e.g. governments, NGOs, or international organizations). Other reasons for public provision or public regulation of certain adaptation measures that lead to less than a socially desirable level of adaptation are discussed in section 17.3.

17.2.2. Broad Categorization of Adaptation Strategies

There are many possible adaptation measures, as indicated in the TAR and FAR plus chapters 14 and 15. In economic terms these include a mixture of public and private actions taken in both domestic and international settings. A broad characterization of these and who might undertake them follows:

- Altered patterns of enterprise management, facility investment, enterprise choice or resource use (mainly private)
- Direct capital investments in public infrastructure (e.g. dams and water management - mainly public)
- Technology development through research (e.g. development of crop varieties - private and public)
- Creation and dissemination of adaptation information (through extension or other communication vehicles mainly public)
- Human capital enhancement (investment in education - private and public)
- Redesign or development of adaptation institutions (e.g. altered forms of insurance - private and public)
- Changes in norms and regulations to facilitate autonomous actions (e.g. altered building codes, technical standards, regulation of grids/networks/utilities, environmental regulations-mainly public)
- Changes in individual behavior (private with possible public incentives)
- Emergency response procedures and crisis management (mainly public)

Not all adaptation involves investment or is costly. Some adaptation measures involve modification of recurring expenditures as opposed to new investments (replacing depreciated equipment with more adapted items). Sometimes adaptation involves changes in behaviors and lifestyles (e.g. due to increased frequency of heat waves).

17.2.3. Broad Definition of Benefits and Costs

The consequences of adaptation decisions cannot be expressed comprehensively through standard economic accounting of costs and revenues. Adaptation decisions can also affect other items such as income distribution and poverty (Jacoby et al, 2011), the regional distribution of economic activity, including employment, non-market factors such as water quality, ecosystem function, and human health, and social organization and cultural practices.

Adaptation choices have broad ranging and complex impacts on such issues as:

- Macroeconomic performance (see, e.g., Fankhauser and Tol, 1995);
- Allocation of funds with a crowding out effect on other climate and non-climate investments with consequences for future economic growth (Hallegatte et al., 2007; Hallegatte and Dumas, 2008; Wang and McCarl, 2013)
- Welfare of current and future generations through resource availability and other non-monetary effects
- Risk distributions on all of the above due to routine variability plus uncertain estimates of the extent of climate change, adaptation benefits and costs.

A number of these items pose challenges for measurement and certainly for monetization. Generally this implies that any analysis be multi metric with part in monetary terms and other parts not, some in precise quantitative terms and others not (for more discussion see section 17.3). Also in view of this it is reasonable to conclude that an unbiased, comprehensive analysis would consist of a multi metric analysis encompassing cost benefit and other monetary items plus non-monetary measures. That analysis would support adaptation decision-making.

17.2.3.1. Ancillary Economic Effects of Adaptation Measures and Policies

In addition to creating an economy that is more resilient to the effects of climate change, adaptation strategies often have ancillary effects of substantial importance. These can be positive (co-benefits) or negative (co-costs). Ancillary effects also arise when actions primarily aimed at mitigation or non-climate related matters alter climate adaptation. Examples include:

- Sea walls that protect against sea level rise and at the same time protect against tsunamis. However they can also have co-costs causing damages to adjacent regions, fisheries and mangroves (Frihy, 2001);
- Crop varieties that are adapted to climate change have enhanced resistance to droughts and heat and so also raise productivity in non-climate change related droughts and temperature extreme (Birthal et al, 2011);
- Better building insulation which mitigates energy use and associated greenhouse gas emissions also improves adaptation by protecting against heat (Sartori and Hestnes, 2007);
- Public health measures that adapt to increases in insect-borne diseases also have health benefits not related to those diseases (Egbendewe-Mondzozo et al, 2011);
- More efficient use of water –adaptation to a drier world- will also yield benefits under current conditions of water scarcity. Development of improved desalination methods has the same merits (Khan et al, 2009);
- Locating infrastructure away from low-lying coastal areas provides adaption to sea level rise and will also protect against tsunamis;
- Reducing the need to use coal-fired power plants though energy conserving adaptation will also provide mitigation, improve air quality and reduce health impacts (Burtraw et al, 2003).

17.2.3.2. Economic Consideration of Ancillary Effects

Many studies argue that co-benefits should be factored into decision making (e.g. Viguie and Hallegatte (2012), Kubal et al. (2009), De Bruin et al. (2009), Brouwer and van Ek (2004), Ebi and Burton (2008), and Qin et al. (2008)). If a country has a fixed sum of money to allocate between two competing adaptation projects, and both strategies generate net positive ancillary effects, then the socially optimal allocation of adaptation investment will differ from the private optimum and will favor the activity with the larger direct plus ancillary effects.

17.2.4. Adaptation as a Dynamic Issue

Adaptation is not a static concern. Rather it evolves over time in response to a changing climate (Hallegatte, 2009). Adaptation is perhaps best handled via a long-term transitional, continuous, flexible process that involves learning and adjustment (IPCC SREX, Ch 8; Berkhout *et al.*, 2006; Pelling *et al.*, 2007; Leary et al., 2008; McGray et al., 2007; Hallegatte, 2009; Hallegatte et al., 2011c). Generally the literature indicates that optimal adaptation and the desirability of particular strategies will vary over time depending on climate forcing plus other factors like technology availability and its maturity (De Bruin et al, 2009b). In the next few decades, during which time projected temperatures do not vary substantially across socioeconomic/climate scenarios, adaptation is the main economic option for dealing with realized climate change. Risk is also an important aspect with the longer term being more uncertain that the near term. Risk-sensitive decisions often include the options of acting or of waiting (Linquiti and Vonortas, 2012). The issue of options is discussed further in Beltratti, Chichilnisky and Heal (1998) which covers uncertainty about future preferences through option values.

Dynamics also are involved with strategy persistence due to the decadal to century time scale implications of some adaptation strategies like construction of seawalls or discovery of drought resistant crop genes. The desirability of investments with upfront costs and persistent benefits increases when the benefits are long lasting or when climate change damages accumulate slowly (de Bruin 2011, Agrawala et al, 2011; Wang and McCarl, 2013). However, maladaptation effects rising over time are also possible as protecting now can expand investment in vulnerable areas and worsen future vulnerability (Hallegatte, 2011).

17.2.5. Practical Adaptation Strategy Attractiveness and Feasibility

Adaptation cannot reasonably overcome all climate change effects (Parry et al 2009). A number of factors will limit strategy adoption and preclude elimination of all climate change effects. A conceptual way of looking at this for a given adaptation endeavor is in Figure 17-1. The first outside circle represents the "adaptation needs", i.e. the set of adaptation actions that would be required to avoid any negative effect (and capture all positive effects) from climate change. It can be reduced by climate change mitigation, i.e. by limiting the magnitude of climate change. The second circle represents the subset of adaptation actions that are possible considering technical and physical limits. Improving what can be done, for instance through research and development, can expand this circle. The area between the first and second circles is the area of "unavoidable impacts" that one cannot adapt to (for instance, it is impossible to restore outdoor comfort under high temperature). The third circle represents the subset of adaptation actions that are desirable considering limited resources and competing priorities: some adaptation actions will be technically possible, but undesirable because they are too expensive and there are better alternative ways of improving welfare (e.g., investing in health or education). This circle can be expanded through economic growth, which increases resources that can be dedicated to adaptation. Finally, the last circle represents what will be done, taking into account the fact that market failures or practical, political, or institutional constraints will make it impossible to implement some desirable actions (see chapter 15 and section 17.3). The area between the first and the last circles represents residual impacts (i.e. the impacts that will remain after adaptation, because adapting to them is impossible, too expensive, or impossible due to some barriers).

[INSERT FIGURE 17-1 HERE
Figure 17-1: The narrowing of adaptation from the space of all possible adaptations to what will be done. Forces causing the narrowing are listed in black.]

This discussion has consequences for timing of adaptation financing, given continuous changes in climate over time and uncertainties in the resulting impacts. Mathew et al. (2012) recommend the use of soft, short-term and reversible adaptation options with co-benefits for local governments. Giordano (2012) recommends the use of adaptive policies for modifying infrastructure, which can be robust across a wide range of plausible futures under climate change. Hochrainer and Mechler (2011) suggest that tools such as risk pooling may be more cost effective than risk reduction through engineering methods for low frequency but high impact hazards.

Financing adaptation programs is further discussed in the literature through the lens of distribution of costs. Stern, 2006) argues climate change is characterized by a "double inequity" with those countries that are most vulnerable having generally contributed least (on a per capita basis) to the climate change drivers (Panayotou *et al.*, 2002; Tol *et al.*, 2004; Mendelsohn *et al.*, 2006; Patz *et al.*, 2007; SEGCC, 2007; Srinivasan *et al.*, 2008; Füssel, 2010).

The distribution of responsibilities for financing adaptation has been subject of lively debate. Füssel et al. (2012) note that answering the following questions can inform the debate on such burden sharing issues:

- Who pays for adaptation and how much should they contribute into the adaptation fund and what criteria are appropriate in determining this?
- Who is eligible for receiving payments from the fund, and which criteria could be used for prioritising recipients and for allocating funds?
- Which adaptation measures are eligible for funding, and what are the conditions and modalities for payment?
- How and by whom are such decisions made?

As of now no definitive conclusions have been reached. Table 17-1 sets out different approaches to defining eligibility for receiving adaptation funds.

[INSERT TABLE 17-1 HERE
Table 17-1: Four definitions of eligible adaptation.]

17.2.6. Adaptation Benefits and Costs, Residual Damage and Projects

Adaptation benefits are the reduction in the damages plus any gains in climate related welfare that occur following an adaptation action. (U.S. National Academy of Sciences, 2010; World Bank 2010). Simplistically the cost of adaptation is the cost of any additional investment needed to adapt to or exploit future climate change (UNFCCC, 2007). But a full accounting needs to consider the resources spent to develop, implement and maintain the adaptation action along with accruing reduced damages or welfare increases involving monetary and non- monetary metrics.

Figure 17-2 provides a graphical representation of the link between the cost of adaptation (on the X-axis) and the residual cost of climate change (on the Y-axis). A fraction of climate change damage can be reduced at no cost (e.g. by changing sowing dates in the agricultural sector). With increasing adaptation cost, climate change costs can be reduced further. In some cases (left-hand panel), sufficiently high adaptation spending can take residual cost to zero. In other cases (right-hand panel), some residual cost of climate change is unavoidable. Economics tells that the optimal level of adaptation equalizes the marginal adaptation cost and the marginal adaptation benefit, given by the point on the adaptation curves where the slope is -45^{o}. If barriers and constraints (see section 17.3) impose a suboptimal situation, the marginal costs and benefits of adaptation are not equal, possibly because there is too much investment in adaptation, so that investing $1 in adaptation reduces climate change residual cost by less than $1, or because there is not enough investment in adaptation and investing $1 more in adaptation would reduce residual cost by more than $1 (the situation in the right-hand panel).

[INSERT FIGURE 17-2 HERE
Figure 17-2: Graphical representation of link between the cost of adaptation (on the X-axis) and the residual cost of climate change (on the Y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs.]

Defining the costs and benefits of an “adaptation project” raises conceptual issues. Many actions have an influence on the impact of climate change without being adaptation projects per se (e.g., enhanced building norms). Many “adaptation projects” have consequences beyond a reduction in climate change impacts or an increase in welfare from exploiting opportunities (as discussed in the ancillary impacts section). Defining the adaptation component requires the definition of a baseline (What would be the impact of climate change in absence of the adaptation action? What alternative projects would be implemented in the absence of climate change?), and the definition of “additionality” – what amount of additional loss reduction or welfare gain happens because of the project. For instance, the building of new infrastructure may be marginally more costly because of adaptation to climate change but would still be undertaken without climate change and thus only a fraction of that cost and the resultant benefits would be labeled as occurring because of adaptation (See Dessai and Hulme 2007.)

In the climate change context, residual damages are those damages that remain after adaptation actions are taken. De Bruin et al (2009b) and Hof et al (2009) have examined the relationship between increasing adaptation effort and diminished residual damages.

17.2.7. A Broader Setting for Adaptation

Adaptation can be complementary to mitigation and to non-climate policies. An important concern is determining the balance between spending on adaptation versus that on other investments – mitigation and non-climate endeavors. Economics indicates the marginal social returns to all forms of expenditure should be the same, allowing for distributional impacts (which can be done by differentially weightings of benefits and costs to alternative income groups (Brent, 1996; Musgrave and Musgrave, 1973)).

17.2.7.1. Adaptation and Mitigation as Competitive or Complementary Investments

Adaptation and mitigation funding require coordination as they are competing uses for scarce resources (AR4 WGII chapter 18, Gawel et al, 2012). They also compete with consumption and non-climate investments. For example some adaptation strategies use land (a shift from crops to livestock) as does mitigation via afforestation or biofuels and all three would reduce ongoing crop production. Nevertheless considering both adaptation and mitigation widens the set of actions and lowers the total cost of climate change (de Bruin et al, 2009; Wang and McCarl, 2013; Koetse and Rietveld, 2012).

17.2.7.2. Adaptation and Development

There is a relationship between adaptation and socio-economic development, particularly in lower income countries (as extensively discussed in chapters 10, 13 and 20). In terms of complementarity between the two, studies show that both development and adaptation can be enhanced via: climate resilient road development (World Bank 2009); installation of agricultural investments that enhance income, heat tolerance and drought resilience (Butt et al. 2006, Ringer et al 2008); or improvements in public health infrastructure that increase capability to deal with climate-enhanced disease and other diseases (Samet 2010, Markandya and Chiabai 2009). Additionally development in general can increase adaptive capacity through enhancements in human and other capital (IPCC- SREX, 2012; Schelling 1992, 1997; Tol 2005). Finally adaptation efforts may reduce adaptation deficits regarding vulnerability to existing climate and enhance general development (Burton, 2004). Thus development goals can be generally consistent with adaptation goals, with one possibly being an ancillary effect of the other, although this is not always the case. For example, Hansone et al (2001) find that urbanization of flood-prone areas increases vulnerability and adaptation needs while Burby et al (2001) and Hallegatte (2012) indicate better protection may trigger additional development in at-risk areas and create increased vulnerability to extreme events.

17.3. Decision-Making and Economic Context for Adaptation

Adaptation will be carried out by multiple public and private actors who face a number of decision-making barriers that may limit adaptation. Chapter 16 and many papers (e.g., Fankhauser et al., 1999, Moser and Eckstrom 2010; Cimato and Mullan, 2010; Biesbroek et al 2011; Fankhauser & Soare, 2013) investigate these barriers. This section reviews them from an economic perspective, and then turns to the decision-making frameworks that can help implement adaptation actions in spite of these barriers.

17.3.1. Economic Barriers to Adaptation Decision-Making

17.3.1.1. Transaction Costs, Information, and Adjustment Costs

Transaction costs include the costs of accessing markets and information, along with reaching an agreement and enforcement costs (Coase, 1937 and 1960; Williamson, 1979). Because of transaction costs, a beneficial adaptation action may be undesirable. Two specific types of transaction costs are those relating to information and those relating to adjustment. Information acquisition costs can represent a significant obstacle, for instance when climate and weather data are costly or difficult to access (e.g., Cimato and Mullan 2010; Scott et al 2011; Ford et al. 2011). Since information is a public good, private actors tend to underprovide it and there is a role for government and public authorities to support its production and dissemination (e.g., through research funding, observation networks, or information distribution systems) (Fankhauser et al., 1999; Mendelsohn 2000; Trenberth 2008). Adjustment costs represent another barrier, especially in the presence of uncertainty and learning, and when long-lived capital is concerned. Fankhauser et al (1999) discuss adjustment costs as a barrier to early capital replacement to adapt to a different climate. Kelly and Kolstad (2005) define adjustment costs as the cost incurred while learning about new climate conditions. Using these different definitions, these analyses suggest that adjustment costs can represent a significant share of adaptation costs.

17.3.1.2. Market Failures and Missing Markets

Adaptation may also face market failures such as externalities, information asymmetry, and moral hazards (see 17.2.1; Osberghaus et al 2010). As a consequence, some socially desirable actions may not be privately profitable. For example, flood mitigation measures may not be implemented in spite of their benefits, when flood risks are partly assumed by insurance or post-disaster support, transferring risk to the community (a case of moral hazard, Burby et al., 1991; Laffont 1995). There are also externalities, since adaptation actions by one household, firm, or even country may create higher damages for others. This is the case with trans-boundary waters, when increased irrigation in one country creates water scarcity downstream (Goulden et al 2009). Trans-sector effects can also take place, for instance when adaptation in one sector creates needs in another sector (e.g., the impact on transportation of agriculture adaptation, see Attavanich et al 2013). Incentives for private adaptation actions may also be lacking for public goods and common resources without property rights (e.g., biodiversity and natural areas, tradition and culture). And adaptation may exhibit increasing returns or large fixed costs, leading to insufficient adaptation investments (e.g., Eisenack 2013). In such contexts, public norms and standards, direct public investment, tax measures, or national or international institutions for adaptation coordination are needed to avoid maladaptation.

17.3.1.3. Behavioral Obstacles to Adaptation

Economic agents adapt continuously to climate conditions, though not always using the available information, especially long-term projections of consequences (Camerer and Kunreuther, 1989, Thaler, 1999, Michel-Kerjan, 2008). Individuals often defer choosing between ambiguous choices (Tversky and Shafir 1992; Trope and Lieberman, 2003) and make decisions that are time inconsistent (e.g., they attribute a lower weight to the long term through “hyperbolic discounting”, see Ainslie 1975). They also systematically favor the status quo and familiar choices (Johnson and Goldstein, 2003). Also, individuals value profits and losses differently (Tversky and Kahnman 1974). Behavioral issues may lead to suboptimal adaptation decisions, as illustrated with case studies in Germany and Zimbabwe in Grothmann and Patt (2005). Particularly important is the fact that the provision of climate information needs to account for cognitive failures (Suarez and Patt 2004; Osberghaus et al 2010b). Individual behavioral barriers extend to cultural factors and social norms, which can support or impair adaptation as illustrated by Nielsen and Reenberg (2010) in Burkina Faso.

17.3.1.4. Ethics and Distributional Issues

A difficulty in allocating adaptation resources noted in 17.2.3 is the limitation of indicators based on costs and benefits (Adger et al, 2005; Füssel, 2010). Outcomes are often measured using such methods but their limits are well known, (e.g., CMEPSP, 2009; OECD, 2009, Heal 2012) and include the failure to take into account resource depletion, environmental change, and distributional issues.

Distributional issues may justify public intervention based on ethics and values. Climate change impacts vary greatly by social group, and many have suggested that the poor are particularly vulnerable (e.g., Stern, 2006; Füssel et al. 2012). Some individuals, firms, communities and even countries may be unable to afford adaptation, even if it is in their own interest. Also, individuals with different world views or preferences (e.g., regarding risk aversion, see Adger et al 2009) may ask for different adaptation measures and have different views of what is an acceptable level of residual risk (Peters and Slovic 1996). Consideration of justice and fairness will play a role in adaptation option design (Adger et al 2006; Pelling and Dill, 2009; O'Brien et al., 2009; Dalby 2009; Brauch, 2009a, 2009b; O'Brien et al., 2010b). The implementation of adaptation options may thus require taking into account the political economy of reforms and the need to compensate losers (World Bank 2012).

The traditional economic approach suggests choosing the most cost-effective projects and then resorting to financial transfers to satisfy equity objectives (Atkinson and Stiglitz, 1976; Brown and Heal 1979). However this embodies strong assumptions including the ability to realize perfect and costless financial transfers. In more realistic situations the choice is not so clear cut. In practical terms transfers are difficult to organize and may not be politically acceptable (Kanbur 2010). In these cases, adaptation decision-making needs to account for both the net benefits and the impacts on equity (Aakre and Rübbelke 2010).

17.3.1.5 Coordination, Government Failures, and Political Economy

One of the main roles of governments and local authorities is to remove barriers: realigning the incentives of individuals with the goals of society, providing the public goods needed for adaptation, or helping with behavioral and cognitive biases. But governments and local authorities face their own barriers, often referred to as government or regulatory failures (Krueger 1990). First, government and local authority decision makers, as individuals, face their own barriers, such a cognitive and behavioral biases (Podsakoff et al, 1990). Public decision-makers are also confronted with moral hazard, for instance when subnational entities are provided support from the government in case of disaster (Michel-Kerjan 2008). Second, governments may have access to insufficient resources or limited adaptation capacity, especially in poorer countries and where governments have limited access to capital markets and are unable to fund projects, even when they are cost-efficient (e.g., Smit and Wandel 2006; Brooks et al 2005; World Bank 2012). There can also be coordination failures within the government, since many adaptation options require multi-ministry actions (e.g., the reduction of flood risks may require some prevention measure implemented by the environmental ministry and an insurance scheme regulated by the ministry of finance, World Bank 2013).

Other government failures can arise. Frequently government action is driven by narrow interest groups and is not in the public interest (James 2000, Levine and Forrence 1990). Multi-stakeholders approaches have been shown to help address these problems, a relevant example for this context being coral reef management in Tobago (Adger et al 2005).

17.3.1.6. Uncertainty

Decisions about adaptation have to be made in the face of uncertainty on items ranging from demography and technology to economic futures. Climate change adds additional sources of uncertainty, including uncertainty about the extent and patterns of future climate change (see the AR5 WGI report), which is dependent on uncertain socio-economic development pathways and climate policies (see the AR5 WGIII report), and uncertainty about the reaction and adaptation of ecosystems (see Chapters 3 to 13).

Patt and Schröter (2008) show in a case study in Mozambique that major uncertainties are a strong barrier to successful adaptation. Uncertainty coupled with the long lifespan of a number of options can lead to "maladaptation," i.e. an adaptation action that leads to increased vulnerability. An "*avoidable*" maladaptation arises from a poor *ex ante choice*, where available information is not used properly. An "*unavoidable*" *ex post* maladaptation can result from entirely appropriate decisions based on the information that was the best available *at the time of decision-making*, but subsequently proves to have been wrong. An example of the latter is a precautionary restriction prohibiting new construction in areas potentially at risk of sea level rise. Applying such a precautionary approach makes sense when (i) decisions are at least partly irreversible (e.g., building in flood-prone areas cannot easily be "un-built") and (ii) the cost of a worst-case scenario is very high. Such a precautionary measure can make economic sense *ex ante*, even if sea level rise eventually remains in the lower range of possible outcomes, making the construction restriction unnecessary.

17.3.2. Economic Decision making with Uncertainty

Decision making under uncertainty is a central question for climate change policy and is discussed in many chapters of the AR5, and especially in chapter 2 of WGII and chapters 2 and 3 of WGIII. This section focuses on the economic approaches to decision-making under uncertainty, including decision-making techniques, valuation tools, and multi-metric decision-making.

17.3.2.1. Cost-Benefit Analysis and Related Methods

There are different tools for decision-making that can be applied in different contexts and with different information. Cost-benefit analysis under uncertainty applied to adaptation uses subjective probabilities for different climate futures (e.g., Tebaldi et al., 2005; New and Hulme, 2006; see also chapter 2). The “best” project is the one that maximizes the expected net present value of costs and benefits. Risk aversion can be taken into account through (nonlinear) welfare functions or the explicit introduction of a risk premium.

When conducting cost-benefit analyses under uncertainty, an important question is the timing of action, i.e. the possibility of delaying a decision until more information is available (e.g., Fankhauser and Soare, 2013). Real option techniques are an extension of cost-benefit analysis to capture this possibility and balance the costs and benefits of delaying a decision (Henry 1974, Arrow and Fisher 1974). The benefits depend on how much learning can take place over time. A key issue concerns irreversible actions, such as the destruction of a unique environment (Heal and Kristrom 2003).

Application of cost-benefit or real option analysis requires evaluations in monetary terms. For market impacts, prices may need to be corrected for policies, monopoly power or other external factors distorting market prices (Squire and van der Tak, 1975). But a cost-benefit analysis also often requires the valuation of non-market costs and benefits. This is the case for impacts on public health, cultural heritage, environmental quality and ecosystems, and distributional impacts. Valuation of non-market impact is difficult because of values and preferences heterogeneity, and subject to controversies; e.g., on the value to attribute to avoided death, see Viscusi and Aldy (2003).

There has been progress in valuation of ecosystem services, as elaborated in the Millennium Ecosystem Assessment (MEA, 2005), The Economics of Ecosystems and Biodiversity (TEEB 2010) and Bateman et al (2011). Two main categories of approaches have been developed: revealed and stated preference methods. The latter is based on what people say about their preferences, while the former uses their actual decisions (e.g. how much they pay for a house) and are often considered more accurate. Other approaches include avoided or replacement cost, i.e. measuring the cost of providing the ecosystem service artificially. When local information is not available, value transfer techniques can be applied moving information from other locations. For example Brander et al (2012) applies value transfer to climate change impacts on wetlands but caution is required in making such transfers (Navrud and Ready 2007, U.S. National Research Council 2005).

Theoretically, cost-benefit approaches can account for distributional impacts, for instance through attribution of a higher weight to the poorest (Harberger, 1984). Results are however highly dependent on preferences that can be extremely heterogeneous and difficult to measure (Barsky et al 1997). As discussed in detail in chapter 2, valuation and decision-making cannot be separated from the institutional and social contexts (e.g., what is considered as a right). Yet, overall, as concluded by the IPCC-SREX, the applicability of rigorous CBAs for evaluations of adaptation to climate variability and change may be limited (Handmer et al., 2012).

17.3.2.2. Multi-Metric Decision-Making for Adaptation

Multi-metric decision-making provides a broader framework, which also permits balancing among multiple, potentially competing objectives *(*Keeney and Raiffa, (1993). This branch of decision analysis is also known as multi-criterion analysis. Such an approach is helpful when decision-makers have difficulty in trading off different objectives (Martinez-Alier et al 1998). Using multiple criteria, decision-makers can include a full range of social, environmental, technical, and economic criteria—mainly by quantifying and displaying trade-offs. Multi-criterion analyses have been applied to adaptation issues including urban flood risk (Grafakos 2011; Kubal et al. 2009; Viguie and Hallegatte 2012), agricultural vulnerability (Julius and Scheraga 2000) and choice of adaptation options in the Netherlands (De Bruin et al. 2009; Brouwer and van Ek 2004), Canada (Qin et al. 2008) and Africa (Smith and Lenhart 1996). The UNFCCC developed guidelines for the adaptation assessment process in developing countries in which it suggests the use of multi-criteria analysis (UNFCCC 2002). As an illustration, Figure 17-3 shows a multi-criteria analysis of three urban policies in the Paris agglomeration, using five policy objectives and success indicators (climate change mitigation, adaptation and risk management, natural area and biodiversity protection, housing affordability, and policy neutrality).

[INSERT FIGURE 17-3 HERE
Figure 17-3: Consequences of three policies in the Paris agglomeration: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding, measured using 5 different metrics representing 5 policy objectives. Axes orientation is such that directions towards the exterior of the radar plot represent positive outcomes. Source: Viguié and Hallegatte, 2012.]

17.3.2.3. Non-Probabilistic Methodologies

Cost-benefit analysis and related methods require probabilities for each climate scenario. But in most cases, it may be impossible to define (or to agree upon) probabilities for alternative outcomes, or even to identify the set of possible futures (including highly improbable events) (Gilboa 2010, Henry and Henry, 2002, Millner et al 2010 and Kunreuther et al 2012). This is especially true for low-probability, high-impact cases or poorly-understood risks (Weitzman 2009, Kunreuther et al. 2012). In such context, various approaches have been proposed (see reviews in Ranger et al, 2010; Hallegatte et al 2012; and chapter 2).

Scenario-based analyses study different policies in different scenarios that try and cover the uncertainty space for key parameters (Schwartz 1996). This is the approach followed by many climate change impact and adaptation studies when using several SRES scenarios (Carter et al., 2001; Carter et al., 2007, Hallegatte et al, 2011). Then, various methodologies or criteria can be used to make a decision.

The *maxi-min* criterion suggests choosing the decision with the best worst-case outcome and the *mini-max regret* criterion (Savage, 1951) suggests choosing the decision with the smallest deviation from optimality in any state of the world. Proposals for ‘no regrets’ adaptation decisions (Callaway and Hellmuth, 2007; Heltberg et al., 2009) employ such criteria. Hybrid criteria balance between optimal and worst case performance (Hurwicz, 1951; Aaheim and Bretteville, 2001; Froyn, 2005).

Another criterion is based on “robustness”, a criterion that seeks decisions that will perform well over a wide range of plausible climate futures, socio-economic trends, and other factors (Lempert and Schlesinger, 2000; Lempert et al 2006; Lempert and Collins 2007; Dessai and Hulme, 2007; Groves et al., 2008; Wilby and Dessai, 2010; WUCA, 2010; Brown et al., 2011; Lempert and Kalra, 2011). Instead of starting from a few scenarios, these methods start with an option or a project and test it under a large number of scenarios to identify its vulnerabilities to uncertain parameters. Small adjustment or large changes in options or projects can then be identified to minimize these vulnerabilities. Example implementations include InfoGap, which has been used to inform adaptation decisions in water management (Ben-Haim, 2001; Korteling et al., 2013); RDM (robust decision making), which has been used for water management and flood risk management planning (Lempert et al., 2003; Lempert and Groves, 2010; Lempert and Kalra, 2011; Matrosov et al., 2013); and robust control optimization (Hansen and Sargent, 2008).

Figure 17-4 illustrates the application of robust decision-making on flood risks in Ho Chi Minh City (Lempert et al 2013). The analysis examined different risk management portfolios (including for instance raising homes and retreat). Each portfolio was simulated in 1,000 scenarios, covering socio-economic and climate uncertainty. The RDM analysis found that the current plan is robust to a wide range of possible future population and economic trends. But it would keep risk below current levels only if rainfall intensities increase by no more than 5 percent and if the Saigon River rises less than 45 centimeters. Additional measures were found that made the situation robust for increases in rainfall intensity of up to 35 percent and increases in the level of the Saigon River of up to 100 centimeters.

[INSERT FIGURE 17-4 HERE
Figure 17-4: Various risk management strategies in Ho Chi Minh City, and their robustness to increases in river levels and rainfall intensity. Different options can cope with different amplitudes of environmental change. Source: Lempert et al., 2013.]

17.4. Costing Adaptation

Interest in estimating the costs of adaptation has grown as the need for action has become clearer. The literature focuses on two levels of costing: global scale estimates, largely to assess the overall need for adaptation finance funds; and regional and local-scale estimates, often limited to a particular vulnerable economic sector, which may be applied to inform budgeting or to support adaptation decision-making, or to allocate scarce resources among the best prospects for effective adaptation. The methods for these two types of studies vary considerably, but for the important methodological considerations for costing adaptation are similar for both types.

17.4.1. Methodological Considerations

Data Quality and Quantity: There is very little discussion of data gaps related to assessing the benefits of adaptation, but poor or sparse data obviously limit the accuracy of these estimates. Callaway (2004) suggests that a major challenge is the low quality and limited nature of data, especially in many developing countries, and notes many transactions are not reported because they occur in informal economies and social networks. In a more general setting Hughes et al (2010) note that historical weather data is not typically sufficiently detailed while others note sparse data on costs of adaptation actions. For example, Bjarnadottie et al. (2011) note incomplete and contradictory data on house retrofit costs for hurricane protection . Also there are simply missing non-market data on such items as the value of ecosystem services (Agrawala and Fankhauser 2008), particularly as affected by climate and possible adaptation.

Costs and Benefits are Location-Specific: Calculating localized impacts requires detailed geographical knowledge of climate change impacts, but these are a major source of uncertainty in climate models (see Refsgaard et al. 2013). Global estimates of adaptation cost are generally not grounded in local-scale physical attributes important for adaptation, which in part explains why local and regional-scale adaptation cost estimates are not consistent with global estimates (Agrawala and Fankhauser 2008). Compared with developed countries, there is also a limited understanding of the potential market sector impacts of climate change in developing countries.

Costs and Benefits Depend on Socio-Economics: It is sometimes assumed that climate will change but society will not (Pielke, 2007; Hallegatte et al 2011; Mechler and Bouwer, 2013). Future development paths affect climate change impact estimates, and can alter estimates from positive to negative impacts or vice versa. Some studies show higher growth rates raise hurricane vulnerability (Bjarnadottir, 2011). On the other hand, higher incomes allow the funding of risk-reducing policies.

Discount Rates Matter: Because adaptation costs and consequences occur over time, discount rates are a core question. Opinions vary sharply on this question (Baum, 2009, Heal 2009). Hof et al (2010) notes that a low discount rate is needed for distant future climate change to matter. A low discount rate is the primary reason for the relatively high estimates of climate damage in the Stern Review (Stern 2006).

For climate adaptation projects, the social or consumption discount rate is the relevant one (Heal 2009). The rates used fall between 0.1 and 2.5%, although without good arguments for specific values (see Heal 2009). Nordhaus (2007) chooses a value of 1.5% while Stern uses a much lower value of 0.1%. Nordhaus emphasizes consistency with the rate of return on investment as a driving rationale while Stern points to ethical issues. Allowing environmental services to enter consumption can change the social discount rate substantially and generate a low or even negative social discount rate (Heal, 2009; Guesnerie, 2004; and Sterner and Persson, 2007). The UK Treasury now mandates the use of declining discount rates for long-term projects, as suggested by behavioral studies and by theoretical analysis (Arrow et al. 2012).

17.4.2. Review of Existing Global Estimates: Gaps and Limitations

There has been a limited number of global and regional adaptation cost assessments over the last few years (World Bank, 2006; Stern, 2006, Oxfam, 2007; UNDP, 2007, UNFCCC, 2007; 2008; World Bank, 2010a). These estimates exhibit a large range and have been completed mostly for developing countries. The most recent and most comprehensive to date global adaptation costs range from $70 to more than $100 billion annually by 2050 (World Bank, 2010a, see Table 17-2).

[INSERT TABLE 17-2 HERE
Table 17-2: Estimates of global costs of adaptation.]

IPCC (2011) considers confidence in these numbers to be *low* because the estimates are derived from only three relatively independent lines of evidence. The World Bank (2006) estimates the cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA), as does the Stern Review (2006), Oxfam (2007) and UNDP (2007). UNFCCC (2007) calculated existing and planned investment and financial flows (I&FF), and then estimated the additional investment required for adaptation as a premium on existing and planned investments. The World Bank (2010) followed the UNFCCC (2007) methodology of estimating the premium climate change imposes on a baseline of existing and planned investment, but included more extensive modeling as opposed to developing unit cost estimates, constructed marginal cost curves and climate stressor-response functions for adaptation actions, and included maintenance and coastal port upgrading costs.

Given their common approaches these estimates are interlinked, which explains the seeming convergence of their estimates in later years, as discussed by Parry et al (2009). However there are important differences in terms of sectoral estimates, as Figure 17-5 shows in comparing the UNFCCC (2007) and World Bank (2010a) studies. Extreme events, a potential source of large adaptation costs, are not properly covered, and these studies take into account a limited set of adaptation options. In addition, the World Bank (2010a) estimates report higher ranges of estimates, reflecting additional effort to account for uncertainty Parry et al. (2009) consider the UNFCCC (2007) estimates a significant underestimation by at least a factor of two to three plus omitted costs in ecosystem services, energy, manufacturing, retailing and tourism. Thus the numbers have to be treated with caution. There are a number of gaps, challenges and omissions associated with those global estimates that merit further discussion.

[INSERT FIGURE 17-5 HERE
Figure 17-5: Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges, points indicate point estimates.]

The practical challenges of conducting global adaptation cost studies are apparent in the literature (as assessed in IPCC 2011; World Bank 2010a; Parry et al. 2009). The broad scope of these studies limits the analysis to few climate scenarios, and while the scenarios might be strategically chosen it is difficult to fully represent the range of future adaptation costs across all sectors. The broad scope also limits comprehensive consideration of adaptation options, non-market and co-benefits, equity issues, and adaptation decision-making (such limitations also apply to local and regional scale studies - see Section 17.4.3). The global studies, designed to reflect the best available methods and data for the purpose of estimating the magnitude of the global economic adaptation challenge, achieve this limited goal but must be interpreted in light of these important limitations and uncertainties.

17.4.3. Consistency between Localized and Global Analyses

Adaptation costs and benefits are derived to guide specific investment decisions, generally at national and local levels, or to derive a "price tag" for overall funding needs for adaptation (generally at a global level). Given these different purposes it is difficult to compare "local", i.e, national and sectoral, with global numbers. The quantity/quality of local studies also varies by sector with more treatment of adaptation in coastal zones and agriculture (Agrawala and Fankhauser, 2008 – see Table 17-3). Less is known and many gaps remain for sectors such as water resources, energy, ecosystems, infrastructure, tourism and public health. Also assessments have predominantly been conducted in a developed country context (see Table 17-1 for examples of costs and benefits assessment).

[INSERT TABLE 17-3 HERE
Table 17-3: Coverage of adaptation costs and benefits.]

However, as Fankhauser (2010) notes, with the sole exception of coastal protection costs, adaptation costs have shown little convergence locally or in terms of sectoral to global costs. The World Bank (2010a) study uniquely takes a two-track approach doing parallel national (7 cases) and global adaptation estimates. For a number of country studies (Bangladesh, Samoa and Vietnam) a cross-country comparison of local and global adaptation costs was made, with the costs in terms of GDP found to be in reasonable agreement. Costs for strengthening infrastructure against windstorms, precipitation and flooding were about 10-20% higher compared to disaggregated global estimates, largely owing to the ability of country-level studies to consider at least some socially contingent impacts (World Bank 2010b, 2010c, 2010d). Further, there is evidence of under investment in adaptation (UNDP, 2007) with global estimates of the need for adaptation funds variously estimated in the range of $70-100 billion annually (World Bank 2010a), but with actual expenditures in 2011 estimated at $244 million (Elbehri et al, 2011), and in 2012 estimated at $395 million (Schalatek et al., 2012).

17.4.4. Selected Studies on Sectors or Regions

This section focuses on studies that illustrate current practice in estimating adaptation economics, with a particular focus on support of adaptation decision-making through economic analysis. Within that class of work, there are two broad categories of economic analyses of adaptation at the sectoral level: econometric and simulation approaches.

Econometric studies generally examine the nature of observed adaptations or the estimation of climate change effects to which farmers have adapted. Such studies rely on observed cross-sectional, time series, or panel data. Examples include those where one implicitly assumes adaptation has occurred linking temperature and precipitation to land values and crop yields or land values (e.g., Mendelsohn et al., 1994; Schlenker et al., 2006) or those identifying adaptations in terms of altered decisions (e.g. Seo and Mendelsohn, 2008a and 2008c) look at enterprise choice - while Mu et al., 2013 look at stocking rate adjustments). Such approaches can also be used to estimate the marginal effect of adaptation, provided that "without adaptation" estimates can be developed (Mendelsohn and Dinar, 2003).

The simulation approach, by contrast, traces costs and benefits of adaptation strategies through mechanisms of interest, typically through a series of climate-biophysical-behavioral response–economic components. Within simulation modeling there are two main threads in the behavioral response/economic component of the simulation. The first involves rational actors who consider the benefit and cost consequences of their choices and pursue economically efficient adaptation outcomes, and the second involves a decision-rule or reference based characterization of the response of actors to climate stressors (Dinar and Mendelsohn, 2011; Schlenker et al, 2006). As noted below, in many sectors the current practice begins with the simpler decision-rule based approach, and may progress to consider benefits and costs, and then perhaps to consider other factors, such as equity and nonmarket values.

The key advantages of an econometric approach are reliance on real-world data, the use of "natural experiments" in some cases, and an ability to reflect the joint costs and benefits of multiple adaptation strategies to the extent they are employed together in real world (Mendelsohn and Neumann, 1999; Dinar and Mendelsohn, 2011). The econometric approach does not require the analyst to simulate all adaptation mechanisms, only to establish that there is a robust relationship is between a climate stressor and the outcome of interest. The data required to implement the approach are limited, so the approach can be applied broadly. The key disadvantages of the econometric approach are an inability to trace transmission mechanisms of specific adaptation measures or to isolate the marginal effect of these strategies or measures; the inability to transfer estimates out of context (e.g., an African study does not apply to Asia, where the climate, adaptation, and social context all differ and affect the marginal costs and benefits of adaptation measures); and that the statistical estimation can be challenging and sometimes subject to multiple interpretations (Schlenker et al., 2005).

Simulation modeling can be demanding – a key disadvantage – as it requires extensive data inputs and careful calibration. Where data and models are available, however, the simulation modeling method works well. For example, an agricultural adaptation modeling system can estimate such factors as the incremental change in crop output and water supply in response to changes in climatic conditions and agricultural and water resource management techniques. A further advantage of the simulation approach is that it provides an opportunity for stakeholder involvement at several stages of the analytic process: designing scope, adjusting parameters, selecting inputs, calibrating results, and incorporating adaptation measures of specific local interest (Dinar and Mendelsohn, 2011).

There is a wide range of studies available attempting an economic evaluation of adaptation options. From these, several desirable characteristics can be identified:

- A broad representation of climate stressors, including both gradual change and extreme events, spanning multiple future outcomes(for example, a range of individual climate model forecasts and greenhouse gas emissions scenarios). Consideration of multiple outcomes reflects forecasting uncertainty and can help to ensure the adaptation rankings that result from the analysis are robust across a range of future outcomes (Agrawala *et al.*,2011; Lempert and Kalra 2009, also see Chapter 2).
- Representation of a wide variety of alternative adaptation responses (for example, in the agriculture sector, consideration of changes in crop varieties and farmer education to ensure the varieties are grown with the best available know-how). Depending on the context, single adaptation response with variation in dimension may be useful (for example, varying the height of a levee or the capacity of a dam spillway) (World Bank 2010, Fankhauser 2010, Fankhauser et al. 1999).
- Rigorous economic analysis of costs and benefits, which ideally includes consideration of market, nonmarket, and socially contingent implications (Watkiss, 2011); one-time and replacement capital and ongoing recurring costs; and costs of residual damages after an adaptation response is implemented (World Bank, 2010a).
- A strong focus on adaptation decision making, including a clear exposition of the form of adaptation decision-making that is implied in the study, and consideration of both climate and non-climate sources of uncertainty (Lempert et al. 2006, also see Chapter 2).

Table 17-4 highlights studies that illustrate some of these characteristics. The studies include both simulation studies of the economic implications of adaptation options, and econometric ones which examine choices that producers make to adapt. These studies generally fall in the category of positive economics, where economic tools and analysis are used to examine the implications of alternative choices without imposing values of the author (see Friedman (1953)). A few studies incorporate a normative perspective, either explicitly or implicitly, reflecting value judgments of authors or study participants.

[INSERT TABLE 17-4 HERE
Table 17-4: Studies illustrating economic evaluation of adaptation options.]

17.5. Economic and Related Instruments to Provide Incentives

Through regulations, subsidies and direct intervention, there are many opportunities for policy makers to encourage autonomous adaptation. However, these efforts need to be designed so as to yield efficient, cost effective responses while avoiding perverse results. A basic issue of designing efficient policies is to understand that they affect the behavior of those who have the most to gain. For this and other reasons, economists tend to favor policies based on voluntary actions influenced by incentives, either positive or negative, over mandates or uniform policies. Examples of these include insurance markets, water markets and various Payments for Environmental Services (PES), as we discuss below. A second consideration in policy design is cost effectiveness, i.e. the extent to which governments make the best use of their resources. The measurement of the net effect of a policy is challenging because it is difficult to anticipate what would have occurred without the policy.

Finally, policies must be carefully designed to avoid perverse outcomes that run counter to the policy maker's objectives. A classic example is found in policies that encourage adoption of water-saving technology. Pfeiffer and Lin (2010) review cases where subsidizing irrigation water conservation leads farmers to increase total water use by increasing the acreage under irrigation. This is an example of what is often called the rebound effect (Roy, 2000) whereby increases in efficiency of resource use result in more being demanded.

With the exception of insurance and trade related instruments there is relatively little literature on the use of economic instruments for adaptation (see chapter 10). One reason is that, apart from insurance, few adaptation policies work directly via economic incentives and markets. The potential of economic instruments in an adaptation context is, however, widely recognized. In line with Agrawala and Fankhauser (2008) we distinguish, among others the following incentive-providing instruments relevant for key sectors: (i) Insurance schemes (all sectors; extreme events), (ii) Price signals / markets (water; ecosystems (iv) Regulatory measures and incentives (building standards; zone planning); and (v) Research and development incentives (agriculture, health).

17.5.1. Risk Sharing and Risk Transfer, Including Insurance

Insurance-related formal and informal mechanisms can directly lead to adaptation and provide incentives or disincentives. Informal mechanisms include reliance on national or international aid or remittances, and while such mechanisms are common, they tend to break down for large, covariate events (Cohen and Sebstad, 2005). Another informal mechanism is the inclusion of climate change risk under corporate disclosure regulations (National Round Table on the Environment and the Economy, 2012). Formal mechanisms include insurance, micro-insurance, reinsurance, and risk pooling arrangements. Insurance typically involves ongoing premium payments in exchange for coverage and post event claim payments. In contrast to indemnity-based insurance, index-based insurance insures the event (as e.g. measured by lack of rainfall) not the loss, and is a possibility for providing a safety net without moral hazard, yet suffers from basis risk, the lack of correlation of loss to event (Hochrainer et al. 2009; Collier et al. 2009) (see also 10.7 for a supply-side-focussed perspective on insurance). Markets differ substantially according to how liability and responsibility is distributed (Botzen et al., 2009; Aakre et al., 2009), and in many instances governments play a key role as regulators, insurers, or reinsurers (Linnerooth-Bayer et al., 2005). Insurance penetration in developed countries is considerable, whereas it is low in many developing regions. In the period 1980-2004 about 30% of losses were insured in high-income countries; but only about 1% in low-income countries (Linnerooth-Bayer et al., 2011). Developing countries are beginning to pool risks and transfer portions to international reinsurance markets. The Caribbean Catastrophic Risk Insurance Facility (CCRIF) set the precedent by pooling risks basin wide, thus reducing insurance premiums against hurricane and earthquake risks (World Bank, 2007). Similar schemes are under development planning in Europe, Africa and the Pacific (Linerooth-Bayer et al. 2011).

Insurance-related instruments may promote adaptation directly and indirectly: i) instruments provide claim payments after an event, and thus reduce follow-on risk and consequences; (ii) they alleviate certain pre-event risks and allow for improved decisions (Skees et al., 2008; Hess and Syroka, 2005; Hoppe and Gurenko, 2006). As one interesting example, using crop micro insurance linked to loans, farmers exposed to severe drought in Malawi were able to grow higher-yield, yet higher-risk crops, which allowed them to increase incomes (Linnerooth-Bayer and Mechler, 2011).

The indirect effects occur via the provision of incentives and disincentives. Premiums for risk coverage can provide an incentive to reduce the premium by reducing the risk. In practice, the incentive effect is generally weak. Kunreuther et al. (2009) found that insurance decisions are not based solely on costs and premiums, but also desires to reduce anxiety, comply with mortgage requirements, and satisfy social norms. Further, purchasing insurance may reduce adaptation with insured agents reducing their risk-minimizing efforts after taking out coverage. This is termed moral hazard and has been found to be rational (Kunreuther, 1998). Moral hazard can be reduced though the use of index-based insurance, although this has the drawback of operating from a high base risk (Hochrainer et al. 2009: Collier et al., 2009). Another difficulty arises when local or state regulations undermine incentives to decrease risk (for instance, by not allowing insurance rates to be fully risk adjusted). Some analysts suggest the removal of existing regulations that distort market signals in order to re-align incentives, yet this is likely to be ineffective given that the incentive effect is not considered very strong and often premiums are not fully risk-based (Michel-Kerjanand Kunreuther, 2011). Also, Rao and Hess (2009) argue there is the possibility that some current insurance schemes may increase maladaptation. Under-insurance can also arise when agents expect that the public sector will provide disaster assistance. Some refer to this as the Samaritan's dilemma (Gibson et al., 2005; Raschky et al., 2013).

17.5.2. Payments for Environmental Services

Payment for Environmental services (PES) pay landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change adaptation and mitigation. There are ample cases of mitigation–focused PES schemes (e.g. Wunder and Borner (2011), Pagiola (2008), Wunder and Albán (2008)), and more recently emerging evidence of the use of PES in adaptation which are of pilot nature and location-specific however. (Butzengeiger_Geyer et al., 2011; van de Sand, 2012; Schultz, 2012). Potentially well designed PES schemes offer a framework for adaptation and there is a view among development agencies that with more experience and guidance on implementation PES might well contribute to adaptation as one of a multitude of feasible measures (e.g.. taxes, charges, subsidies, loans). Chishakwe *et al* (2012) draws comparisons and find synergies between PES community based natural resources management approaches in Southern Africa and community-based adaptation.

17.5.3. Improved Resource Pricing and Water Markets

Studies of water sector adaptation often begin by citing the implications of future water shortages and the potential for conflict. Techniques frequently cited for resolving these conflicts include the establishment of water markets or water pricing schemes (e.g., Alavian et al. 2009; Vorosmarty et al. 2000, Adler, 2008), which is in itself, however, also often associated with conflict (Miller et al., 1997). Traditionally water markets facilitate transfer from lower to higher-valued uses (Olmstead, 2010) but pricing rules can also function through urban fees and real estate taxes (as they do for water supply and urban storm water regulation in many countries). A few studies make the case that water markets and pricing improves climate change adaptation (Medellin-Azuara et al. 2008). In many cases, the projected increase in climate-induced water demand (particularly in the agriculture sector), coupled with a projected decrease in water supply, suggests that adaptation will be needed.

Many countries have instituted structures for water pricing in the household and agricultural sectors. Nevertheless such prices are unevenly applied, collection rates are low, metering is rarely implemented (at least for the agricultural sector, which is typically the largest water user) and pricing is often based on annual rather than usage-based fees (Saleth et al., 2012). In many countries, a number of important institutional barriers to water markets and pricing remain. These include a lack of property rights including an thorough consideration of historical and current entitlements, limits on transferability, legal and physical infrastructures and institutional shortcomings (Turral et al. 2005 ; Saleth et al. 2012) coupled with issues involved with return flows, third part impacts, market design, transactions costs, and average versus marginal cost pricing (Griffin, 2012).

17.5.4. Charges, Subsidies, and Taxes

The environmental economics literature over the past 30 years has emphasized the importance of market-based instruments (MBIs) relative to command and control regulations. MBIs are shown to be generally more cost effective, providing stronger incentives for innovation and dynamic efficiency. Within the wide range of instruments that qualify as market based, there is a general preference in terms of overall efficiency for taxes over subsidies (Sterner, 2002; Barbier and Markandya, 2012). MBIs include charges on harmful emissions and wastes, subsidies to clean energy, subsidized loans and others.

In many cases climate change exacerbates the effects of pricing resources below their social costs. This is true for some forms of energy (e.g. hydro and fossil fuel-based) as well as many ecosystem services. If these resources were optimally priced, there would be greater incentives to investment in clean technologies and the need for additional public sector adaptation measures would be lessened (ESMAP, 2010).

In addition to the instruments already identified, others that are potentially important include: raising the price of energy through a tax (Sterner, 2011), developing markets for genetic resources (Markandya and Nunes, 2012) and strengthening property rights so schemes such as PES can be more effective. These measures are desirable even in the absence of climate change; they become even more so when climate impacts are accounted for. Yet it is important to note that while the case for such social cost pricing through the use of charges is strong, it also has its limitations. Higher prices for key commodities can hurt the poor and vulnerable and complementary measures may need to be taken to address such effects.

17.5.5. Intellectual Property Rights (IPR)

Technology transfer is increasingly seen as an important means of adaptation because of the global benefits it provides through the transfer of knowledge. Christiansen et al. (2011) in a Technology Needs Assessments carried out in developing countries list about 165 technological needs related to mitigation and adaptation. Examples include applications to agriculture in Cambodia and Bangladesh and coastal zones in Thailand. In many of these cases patents and other intellectual property protection constrain technology transfer. Patent buy-outs, patent pools, compulsory licenses and other open source approaches have been used to relax this constraint (Dutz and Sharma, 2012). Patent buy-outs involve third parties (e.g. international financial institutions or foundations) acquiring the marketing rights for a patented product in a developing country. Patent pools represent a group of patent holders who agree to license their individual patents to each other (closed pool) or to any party (open pool). Compulsory licenses are issued by governments and allow patent rights to be overridden in critical situations. For all the above reasons therefore, it is suggested that limits to technology transfer are limiting climate change adaptation (Henry and Stiglitz, 2010). There is also the view, however, that strong IP protection in receiving countries is facilitating technology transfer from advanced countries and the evidence indicates a systematic impact of IP protection on technology transfer through exports, FDI and technology licensing, particularly for middle-income countries for which the risk of imitation in the absence of such protection is relatively high.

17.5.6. Innovation and R&D Subsidies

Subsidies to encourage innovation through R&D may be employed as a measure to encourage adaptation investments as well as behavioral change (Bräuninger at al., 2011). Subsidies involve direct payments, tax reductions or price supports that enhance the rewards from the implementation of an activity (Gupta et al., 2007). There has been some criticism of the efficiency of subsidies in terms of rent seeking and adverse effects on competitiveness (Barbier and Markandya, 2012). They are often poorly targeted and end up getting captured by middle and upper income groups. Moreover they imply increasing budgetary burdens. Yet they are popular with decision-makers and the wider public. Subsidies are today mostly used for reasons other than climate adaptation, and evidence regarding its use for adaptation as well as regarding the incentivizing of adaptation R&D specifically is missing.Popp, 2004 is partly an exception, which focuses on subsidies for mitigation. It shows that such subsidies have little impact on their own but they do work to enhance the effects of other instruments such as energy taxes and regulations that mandate improvements in energy efficiency the use of lower carbon options

17.5.7. The Role of Behavior

It is well recognized that often human behavior is characterized by bounded rationality, particularly in relation to choices under risk and uncertainty, which affects the effectiveness of incentive-based approaches. Individuals may over- or underestimate risks (Ellsberg 1961; Kahneman and Tversky 1979), and may not consistently weigh long term consequences (Ainslie 1975). One well documented explanation is that individuals do not fully use available information on risks when they make their choices (Magat et al., 1987; Camerer and Kunreuther, 1989; and Hogarth and Kunreuther, 1995). Policies that well consider such risk perceptions and behavioral biases increase their efficiency. For instance, people react differently to abstract information on distant events as opposed to concrete, current, emotionally-charged information (Trope and Liberman, 2003). In practice, this can limit the impact of simply communicating “dry”, emotion-free, information, such as that on flood return periods, and underlines the importance of participatory, reflexive and iterative approaches to decision-support(Fischhoff et al., 1978; Slovic, 1997; Renn, 2008; IRGC, 2010) [see also 2.1.2].

Frequently Asked Questions

FAQ 17.1: Given the significant uncertainty about the effects of adaptation measures, can economics contribute much to decision-making in this area? *[to be inserted in Section 17.3]*
Economic methods have been developed to inform a wide range of issues that involve decision making in the face of uncertainty. Indeed some of these methods have already been applied to the evaluation of adaptation measures, such as decisions on which coastal areas to protect and how much to protect them.

A range of methods can be applied, depending on the available information and the questions being asked. Where probabilities can be attached to different outcomes that may result from an adaptation measure, economic tools such as risk and portfolio theory allow us to choose the adaptation option that maximizes the expected net benefits, while allowing for the risks associated with different options. Such an approach compares not only the net benefits of each measure but also the risks associated with it (e.g. the possibility of a very poor outcome).

In situations where probabilities cannot be defined, economic analysis can define scenarios that describe a possible set of outcomes for each adaptation measure which meet some criteria of minimum acceptable benefits across a range of scenarios, allowing the decision-maker to explore different levels of acceptable benefits in a systematic way. That, of course, hinges on the definition of “acceptability”, which is a complex matter that accounts for community values as well as physical outcomes. These approaches can be applied to climate change impacts such as sea level rise, river flooding and energy planning.

In some cases it is difficult to place specific economic values on important outcomes (e.g. disasters involving large scale loss of life). An alternative to the risk or portfolio theory approach can then be used, that identifies the least-cost solution that keeps probable losses to an acceptable level.

There are, however, still unanswered questions on how to apply economic methods to this kind of problem (particularly when the changes caused by climate change are large and when people’s valuations may be changed), and on how to improve the quality of information on the possible impacts and benefits.

FAQ 17.2: Could economic approaches bias adaptation policy and decisions against the interests of the poor, vulnerable populations, or ecosystems? *[to be inserted in Section 17.4]*
A narrow economic approach can fail to account adequately for such items as ecosystem services and community value systems, which are sometimes not considered in economic analysis or undervalued by market prices, or for which data is insufficient. This can bias decisions against the poor, vulnerable populations, or the maintenance of important ecosystems. For example, the market value of timber does not reflect the ecological and hydrological functions of trees nor the forest products whose values arise from economic sectors outside the timber industry, like medicines. Furthermore some communities value certain assets (historic buildings, religious sites) differently than others. Broader economic approaches, however, can attach monetary values to non-market impacts, referred to as

externalities, placing an economic value on ecosystem services like breathable air, carbon capture and storage (in forests and oceans) and usable water. The values for these factors may be less certain than those attached to market impacts, which can be quantified with market data, but they are still useful to provide economic assessments that are less biased against ecosystems.

But economic analysis, which focuses on the monetary costs and benefits of an option, is just one important component of decision making relating to adaptation alternatives, and final decisions about such measures are almost never based on this information alone. Societal decision making also accounts for equity - who gains and who loses - and for the impacts of the measures on other factors that are not represented in monetary terms. In other words, communities make decisions in a larger context, taking into account other socioeconomic and political factors. What is crucial is that the overall decision-framework is broad, with both economic and non-economic factors being taken into consideration.

A frequently used decision-making framework that provides for the inclusion of economic and non-economic indicators to measure the impacts of a policy, including impacts on vulnerable groups and ecosystems, is multi-criteria analysis (MCA). But as with all decision making approaches, the a challenge for MCA and methods like it is the subjective choices that have to be made about what weights to attach to all the relevant criteria that go into the analysis, including how the adaptation measure being studied impacts poor or vulnerable populations, or how fair it is in the distribution of who pays compared to who benefits.

FAQ 17.3: In what ways can economic instruments facilitate adaptation to climate change in developed and developing countries? *[to be inserted in Section 17.5]*

Economic instruments (EIs) are designed to make more efficient use of scarce resources and to ensure that risks are more effectively shared between agents in society. EIs can include taxes, subsidies, risk sharing and risk transfer (including insurance), water pricing, intellectual property rights , or other tools that send a market signal that shapes behavior. In the context of adaptation, EIs are useful in a number of ways.

First, they help establish an efficient use of the resources that will be affected by climate change: water pricing is an example. If water is already priced properly, there will be less overuse that has to be corrected through adaptation measures should supplies become more scarce.

Second, EIs can function as flexible, low-cost tools to identify adaptation measures. Using the water supply example again, if climate change results in increasing water scarcity, EIs can easily identify adjustments in water rates needed to bring demand into balance with the new supply, which can be less costly than finding new ways to increase supply.

Insurance is a common economic instrument that serves as a flexible, low cost adaptation tool. Where risks are well-defined, insurance markets can set prices and insurance availability to encourage choices and behaviors that can help reduce vulnerability, and also generate a pool of funds for post-disaster recovery. Insurance discounts for policy holders who undertake building modifications that reduce flood risk, for example, are one way that EIs can encourage adaptive behavior.

Payments for environmental services (PES) schemes are another economic instrument that encourages adaptive behavior. This approach pays landholders or farmers for actions that preserve the services to public and environmental health provided by ecosystems on their property, including services that contribute to both climate change mitigation and adaptation. A PES approach is being used in Costa Rica to manage natural resources broadly, for example. Paying timber owners not to cut down forests that serve as carbon sinks (the idea behind the REDD proposal to the UNFCCC), or paying farmers not to cultivate land in order reduce erosion damage (as is being done in China and the US), are examples. In developed countries, where markets function reasonably well, EIs can be directly deployed through market mechanisms. In developing countries (and also in some developed ones), however, this is not always the case and markets often need government action and support. For example, private insurance companies sometimes don’t cover all risks, or set rates that are not affordable, and public intervention is required to make sure the insurance is available and affordable. Government also has an important role in ensuring that voluntary market instruments work effectively and fairly, through legal frameworks that define property rights involving scarce resources such as land and water in areas where such rights are not well established. An example of this is the conflict between regions over the use of rivers for water supply and hydropower, when those rivers flow from one jurisdiction to the next and ownership of the water is not clearly established by region-wide agreements. PES schemes can only function well when the public sector ensures that rights are defined and agreements honored.

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Table 17-1: Four definitions of eligible adaptation.

Relevant climatic factors **Motivation for action**	**Observed and/or projected climate change**	**Climate change as well as natural climate variability**
Climate is the main reason	**Definition 1:** Action occurs mainly to reduce the risks of observed or projected climate change **Example:** Raising of existing dykes	**Definition 2:** Action occurs mainly to reduce risks of climate change and climate variability **Example:** Building of new dykes in areas that are currently unprotected
Climate is one of several reasons	**Definition 3:** Actions that reduce the risks of observed or projected climate change even if they are also justified in the absence of climate change **Example:** Economic diversification in predominantly agricultural regions	**Definition 4:** Actions that reduce the risks of climate change and climate variability even if they are also justified in the absence of climate change **Example:** Improved public health services

Source: Füssel et al. (2012), adapted from Hallegatte (2008).

Table 17-2: Estimates of global costs of adaptation.

Study	**Results (billion USD/year)**	**Time frame**	**Sectors**	**Methodology and comment**
World Bank, 2006	9-41	Present	Unspecified	Cost of climate proofing foreign direct investments (FDI), gross domestic investments (GDI) and Official Development Assistance (ODA)
Stern, 2007	4-37	Present	Unspecified	Update of World Bank (2006)
Oxfam, 2007	>50	Present	Unspecified	WB (2006) plus extrapolation of cost estimates from national adaptation plans (NAPAs) and NGO projects.
UNDP, 2007	86-109	2015	Unspecified	WB (2006) plus costing of targets for adapting poverty reduction programs and strengthening disaster response systems
UNFCCC, 2007	28-67	2030	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure	Planned investment and Financial Flows required for the international community
World Bank, 2010a	70-100	2050	Agriculture, forestry and fisheries; water supply; human health; coastal zones; infrastructure; extreme events	Improvement upon UNFCCC (2007): more precise unit cost, inclusion of cost of maintenance and port upgrading, risks from sea-level rise and storm surges.

Source: Modified from Agrawala and Fankhauser (2008) and Parry et al. (2009) to include estimates from World Bank (2010a).

Table 17-3: Coverage of adaptation costs and benefits.

Sector	Analytical Coverage	Cost Estimates	Benefit Estimates
Coastal Zones	Comprehensive	√√√	√√√
Agriculture	Comprehensive	-	√√√
Water	Isolated case studies	√	√
Energy	N. America, Europe	√√	√√
Infrastructure	Cross-cutting, partly covered in other sectors	√√	-
Health	Selected impacts	√	-
Tourism	Winter tourism	√	-

Note: Three checks indicates good to excellent coverage of the topic in the literature; two checks indicates medium coverage; one check indicates limited coverage; the absence of a check indicates extremely limited or no coverage. Note that indicators reflect literature review through publication of source in 2008. Source: Agrawala and Fankhauser (2008).

Table 17-4: Studies illustrating economic evaluation of adaptation options.

Sector, Study, and Scope	Methodology	Key Points Illustrated
Agriculture, Forestry, and Livestock		
Seo and coinvestigators (e.g. Seo et al , 2008b, 2009b, 2011): Impacts to livestock producers in Africa	Econometric. Examines the economic choices that livestock owners make to maintain production in the face of climate Insights into adaption possibilities by examining the ways economic choices vary over locations and times with varying climate conditions.	Consideration of multiple options (implicit) Residual impacts reflected Applicable at multiple geographic scales Results provide a ready means to re-estimate results for multiple climate scenarios.
Butt et al. (2006): Crop sector in Mali	Simulation. Simulates the economic implications of potential adaptation possibilities. Examines the consequences of migration in cropping patterns, development of heat resistant cultivars, reduction in soil productivity loss, cropland expansion, and changes in trade patterns.	Broad consideration of options (explicit, allowing for ranking of measures) Residual impacts reflected Rigorous economic costing of adaptation options and consequences for yields, revenue, and food security.
Sutton et al (2013): Crop and livestock sector in four Eastern European and Central Asian countries	Simulation with benefit-cost analysis. Ranks options initially based on net economic benefits over 2010 to 2050 period. Considers non-market and socially contingent effects through stakeholder consultation process.	Broad consideration of options (explicit, measures ranked) Very broad representation of climate scenarios (56 GCM-SRES combinations) Rigorous economic costing of adaptation options Integrated analysis of agriculture and irrigation water sectors
Sea-level Rise and Coastal Systems		
Nichols and Tol (2006):Coastal regions at a global scale	Simulation of adaptation through construction of seawalls and levees, adoption of beach nourishment to maintain recreational value, and migration of coastal dwellers from vulnerable areas. The study, reflects an economic decision-rule for most categories and benefit-cost analysis for a few categories	Capable of broad representation of sea-level rise scenarios. Optimization of alternatives considering both the impact of adaptation and resulting residual impacts. Rigorous economic costing of adaptation options.
Neumann et al. (2010a): Risks of sea-level rise for a portion of the coastal United States	Simulation of adaptation decision-making including seawalls, bulkheads, elevation of structures, beach nourishment, and strategic retreat, primarily using a benefit-cost framework but with alternatives based on local land-use decision-making rules.`	Capable of broad representation of sea-level rise scenarios Flexibility to consider both benefit-cost and rule-based decision making Rigorous and dynamic economic costing of adaptation options
Purvis et al. (2008): Risks of coastal flooding in Somerset, England	What is adaptation strategy here Simulation using a probabilistic representation to characterize uncertainty in future sea-level rise and, potentially, other factors that could affect coastal land-use planning and development investment decisions	Considers the impact of both gradual climate change (sea-level rise) and extreme events (the 1 in 200 year recurrence interval coastal flooding event). Incorporates probabilistic uncertainty analysis
Water		
Ward et al. (2010): Future needs and costs for municipal water across the world, scalable to national and local scale	Assesses costs with and without climate change of reaching a water supply target in 2050. The aggregation level used is the food producing units level, and storage capacity change, using the secant peak algorithm to determine the storage yield relationship and the cost of various alternative sources of water. Find that baseline costs exceed adaptation costs ($73 billion per year versus $12 billion per year for adaptation), with most of the adaptation costs (83-90%) incurred in developing countries.	Multiple climate scenarios Scalable to multiple spatial resolutions, with national and regional results reported Multiple alternative adaptation options considered Rigorous economic costing of site-specific capital and operating costs

Urban Flooding		
Ranger et al. (2011): direct and indirect impacts of flooding in Mumbai, India	Investigates the consequences of floods with different return periods, with and without climate change; the effect of climate change is from a weather generator that downscales simulations from a global climate model. Estimates direct losses from a 100-yr event rising from $600 million today to $1,890 million in the 2080's, and total losses (including indirect losses) rising from $700 to $2,435 million. Impacts give rise to adaptation options, some targeting direct losses (e.g., improved building quality, improved drainage infrastructure) and others targeting indirect losses (e.g., increased reconstruction capacity, micro-insurance). Analysis finds that improved housing quality and drainage could bring total losses in the 2080's below current levels and that full access to insurance would halve indirect losses for large events.	Considers multiple adaptation options Explicitly considers both direct and indirect costs Rigorous economic costing of adaptation options
Energy		
Lucena et al. (2010): Energy production in Brazil, particularly from hydropower	Simulation of multiple adaptation options, including energy source substitution and regional "wheeling" of power coupled with modeling of river flow and hydropower production under future climatic conditions. Uses an optimization model of overall energy production	Considers two GHG emissions scenarios and a "no-climate change" baseline Scalable to multiple spatial resolutions, with national and regional results reported Considers multiple adaptation strategies Rigorous economic costing of capital and recurring adaptation costs
Health		
Ebi (2008): Global adaptation costs of treatment of diarrhoeal diseases, malnutrition, and malaria	What is the adaptation considered The costs of three diseases estimated in 2030 for three climate scenarios using (1) the current numbers of cases; (2) the projected relative risks of these diseases in 2030; and (3) current treatment costs. The analysis assumed that the costs of treatment would remain constant. There was limited consideration of socioeconomic development.	Multiple climate scenarios Clear description of framework and key assumptions Rigorous economic costing of adaptation options using multiple assumptions to characterize uncertainty
Macroeconomic analysis		
De Bruin et al. (2009b): Adaptation strategies compared to mitigation strategies within the context of a global integrated assessment model	Use of an integrated assessment model (the DICE model) with refined adaptation functions. Examines the efficacy of "stock" adaptations (mainly infrastructure) adaptations versus "flow" adaptations (mainly operational or market responses), with comparisons to mitigation investments.	Multiple climate scenarios Clear description of framework and key assumptions Considers multiple adaptation strategies Rigorous economic costing of adaptation options
Margulis et al. (2011): Climate change impacts in the economy	Use of a general equilibrium (GCE) model to simulate two climate change-free scenarios regarding the future of Brazil's economy. Climate shocks were projected and captured by the model through impacts on the agricultural/livestock and energy sectors. The socio-economic trends of the scenarios with and without global climate change were reviewed in terms of benefits and costs for Brazil and its regions.	The economic impacts of climate change are experienced across the business sectors, regions, states, and large cities and were expressed in terms of GDP losses. The simulation disaggregates results for up to 55 sectors and 110 products and also provides macro-economic projections as inflation, exchange rate, household sector consumption, government expenditures, aggregate investment, and exports. It also includes expert projections and scenarios on specific preferences, technology and sector policies.

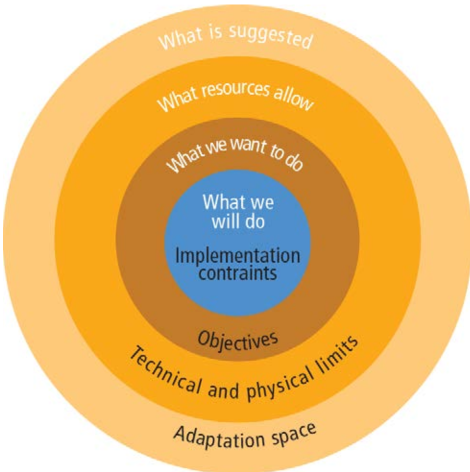

Figure 17-1: The narrowing of adaptation from the space of all possible adaptations to what will be done. Forces causing the narrowing are listed in black.

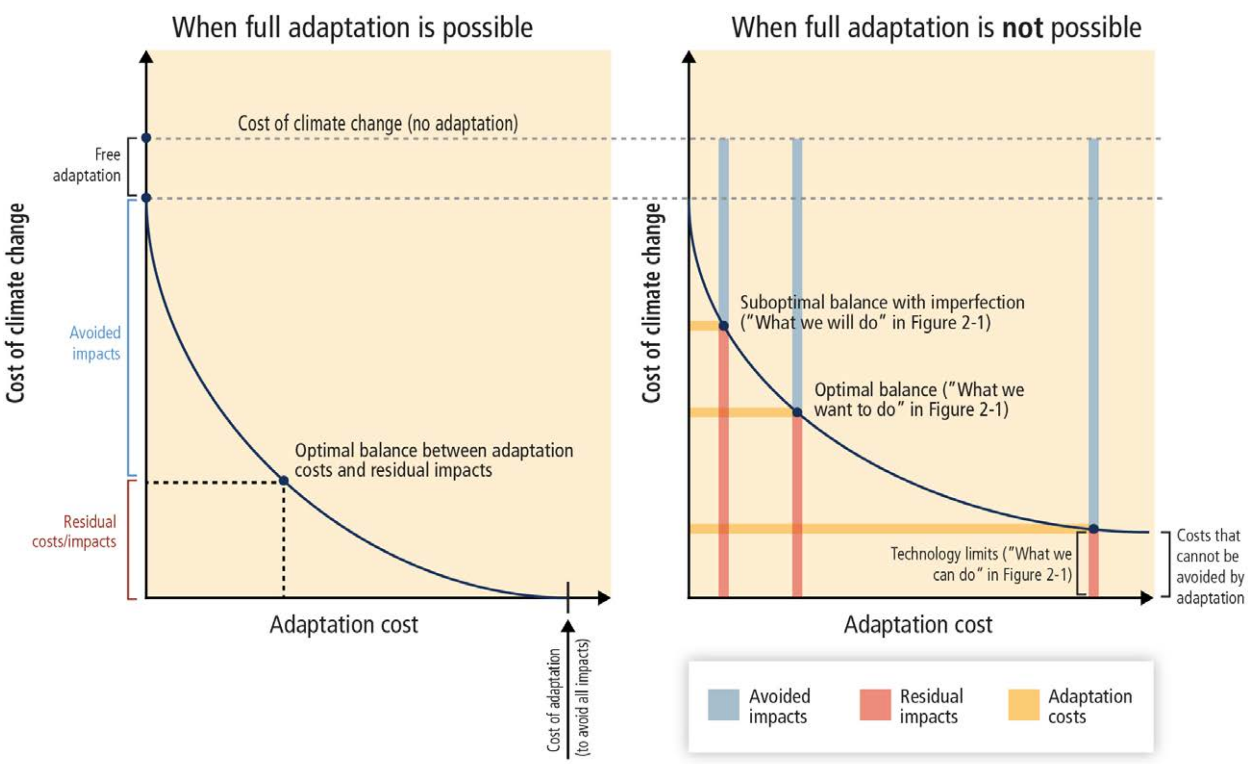

Figure 17-2: Graphical representation of link between the cost of adaptation (on the X-axis) and the residual cost of climate change (on the Y-axis). The left panel represents a case where full adaptation is possible, while the right panel represents a case in which there are unavoidable residual costs.

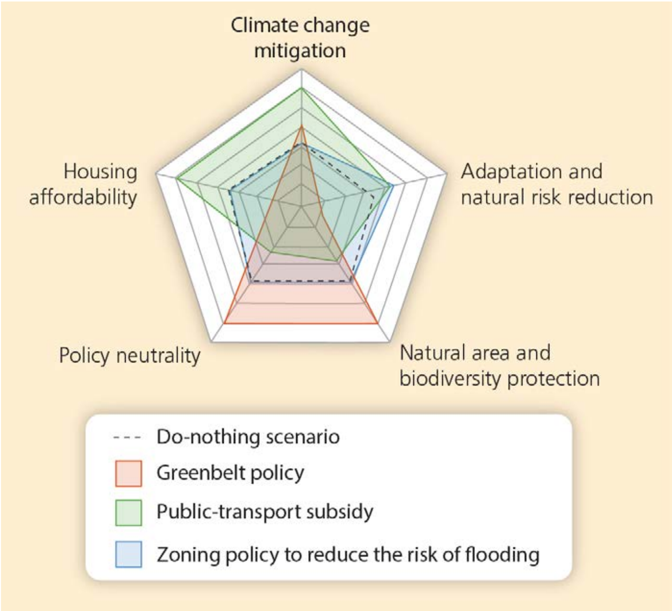

Figure 17-3: Consequences of three policies in the Paris agglomeration: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding, measured using 5 different metrics representing 5 policy objectives. Axes orientation is such that directions towards the exterior of the radar plot represent positive outcomes. Source: Viguié and Hallegatte, 2012.

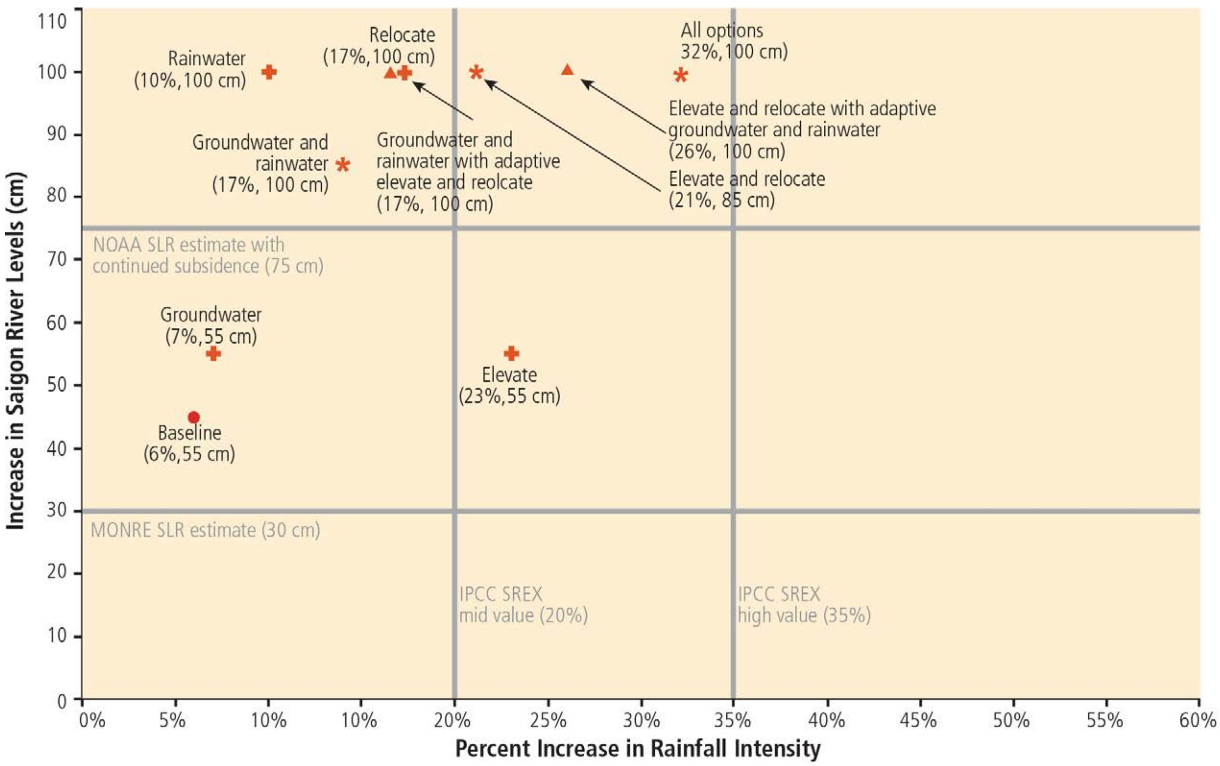

Figure 17-4: Various risk management strategies in Ho Chi Minh City, and their robustness to increases in river levels and rainfall intensity. Different options can cope with different amplitudes of environmental change. Source: Lempert et al., 2013.

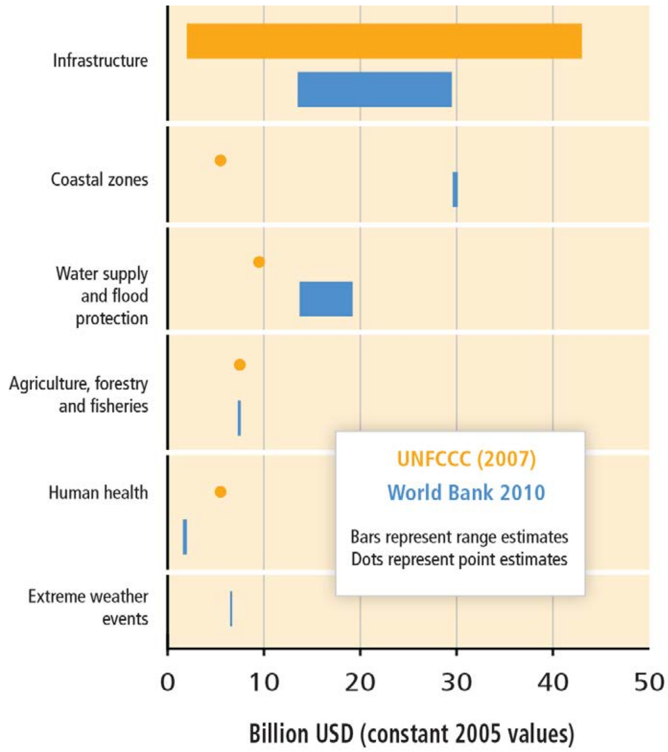

Figure 17-5: Comparison of sectoral results on the costs of adaptation in developing countries across the UNFCCC and World Bank studies. Note: Bars indicate estimates using ranges, points indicate point estimates.

Chapter 18. Detection and Attribution of Observed Impacts

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Contents

Executive Summary

Evidence has grown since the AR4 that impacts of recent changes in climate on natural and human systems occur on all continents and across the oceans. This conclusion is strengthened both by new and longer-term observations, and through more extensive analyses of existing data. [18.3-18.6]

Reported impacts are caused by changes in climate that deviate from historical conditions, irrespective of the driver of climate change. Most reported impacts of climate change are attributed to warming and/or shifts in precipitation patterns. There is also emerging evidence of impacts of ocean acidification. Only some robust attribution studies and meta-analyses link responses in physical and biological systems to *anthropogenic* climate change. [18.1, 18.3-18.5]

For many natural systems there is new or stronger evidence for substantial and wide-ranging impacts of climate change. These systems include the cryosphere, water resources, coastal systems and ecosystems on land and in the ocean. [18.3]

Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands. Glaciers continue to shrink worldwide, due to climate change (*high confidence*), affecting runoff and water resources downstream. Climate change is the main driver of permafrost warming and thawing in both high-latitude and high-elevation mountain regions *(high confidence*). Hydrological systems have changed in many regions due to changing precipitation or melting cryosphere, affecting water resources, water quality and sediment transport (*medium confidence*). [18.3.1, 18.5, Figure 18-2]

Across all climate zones and continents, the major role of climate change and increasing atmospheric CO_2 on terrestrial and freshwater ecosystems has been confirmed by new and stronger evidence on phenology (*high confidence*), productivity (*low confidence*), distribution ranges (*medium confidence*) and other processes, affecting an increasing number of species and ecosystems. The majority of species extinctions and the recession of the Amazon forest cannot be attributed reliably to climate change. Major climate-driven changes occur in the Arctic region (*high confidence*), the boreal forest (*low confidence*) and many freshwater ecosystems (*low to high confidence*, region-dependent). [18.3.2, 18.5]

Despite the known sensitivity of coastal systems to sea-level rise, local natural and human perturbations preclude a confident detection of sea level-related impacts of climate change. Climate change has had a major role in observed changes in abundance and distribution of many coastal species (*medium confidence*). [18.3.3]

The physical and chemical properties of oceans (including the extent of Arctic sea ice) have changed significantly over the past six decades, due to anthropogenic climate change. Marine organisms have moved to higher latitudes, changed their depth distribution or their phenology, mostly as a result of the warming (*high confidence*). Coral reefs have experienced increased mass bleaching and mortality, driven mainly by warming (*high confidence*). [18.3.3., 18.3.4, 18.5, Table 18-8, Box 18-2]

Substantial new evidence has been collected on sensitivities of human systems to climate change. Climate change related impacts on human systems are often dominated by effects of changing social and economic factors. [18.4]

Production of wheat and maize globally and in many regional systems has been impacted by climate change over the past several decades (*medium confidence*). The impacts of climate change on rice and soybean have been small in major production regions and globally (*medium confidence*). Crop production has increased in some mid-latitude regions (United Kingdom, Northeast China) (*high confidence*). Evidence of observed climate change impacts on food systems other than agricultural crops and fisheries is *limited*. [18.4.1]

Economic losses due to extreme weather events have increased globally, mostly due to increase in wealth and exposure, with a possible influence of climate change (*low confidence*). [18.4.3]

There has been a shift from cold- to heat-related mortality in some regions as a result of warming (*medium confidence*), but despite many well-documented sensitivities of human health to other aspects of weather, clear evidence of an additional observed climate change impact on health outcomes is lacking. [18.4.4]

Livelihoods of indigenous peoples in the Arctic have been altered by climate change, through impacts on food security, traditional and cultural values (*medium confidence*). There is emerging evidence of climate change impacts on livelihoods of indigenous people in other regions. [18.4.6, Box 18-5, Table 18-9]

There is emerging literature on the impact of climate change on poverty, working conditions, violent conflict, migration and economic growth from various parts of the world, but evidence for detection or attribution to climate change remains *limited*. [18.4]

Regional impacts of climate change have now been observed at more locations than before, on all continents and across ocean regions. In many regions, impacts of climate change are now detected also in the presence of strong confounding factors such as pollution or land use change. [18.6.2]

'Cascading' impacts of climate change from physical climate through ecosystems on people can now be detected along chains of evidence. Examples include systems in the cryosphere, the oceans, and forests. In these cases, confidence in attribution to observed climate change decreases for effects further down the impact chain. [18.6.3]

Evaluation of observed impacts of climate change supports risk assessment of climate change for four of the "Reasons for Concern" developed by earlier IPCC assessments. (i) Impacts related to *Risks to Unique and Threatened Systems* are now manifested for several systems (Arctic, glaciers on all continents, warm-water coral systems). (ii) High temperature spells have impacted one system with *high confidence* (coral reefs), indicating *Risks Associated with Extreme Weather Events*. Elsewhere, extreme events have caused increasing impacts and economic losses, but there is only *low confidence* in attribution to climate change for these. (iii) While impacts of climate change have now been documented globally with unprecedented coverage, observations are still insufficient to address the spatial or social disparities underlying the *Risks Associated with the Distribution of Impacts*. (iv) *Risks Associated with Aggregated Impacts*: large-scale impacts, indicated by unified metrics, have been found for the cryosphere (ice volume, *high confidence*), terrestrial ecosystems (net productivity, carbon stocks, *medium-high confidence*) and human systems (crop yields, disaster losses, *low-medium confidence*). (v) *Risks Associated with Large-Scale Singular Events*: impacts that demonstrate irreversible shifts with significant feedback potential in the Earth system have yet to be observed, but there is now *robust evidence* of early warning signals in observed impacts of climate change that indicate climate-driven large-scale regime shifts for the Arctic region and the tropical coral reef systems. [18.6.4]

Though evidence is improving, there is a persistent gap in the knowledge regarding how certain parts of the world are being affected by observed climate change. Data collection and monitoring are in need to gain wider coverage. Research to improve the conceptual basis, timeliness and knowledge about detection and attribution is needed in particular for human systems. [18.2, 18.7]

18.1. Introduction

This chapter synthesizes the scientific literature on the detection and attribution of observed changes in natural and human systems in response to observed recent climate change. For policy makers and the public, detection and attribution of observed impacts will be a key element to determine the necessity and degree of mitigation and adaptation efforts. For most natural and essentially all human systems, climate is only one of many drivers that cause – other factors such as technological innovation, social and demographic changes, and environmental degradation frequently play an important role. Careful accounting of the importance of these and other confounding factors is therefore an important part of the analysis.

At any given location, observed recent climate change has happened due to a combination of natural, longer-term fluctuations and anthropogenic alteration of forcings. In order to inform about the sensitivity of natural and human systems to ongoing climate change, the chapter assesses the degree to which detected changes in such systems can be attributed to all aspects of recent climate change. For the development of adaptation policies, it is less important whether the observed changes have been caused by anthropogenic climate change or by natural climate fluctuations. Where possible, the relative importance of anthropogenic drivers of climate change is assessed as well.

18.1.1. Scope and Goals of the Chapter

Previous assessments, notably in the IPCC Fourth Assessment Report (Rosenzweig *et al.*, 2007) indicated that numerous physical and biological systems are affected by recent climate change. Due to a limited number of published studies, human systems received comparatively little attention in these assessments, with the exception of the food system, which is a coupled human/natural system. This knowledge base is growing rapidly, for all types of impacted systems, but the disequilibrium remains (see also 1.1.1, Figure 1-1). The great majority of published studies attributes local to regional changes in affected systems to local to regional climate change.

The objective of the assessment was to cover the growing knowledge about detection and attribution of impacts as exhaustively as possible. In order to improve coverage across sectors and regions, the work was linked directly to the assessments made by most other chapters of the report. This ensured that knowledge gained in the expert assessments of any given sector, system or region found its way into this chapter. This chapter uses a consistent set of definitions for detection and attribution (elaborated in 18.2.1 – these differ from those found in some other chapters).

This chapter first reviews methodologies and definitions for detection and attribution, including the uncertainties that are inherent in such assessments (18.2). It then assesses the scientific knowledge base that has developed since the AR4, focusing on the different types of impacted systems.The assessment covers the state of knowledge across major natural (18.3) and human systems (18.4), based largely on the respective sectoral chapters of this report (3-7, 10-13). Assessment in confidence of the existence and cause of impacts is made according to the definitions elaborated in 18.2.1.2. Based on this material, and on regional assessments mostly drawn from the regional chapters of this report (22-30), an assessment is made in order to highlight regional impacts and also to identify the regional pattern of observed impacts around the globe (18.5). A synthesis (18.6) and an analysis of research and knowledge gaps (18.7) conclude the chapter.

18.1.2. Summary of Findings from the AR4

Rosenzweig *et al*. (2007) reported that "observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases." In particular, they highlighted several areas where this general conclusion was supported by specific conclusions that were reported with *high confidence:*

- Changes in snow, ice and frozen ground had increased ground instability in mountains and other permafrost regions; these changes had led to changes in some Arctic and Antarctic ecosystems and produced increases in the number and size of glacial lakes.
- Some hydrological systems had been affected by increased runoff and earlier spring peak discharges; in particular many glacier- and snow-fed rivers and lakes had warmed, producing changes in their thermal structures and water quality.
- Spring events had appeared earlier in the year so that some terrestrial ecosystems had moved poleward and upward; these shifts in plant and animal ranges were attributed to recent warming.
- Shifts in ranges and changes in algal, plankton and fish abundance as well as changes in ice cover, salinity, oxygen levels and circulation had been associated with rising water temperatures in some marine and freshwater systems.

In terms of a global synthesis, this assessment noted "that it is *likely* that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems" (Rosenzweig *et al.*, 2007). Though it was based on analyses of a very large number of observational datasets, the assessment noted a lack of geographic balance in data and literature on observed changes, with marked scarcity in low and middle income countries.

Evidence reported for human systems was scarce. Rosenzweig *et al*. (2007) concluded with *medium confidence* only that, "other effects of regional climate change on […] human environments are emerging, although many are difficult to discern due to adaptation and non-climatic drivers". They especially noted effects of temperature increases on agricultural and forestry management practices in the higher latitudes of the Northern Hemisphere, various aspects of human health, and some human activities in snow- and glacier dominated environments.

18.2. Methodological Concepts for Detection and Attribution of Impacts of Climate Change

There are substantial challenges to the detection and assessment of the impacts of climate change on natural and human systems. Virtually all such systems are affected by factors other than climate change. Isolating the impacts of climate change therefore requires controlling for the effects of other factors. The problem is further complicated by the ability of many systems to adapt to climate change. In this section we summarize the concepts underlying the detection and attribution of impacts of climate change and the requirements for addressing the main challenges.

18.2.1. Concepts and Approaches

18.2.1.1. Detecting and Attributing Change in the Earth System

Detection and attribution is concerned with assessing the causal relationship between one or more drivers and a responding system. From an analysis perspective, the Earth system can be separated into three coupled subsystems, referred to here as the climate system, the natural system, and the human system (Figure 18-1). Separation of drivers from a responding system is a crucial element of formal detection and attribution analysis. Many external drivers may influence any system, including the changing climate and other confounding factors (Hegerl *et al.*, 2010). Each of the three subsystems affects the other two directly or indirectly. For example, the human system may directly affect the natural system through deforestation, which in turn affects the climate system through changes in albedo; this can alter surface temperatures, which in turn feed back on natural and human systems. If an observed change in the human system impacts the climate system, we call this an anthropogenic driver of climate change.

In this chapter we assess the impacts of *climate change*, where climate change refers to any long-term trend in climate, irrespective of its cause (see Glossary). The great majority of published scientific studies support this type of assessment only. Some studies directly address the detection of and attribution to *anthropogenic climate change*, relating observed impacts, via the climate, to anthropogenic emissions of greenhouse gases and other human activities. Because of the complexity of the causal chain, investigation of this relationship is exceptionally challenging (Parmesan *et al.*, 2011). The findings from such studies are explicitly highlighted in the chapter.

[INSERT FIGURE 18-1 HERE
Figure 18-1: Schematic of the subject covered in this chapter. The Earth system consists of three coupled and overlapping systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone *et al*. (2013).]

18.2.1.2. Concepts of Detection and Attribution of Climate Change Impacts Used in This Chapter

"Detection of impacts" of climate change addresses the question of whether a natural or human system is changing beyond a specified baseline that characterizes its behaviour in the absence of climate change *(Stone et al., 2013).* The baseline may be stationary or non-stationary (e.g., due to land use change), and needs to be clearly defined. This definition of the detection of climate change impacts differs from that in WGI AR5 Chapter 10 which concerns any change in a climate variable, regardless of its cause. The definition adopted here focuses explicitly on the impact of climate change and not on trends related to other factors. The statement of detection is binary: an impact has or has not been detected.

"Attribution" addresses the question of the magnitude of the contribution of climate change to a change in a system. In practice, an attribution statement indicates how much of the observed change is due to climate change with an associated confidence statement. Hence, attribution requires the evaluation of the contributions of all external drivers to the system change. In this chapter we simplify the assessment of this relative contribution by specifying whether observed climate change has had a "minor role" or a "major role" in the overall change in the impacted system. A major role is assessed if the past behavior of the system would have been grossly different in the absence of the observed climate change.

18.2.2. Challenges to Detection and Attribution

Two broad challenges to the detection and attribution of climate change impacts relate to observations and process understanding. On the observational side, high quality, long-term data relating to natural and human systems and the multiple factors affecting them are rare. In addition, the detection and attribution of climate change impacts requires an understanding of the processes by which climate change, in conjunction with other factors, may affect the system in question (see also Box 18-1). These processes can be non-linear – for example, involving threshold effects (e.g., De Young and Jarre, 2009; Wassmann and Lenton, 2012)– and non-local in both space and time, involving lagged responses and trans-regional effects due, for example, to trade or migration.

Conclusions about the effect of climate change on natural and human systems in this report are based on a synthesis of findings in the scientific literature. A potential problem arises through the preferential publication of papers reporting statistically significant findings (Parmesan and Yohe, 2003). Methods exist for detecting and correcting for publication bias in formal quantitative synthesis analysis (Rothstein *et al.*, 2005; Menzel *et al.*, 2006), but these methods cannot be applied in all situations (Kovats *et al.*, 2001). While the assessment in this chapter considers findings in the context of consistency across studies, regions, and similar systems, it has not been possible to quantitatively account for selection bias and to fully differentiate it from the lack of monitoring for some regions and systems.

_____ START BOX 18-1 HERE _____

Box 18-1. Quantitative Synthesis Assessment of Detection and Attribution Studies in Ecological Systems

The wealth of observations in ecological systems now permits the application of quantitative tools for synthesis assessment of detection and attribution (Root *et al.*, 2005). These tools include associative pattern analyses (e.g., Rosenzweig *et al.*, 2008) and regression analyses (Chen *et al.*, 2011) which compare expected changes due to anthropogenic climate change across multiple studies against observed changes.

Quantitative synthesis assessments have been particularly prominent in ecology, where measures of phenology (timing of seasonal events) and geographical range can be assembled across species into standardized indices (Parmesan and Yohe, 2003; Rosenzweig *et al.*, 2008; Chen *et al.*, 2011; Poloczanska *et al.*, 2013; Rosenzweig and Neofotis, 2013). Confidence in the detection of general patterns of change in these indices can increase with the number of species / ecosystems observed, the number of independent studies, the geographical distribution of these observations, the temporal depth and resolution of the data, and the representativeness of species/ecosystems and locations studied. However, increasing spatial coverage, numbers of species, etc. does not a priori increase confidence that climate change is a more credible explanation for biological change than alternative hypotheses. Additional data can contribute to increased confidence in causal relationships, i.e. attribution, in a synthesis assessment when it provides new evidence for explicit testing against a credible range of alternative hypotheses.

_____ END BOX 18-1 HERE _____

18.3. Detection and Attribution of Observed Climate Change Impacts in Natural Systems

The following section provides a synthesis of findings with regard to freshwater resources, terrestrial and inland water systems, coastal systems, and oceans, which are documented in greater detail in Chapters 3, 4, 5, 6 and 30 respectively. It also incorporates evidence from regional chapters and further available literature.

18.3.1. Freshwater Resources

Impacts of climate change on the hydrological cycle, and notably the availability of freshwater resources, have been observed on all continents and many islands, with different characteristics of change in different regions (WGI AR5 Chapters 2 and 10, WGII AR5 Chapters 3, 22-29). Figure 18-2 presents a synthesis of confidence in detection of gobal scale changes in freshwater resources and related systems (notably slope stability and erosion), and their attribution to climate change. Frozen components of freshwater systems tend to show higher confidence in detection and attribution, while components that are strongly influenced by non-climatic drivers, such as river flow, have lower confidence.

[INSERT FIGURE 18-2 HERE
Figure 18-2: Assessment of confidence in detection of observed climate change impacts in global freshwater systems over the past several decades, with confidence in attribution of a major role of climate change, based on expert assessment contained in this section 18.3.1 and augmented by subsections of Chapter 3 as indicated. Numbered symbols refer to: Cryosphere (18.3.1.1): 1 shrinking glaciers (3.2.2), 2 changes in glacier lakes, 3 erosion and degradation of arctic coastal permafrost, 4 degradation and thaw of lowland and mountain permafrost; Rivers, lakes and groundwater (18.3.1.2): 5 groundwater storage change (3.2.4), 6 changing river flow (3.2.3), 7 changing flood frequency or intensity (3.2.3), 8 reduction in lake and river ice duration or thickness in the Northern Hemisphere; Erosion and landslides (18.3.1.3): 9 Increasing erosion (3.2.6), 10 changes in shallow landslides (3.2.6), 11 increasing frequency of high-mountain rock failures.]

18.3.1.1. The Cryosphere

Most components of the cryosphere (glaciers, ice sheets and floating ice shelves, sea, lake and river ice, permafrost and snow) have undergone significant changes during recent decades (*high confidence*), related to climatic forcing (*high confidence*, WGI AR5 Chapter 4). It is *likely* that there is an anthropogenic component in the changes observed in Arctic sea ice, Greenland' surface melt, glaciers, and snow cover (WGI AR5 Chapter 10.5). Glaciers continue to shrink worldwide, with regional variations. It is *likely* that a substantial part of the glacier mass loss is due to anthropogenic warming (WGI AR5 Chapter 10.5.2.2). Climate change has a major role in the absolute contribution of ice loss from glaciers and ice caps to sea level rise has increased since the early 20th Century and has now been close to 1 mm yr^{-1} for the past two decades (WGI AR5 Chapter 4.3.3, 4.4.3), around a third of total observed sea level rise. Recent mass loss of ice sheets and glaciers has accelerated isostatic land uplift in the North Atlantic Region (Jiang *et al.*, 2010). In several high-moutain regions, slope instabilities have occurred as a consequence of recent glacier downwasting (*high confidence*, Vilímek *et al.*, 2005; Haeberli and Hohmann, 2008; Huggel *et al.*, 2011).

The role of climate in changes in runoff decreases from major to minor as the distance from glaciers increases and other non-climatic factors become more important. Runoff from glacier areas has increased for catchments in western and southwestern China over the past several decades, and in western Canada and Europe (Collins, 2006; Zhang *et al.*, 2008; Moore *et al.*, 2009; Li *et al.*, 2010; Pellicciotti *et al.*, 2010; Stahl *et al.*, 2010). Glacier runoff has decreased in the European Alps (Collins, 2006; Huss, 2011), in the central Andes of Chile (Casassa et al., 2009), and in the Cordillera Blanca (Baraer *et al.*, 2012; *medium confidence*), a trend that has also been confirmed by qualitative observations made by local people (Bury *et al.*, 2010; Carey *et al.*, 2012a). For lake and river ice, there is generally *high confidence* in detection of, and a major role of climate change in later freeze-up and earlier break-up over the past 100+ years for several sites in the Northern Hemisphere, yet with regional differences and warmer regions showing higher sensitivities in interannual variability (Livingstone *et al.*, 2010; Voigt *et al.*, 2011;

Weyhenmeyer *et al.*, 2011; Benson *et al.*, 2012). Changes in lake and river ice can have effects on freshwater ecosystems, transport and traffic over frozen lakes and rivers, and ice induced floods during freeze-up and break-up events (Voigt *et al.*, 2011). Some evidence exists in Europe that ice-jam floods were reduced during the last century due to reduced freshwater freezing (Svensson *et al.*, 2006).

The rate of Arctic sea ice decline has increased significantly during the first decade of the 21st Century, due to warming (WGI AR5 Chapter 4.2.2). It is *very likely* that at least some of the decline in Arctic sea ice extent can be attributed to anthropogenic climate forcing (WGI AR5 Chapter 10.5.1). Observations by Inuit people in the Canadian Arctic confirm with *high confidence* the instrumental observations on the various changes of sea ice (see Box 18-5). Antarctic sea ice has slightly increased over the past 30 years, yet with strong regional differences (WGI AR5 Chapter 4.2.3).

Combined *in-situ* and satellite observations indicate indicate a decline of 8% in Northern Hemisphere spring snow cover extent since 1922 (WGI AR5 Chapter 4.5.2). A limited number of studies indicate an anthropogenic influence on snow cover reduction (*high confidence;* WGI AR5 Chapter 10.5.3), including a significant contribution of anthropogenic climate forcing on changes in snow pack and runoff timing between 1950 and 1999 in the Western US (Table 18-6, Barnett *et al.,* 2008).

Climate change generally exerts a major role on permafrost changes. Widespread permafrost warming and thawing, and active layer thickening in both, high-latitude low-lands and high-elevation mountain regions, have been observed over the past decades (*high confidenc;* WGI AR5 Chapter 4.7.2). Climate change impacts have been related to permafrost changes, including an increase of flow speed of rock glaciers and debris lobes in the European Alps and Alaska (*high confidence*), resulting in rockfall, debris flows and potential hazards to transport and energy systems (Kääb *et al.*, 2007; Delaloye *et al.*, 2010; Daanen *et al.*, 2012), expansion, deepening and higher dynamics of thermokarst lakes and ponds in the Arctic (Rowland *et al.*, 2010), and a doubled erosion rate of Alaska's northern coastline over the past 50 years (*high confidence;*18.3.3.1, Table 18-8, Mars and Houseknecht, 2007; Forbes, 2011). Expansion of channel networks (Toniolo *et al.*, 2009), increased river bank erosion (Costard *et al.*, 2007) and an increase in hillslope erosion and landsliding in Northern Alaska since the 1980s (Gooseff *et al.*, 2009) have all been related to climate. Warming and thawing of permafrost in Alaska has adversely affected transport and energy structures and their operation (Karl *et al.*, 2009). Feedbacks and interactions complicate detection of drivers and effects. For example, drying of land surface due to permafrost degradation may cause an increase in wildfires, in turn resulting in a loss of ground surface insulation and change in surface albedo that accelerates permafrost thawing (Rowland *et al.*, 2010; Forkel *et al.*, 2012).

18.3.1.2. The Regional Water Balance

The regional water balance is the net result of gains (precipitation, ice and snow melt, river inflow and groundwater recharge) and losses (evapotranspiration, water use and river outflow, and groundwater discharge). Impacts of climate change include reduced availability of freshwater for use (one of the variables defining drought) or excess water (floods). Evapotranspiration, being a function of solar radiation, surface temperature, vegetation cover, soil moisture and wind, is affected by the changing climate, but also by changing vegetation processes and land cover. At the global scale, human influence has contributed to large scale changes in precipitation patterns over land and, since the mid 20th century, in extreme precipitation (*medium confidence;* WGI AR5 Chapter 10.6.1.2, Min *et al.*, 2011). More locations worldwide have experienced an increase than a decrease in heavy rainfall events, yet with significant regional and seasonal variations (Seneviratne *et al.*, 2012; Westra *et al.*, 2013). In some regions, however, there is *medium confidence* that anthropogenic climate change has affected streamflow and evapotranspiration (WGI AR5 Chapter 10.3.2.3).

Change in river flow is a direct indicator of a changing regional water balance. Globally, about one-third of the top 200 rivers (ranked by river flow) show statistically significant trends during 1948–2004, with more rivers having reduced flow (45) than rivers with increased flow (Dai *et al.*, 2009). Regional reductions in precipitation in southwestern South America are primarily due to internal variability (Dai, 2011, 27.2.1.1). River floods defined as impacts caused by the overtopping of river banks and levées have shown statistically significant increasing and decreasing trends in some regions. The role of climate change in these changes in uncertain, as they may reflect decadal climate variability and be affected by other counfounding factors such as human alteration of river channels and land use (3.2.7). In regions with detected increases in heavy rainfall events (North America, Europe), both increases and decreases in floods have been found (*medium confidence* in detection; Petrow and Merz, 2009; Villarini *et al.*, 2009). In the UK, flood risk has increased due to anthropogenic forcing for events comparable to the 2000 floods (Kay *et al.*, 2011; Pall *et al.*, 2011, see also 18.4.4.2).

Expanding or new lakes as a result of ice melt at the margin of many shrinking glaciers in the Alps of Europe, Himalayas, Andes and other mountain regions have altered the risk of glacier lake outburst floods (GLOF) and required substantial risk reduction measures in the 21st century (Huggel *et al.*, 2011; Carey *et al.*, 2012b). While there is no evidence for a change in frequency or magnitude of GLOFs (Seneviratne *et al.*, 2012), climate change has had a major role in the substantial increase in glacial lake area in the eastern Himalaya region between 1990 and 2009 (Gardelle *et al.*, 2011), and the similarly strong increase in lake numbers in the Andes of Peru in the second half of the 20th century (Carey, 2005), and in northern Patagonia from 1945 to 2011 (Loriaux and Casassa, 2013; *high confidence* in detection). New glacier lakes are not only an additional source of floods but also have become a tourist attraction, led to additional infrastructure, and stimulated assessment of potential for hydropower generation (Terrier *et al.*, 2011).

Since the 1950s some regions of the world have experienced more intense and longer droughts, although a global trend can currently not be established (Seneviratne *et al.*, 2012, 3.2.2 WGI AR5 2.6.2.2). Longer drought periods have affected groundwater recharge (Leblanc *et al.*, 2009; Taylor *et al.*, 2013), but changes in groundwater storage are generally difficult to attribute to climate change, due to confounding factors from human activities (Table 3-1, Rodell *et al.*, 2009; Taylor *et al.*, 2013). Likewise, confounding factors do not permit to attribute observed changes in water quality to climate change (3.2.5, Kundzewicz and Krysanova, 2010).

18.3.1.3. Erosion, Landslides, and Avalanches

Erosion and landsliding typically increase in phase with deglaciation in mountain areas (Ballantyne, 2002; Korup *et al.*, 2012) and there is emerging evidence for this to occur during contemporary deglaciation (Schneider *et al.*, 2011; Uhlmann *et al.*, 2013). In the Western Himalaya, sediment flux has increased (*medium confidence;*Wulf *et al.*, 2012) and been related to hydrologic extreme events over the past 60 years *(low confidence;*Malik *et al.*, 2011), with important consequences for hydropower schemes. In China, a drastic decrease of sediment load in the Yangtze River was observed since the 1980s. There have been local variations in precipitation and runoff since 1950, but changes in sediment load are primarily attributed to over 50,000 dams and vegetation changes (*medium confidence;* Xu *et al.*, 2008). There is clear evidence for decline in sediment load in the Zhujiang (Pearl River) basin since the early 1990s (Zhang *et al.*, 2008).

In the European Alps, no clear evidence exists so far for any change in frequency of shallow landslides and debris flows from recently deglaciated mountain areas (Jomelli *et al.*, 2004; Stoffel and Huggel, 2012). In some cases climate change has had a major role in influencing frequency and magnitude of alpine shallow landslides and debris flows by altering sediment yield, e.g. from rockfall or disintegration of rock glaciers (*low confidence;* Lugon and Stoffel, 2010).

Glacier shrinkage, permafrost degradation and high-temperature events have contributed to many high-mountain rock slope failures since the 1990s (*medium confidence* in major role of climate change; Allen *et al.*, 2010; Ravanel and Deline, 2011; Schneider *et al.*, 2011; Fischer *et al.*, 2012; Huggel *et al.*, 2012a). Rock slope failures have increased over this period in the Western Alps of Europe (*high confidence*), the New Zealand Alps (*medium confidence*), and globally (*low confidence*). Cascading processes of permafrost and ice-related landslides impacting lakes and downstream areas have been observed in many high-mountain regions, causing major damages and risk reduction measures (*high confidence*), with climate change exerting a major role (*medium confidence;* e.g., Xin *et al.*, 2008; Bajracharya and Mool, 2009; Künzler *et al.*, 2010; Carey *et al.*, 2012a; Huggel *et al.*, 2012b). For other landslide types than the above, there is no clear evidence that their frequency or magnitude has changed over the past decades (Huggel *et al.*, 2012b). In general, detection of changes in the occurrence of landslides is complicated by incomplete inventories, both in time and space, and inconsistency in terminology.

Physical understanding suggests that climate change has a major role in changes of snow avalanche activity but no such changes have been reported so far (*medium confidence;* Laternser and Schneebeli, 2002; Voigt *et al.*, 2011), except for the French Alps (Eckert *et al.*, 2013; *medium confidence* in detection). The detection of changes in snow avalanche impacts, such as fatalities and property loss, is difficult over the past decades due to changes in snow sport activities and avalanche defense measures.

18.3.2. Terrestrial and Inland Water Systems

As documented by previous IPCC reports (notably Rosenzweig *et al.*, 2007), climate-driven changes in terrestrial and inland water systems are widespread and numerous. Confidence in such detection of change is often *very high*, reflecting *high agreement* among many independent sources of evidence of change, and *robust evidence* that changes in ecosystems or species are outside of their natural variation. Confidence in attribution to climate change is also often *high*, due to process understanding of responses to climate change, or strong correlations with climate trends and where confounding factors are understood to have limited importance (4.3.2, 4.3.3, Figure 4-4). The scientific literature in this field is growing quickly, detailed traceability is provided in Chapter 4.

Organisms respond to changing climate in a multitude of ways, including through their phenology (the timing of key life history events such as flowering in plants or migration of birds), productivity (the assimilation of carbon and nutrients in biomass), spatial distribution, mortality / extinction, or by invading new territory. Noticeable changes may occur at the level of individual organisms, ecosystems, landscapes, or by modification of entire biomes. Organisms and ecosystems are adapted to a variable environment, and they are capable to adapt to gradual change to some degree. Assessing confidence in the detection of such change involves therefore assumptions about natural variability in these ecosystems, while assessment of confidence in the attribution of detected change to climate drivers (or CO_2) implies the assessment of confounding drivers such as pollution or land use change.

18.3.2.1. Phenology

Since the AR4 there has been a further substantial increase in observations, showing that hundreds of (but not all) species of plants and animals have changed functioning to some degree over the last decades to centuries on all continents (*high confidence* due to *robust evidence* but only *medium agreement* across all species; 4.3.2.1, Menzel *et al.*, 2006; Cook *et al.*, 2012b; Peñuelas *et al.*, 2013). New satellite-based analyses confirm earlier trends, showing, for example, that the onset of the growing season in the Northern Hemisphere has advanced by 5.4 days from 1982 to 2008 and its end has been delayed by 6.6 days (Jeong *et al.*, 2011). Significant changes have been detected, by direct observation, for many different species, for example, for amphibians (e.g., Phillimore *et al.*, 2010), birds (e.g., Pulido, 2007; Devictor *et al.*, 2008), mammals (e.g., Adamík and Král, 2008), vascular plants (e.g., Cook *et al.*, 2012a), freshwater plankton (Adrian *et al.*, 2009) and others (4.3.2.1); a number of new meta-analyses have been carried out summarizing this literature (e.g., Cook *et al.*, 2012a). Attribution of these changes to climate change is supported by more refined analyses that consider also the regional changes in several variables such as temperature, growing season length, precipitation, snow cover duration and others, as well as experimental evidence (Xu *et al.*, 2013). The *high confidence* in attributing many observed changes in phenology to changing climate is a result of these analyses, as well as of improved knowledge of confounding factors such as land use and land management (see also 4.3.2.1).

18.3.2.2. Productivity and Biomass

Many terrestrial ecosystems are now net sinks for carbon over much of the Northern Hemisphere and also in parts of the Southern Hemisphere (*high confidence*, see also 4.3.2.2 and 4.3.2.3). This is shown, for example, by inference from atmospheric chemistry, but also by direct observations of increased tree growth in many regions including

Europe, the United States, tropical Africa and the Amazon. During the decade 2000 to 2009, global land net primary productivity was approx. 5% above the preindustrial level, contributing to a net carbon sink on land of 2.6 ± 1.2 Pg C yr^{-1} (Raupach *et al.*, 2008; Le Quéré *et al.*, 2009, 4.3.3.2, WGI AR5 Chapter 6), despite ongoing deforestation. Forests have increased in biomass for several decades in Europe (Luyssaert *et al.*, 2010) and the USA (Birdsey *et al.*, 2006). These trends are in part due to nitrogen deposition, afforestation and altered land management which makes direct attribution of the increase to climate change difficult. The degree to which rising atmospheric CO_2 concentrations contribute to this trend remains a particularly important source of uncertainty (Raupach *et al.*, 2008). Canadian managed forests increased in biomass only slightly during 1998-2008, because growth was offset by significant losses due to fires and beetle outbreaks (Stinson *et al.*, 2011). In the Amazon forest biomass has generally increased in recent decades, dropping temporarily after a drought in 2005 (Phillips *et al.*, 2009). A global analysis of long-term measurements suggests that soil respiration has increased over the past two decades by approximately 0.1 Pg C yr^{-1}, some of which may be due to increased productivity (Bond-Lamberty and Thomson, 2010). Man-made impoundments in freshwater ecosystems represent an increasing and short-lived additional carbon store with conservative annual estimates of 0.16 – 0.2 Pg C yr^{-1} (Cole *et al.*, 2007).

18.3.2.3. Species Distributions and Biodiversity

Each species responds differently to a changing environment, therefore the composition of species, genotypes, communities and even ecosystems varies in different ways from place to place, in response to climate change. The consequences are changing ranges of species, changing composition of the local species pool, invasions, mortality and ultimately extinctions. For different species and species groups, detected range shifts vary, and so do the confidence of detection and the degree of attribution to climate change. The number of species studied has considerably increased since the AR4. Overall, many terrestrial species have recently moved, on a global average, 17 km poleward and 11 m up in altitude per decade (e.g., Europe, North America, Chile, Malaysia), which corresponds to predicted range shifts due to warming (Chen *et al.*, 2011) and is 2 to 3 times faster than previous estimates (Parmesan and Yohe, 2003; Fischlin *et al.*, 2007), with *high confidence* in detection. Europe, forest species are moving up in altitude, probably due to climate warming at the end of the 20th century (Gehrig-Fasel *et al.*, 2007; Lenoir *et al.*, 2008). Species with short life cycles and high dispersal capacity – such as butterflies (*high confidence* in a major role of climate change) – are generally tracking climate more closely than longer-lived species or those with more limited dispersal such as trees (Devictor *et al.*, 2012; *medium confidence* in a major role of climate change). There are many less well-studied species for which detection of change and its attribution to climate change are more uncertain.

Changes in abundance, as measured by changes in the population size of individual species or shifts in community structure within existing range limits, have occurred in response to recent global warming (Thaxter *et al.*, 2010; Bertrand *et al.*, 2011; Naito and Cairns, 2011; Rubidge *et al.*, 2011; Devictor *et al.*, 2012; Tingley *et al.*, 2012; Vadadi-Fülöp *et al.*, 2012; Cahill *et al.*, 2013; Ruiz-Labourdette *et al.*, 2013), but due to confounders, confidence in a major role of climate change is often *low*. Across the world, species extinctions are at or above the highest rates of species extinction in the fossil record (*high confidence;* Barnosky *et al.*, 2011). However, only a small fraction of observed species extinctions have been attributed to climate change — most have been ascribed to non-climatic factors such as invasive species, overexploitation or habitat loss (Cahill *et al.*, 2013). For those species where climate change has been invoked as a causal factor in extinction (such as for the case of Central American amphibians), there is *low agreement* among investigators concerning the importance of climate variation in driving extinction and even less agreement that extinctions were caused by climate change (Pounds *et al.*, 2006; Kiesecker, 2011). *Confidence* in the suggested attribution of extinctions across all species to climate change is *very low* (see also 4.3.2.5).

Species invasions have increased over the last several decades world-wide, notably in freshwater ecosystems (*very high confidence*), often causing biodiversity loss or other negative impacts. There is only *low confidence* that species invasions have generally been assisted by recent climatic trends because of the overwhelming importance of human facilitated (intentional or non-intentional) dispersal in the transfer from the area of origin. Once established in a new environment, many introduced species have recently become invasive due to climate change (*medium to high confidence*, depending on the taxon (see also 4.2.4.6).

18.3.2.4. Impacts on Major Systems

Field and satellite measurements indicate substantial changes in freshwater and terrestrial ecosystems (often linked to permafrost thawing) in many areas of the Arctic tundra (*high confidence*; Hinzman *et al.*, 2005; Axford *et al.*, 2009; Jia *et al.*, 2009; Post *et al.*, 2009; Prowse and Brown, 2010; Myers-Smith *et al.*, 2011; Walker *et al.*, 2012). Vegetation productivity has systematically increased over the past few decades in both North America and northern Eurasia (Goetz *et al.*, 2007; Jia *et al.*, 2009; Elmendorf *et al.*, 2012). Most sub-populations of the polar bear are declining in number (Vongraven and Richardson, 2011). These changes correspond to expectations, based on experiments, models and paleoecological responses to past warming, of broad-scale boreal forest encroachment into tundra, a process which takes decades and which would have very large impacts on ecosystem structure and function. The particular strength of warming over the last 50 years for most of the Arctic further facilitates attribution of a major role of climate change (*high confidence*). The change affects a significant area of the tundra biome and can be considered an early warning for an ongoing regime shift (4.3.3.4, Figure 4-4).

For the boreal forest, increases in tree mortality are observed in many regions, including wide-spread dieback related to insect infestations and/or fire disturbances in North America (Fauria and Johnson, 2008; Girardin and Mudelsee, 2008; Kasischke *et al.*, 2010; Turetsky *et al.*, 2010; Wolken *et al.*, 2011) and in Siberia (Soja *et al.*, 2007), but there is *low confidence* in detection of a global trend. Many areas of boreal forest have experienced productivity declines (*high confidence;* Goetz *et al.*, 2007; Parent and Verbyla, 2010; Beck and Goetz, 2011), related to warming-induced drought, specifically the greater drying power of air (Williams *et al.*, 2012), inducing photosynthetic down-regulation of boreal tree species not adapted to the warmer conditions (Welp *et al.*, 2007; Bonan, 2008). Conversely, productivity has increased along the boreal-tundra ecotone where more mesic (moist) conditions may be generating the expected warming-induced positive growth response (McGuire *et al.*, 2007; Goldblum and Rigg, 2010; Beck and Goetz, 2011). Overall, these multiple impacts in the boreal forest biome can be considered an early warning for an ongoing regime shift only with *low confidence* (4.3.3.1.1, Figure 4-4). Many of the aforementioned changes take place in the tundra-boreal ecotone, affecting both biomes significantly (Box 4-4, Figure 4-10).

In tropical forests, climate change effects are difficult to identify against the confounding effects of direct human influence as is well illustrated for the Amazon forest (Davidson *et al.*, 2012) but also applies elsewhere. Since AR4, there is new evidence of more frequent severe drought episodes in the Amazon region that are associated with observed sea surface temperature increases in the tropical North Atlantic (*medium confidence;* Marengo *et al.*, 2011a). There is *low confidence*, however, that these changes can be attributed to climate change (4.3.3.1.3). There is *medium confidence* that tree mortality in the Amazon region is has increased due to severe drought and increased forest fire occurrence and *low confidence* that this can be attributed to warming (4.3.3.1.3, Figure 4-4, Figure 4-8).

In freshwater ecosystems of most continents and climate zones, rising temperatures have been linked to shifts in invertebrate and fish community composition, especially in headwater streams where species are more sensitive to warming (Brown *et al.*, 2007; Durance and Ormerod, 2007; Chessman, 2009; 4.3.3.3; *high confidence* in detection, *low confidence* in a major role of climate change due to numerous confounding factors). Long-term shifts in macroinvertebrate communities have been observed in European lakes where temperatures have increased (Burgmer *et al.*, 2007).

18.3.3. Coastal Systems and Low Lying Areas

Coastal systems are influenced by many anthropogenic and natural processes. Important climate-related drivers include changes in ocean temperature, salinity, and pH; and sea level (see Table 5-2). In coastal waters, both annual and seasonal changes in temperature tend to be larger than the average rate for the open ocean (5.3.3). Sea surface temperatures have increased significantly during the past 30 years along more than 70% of the world's coastlines, with large spatial and seasonal variation, and the frequency of extreme temperature events in coastal waters has changed in many areas (Lima and Wethey, 2012). Seawater pH spans larger ranges and exhibits higher variability near coastlines, and anthropogenic ocean acidification can be enhanced or reduced by coastal geochemical processes (Borges and Gypens, 2010; Feely *et al.*, 2010; Duarte *et al.*, 2013, see also Box CC-OA).

While it is *likely* that extreme sea levels have increased globally since the 1970s, mainly as a result of mean sea level rise due in part to anthropogenic warming (WGI AR5 3.7.5, 3.7.6; WGI AR5 10.4.3), local sea level trends are also influenced by factors such as regional variability in ocean and atmospheric circulation, subsidence, isostatic adjustment, coastal erosion, and coastal modification (see also 5.3.2). As a consequence, the detection of the impact of climate change in observed changes in relative sea level remains challenging (Nicholls *et al.*, 2007; Nicholls *et al.*, 2009; Menéndez and Woodworth, 2010). An exception is lower sea level in regions of isostatic rebound in response to reduced ice cover due to climate change (Kopp *et al.*, 2010; Tamisiea and Mitrovica, 2011). In these regions, climate change has played a major role in the lowering sea level (*medium confidence*).

18.3.3.1. Shoreline Erosion and other Coastal Processes

Throughout the world, the rate of shoreline erosion is increasing (5.4.2.1). While processes related to climate change, such as rising mean sea levels (Leatherman *et al.*, 2000; Ranasinghe and Stive, 2009), more frequent extreme sea levels (Woodworth *et al.*, 2011), or permafrost degradation and sea ice retreat (Forbes, 2011) can be expected to enhance global erosion, there are multiple drivers involved in shoreline erosion that are unrelated to climate change including long shore sediment transport, the diversion of sediments by dams, subsidence due to resource extraction, mining and coastal engineering and development (see also Table 5-3). Due to the fragmentary nature of the information available, and to the multiple natural and anthropogenic stressors contributing to coastal erosion, confidence in detection of a climate change contribution to observed shoreline changes is *very low*, with the exception of Polar Regions (Table 18-8, Mars and Houseknecht, 2007; Forbes, 2011).

Coastal lagoons and estuaries, as well as deltas are highly susceptible to alterations of sediment input and accumulation (Syvitski *et al.*, 2005; Ravens *et al.*, 2009), processes that can be influenced by climate change via changes in mean and extreme sea levels, storminess, and precipitation. However, the primary drivers of widespread observed changes in those systems are human drivers other than climate change so that there is *very low confidence* in the detection of impacts related to climate change (5.4.2).

Coastal aquifers are crucial for the water supply of densely populated coastal areas, in particular in small island environments and dry climates. Aquifer recharge is sensitive to changes in temperature and precipitation; and rising sea levels and saltwater overwash from storm surges can contribute to saline intrusion into groundwater (Post and Abarca, 2010; Terry and Falkland, 2010; White and Falkland, 2010, see also 29.3.2, Table 18-8). However, groundwater extraction for coastal settlements and agriculture is the main cause for widely observed groundwater degradation in coastal aquifers (e.g., White *et al.*, 2007a; Barlow and Reichard, 2010). It is not yet possible to detect the impact of climate change on coastal aquifers with any degree of confidence (Rozell and Wong, 2010; White and Falkland, 2010).

Changes in water column mixing have combined with other factors such as nutrient loading to drive down oxygen concentrations and increase the number and extent of hypoxic zones (Vaquer-Sunyer and Duarte, 2011). These zones are characterized by very low oxygen and high CO_2 levels and, in some cases, exert strong local and regional effects on marine biota such as distribution shifts, habitat contraction or loss, and fish kills (Diaz and Rosenberg, 2008). The operation of other factors makes the detection of a climate change impact on the frequency, distribution, and intensity of hypoxia possible with only *medium confidence* and it is difficult to assess the relative magnitude of this impact (see Table 18-1).

18.3.3.2. Coastal Ecosystems

Coastal habitats and ecosystems experience cumulative impacts of land- and ocean-based anthropogenic stressors (Halpern *et al.*, 2008). Most coral reefs, seagrass beds, mangroves, rocky reefs and shelves have undergone substantial changes over the course of the last century. Fishing and other extractive activities, land use changes, and pollution have been responsible for a large proportion of these historical changes (Lotze *et al.*, 2006). Biological responses to changes in the temperature, chemistry, and circulation of the ocean are complex and often interact with other anthropogenic factors.

Coral reefs have been degraded due both to local anthropogenic factors such as fishing, land use changes, and pollution and to ocean warming related to climate change and also possibly to acidification (see Box CC-CR). Over the past 30 years, mass coral bleaching has been detected with *very high confidence* on all coasts, and warming is a major contributor (*high confidence,* for further discussion see Box 18-2, and Box CC-OA).

Changes in abundance and distribution of rocky shore species have been observed since the late 1940s in the North East Atlantic (Hawkins *et al.*, 2008), and the role of temperature has been demonstrated by experiments and modelling (Poloczanska *et al.*, 2008; Wethey and Woodin, 2008; e.g., Peck *et al.*, 2009; Somero, 2012, see also 5.4.2.2). Globally, the ranges of many rocky shore species have shifted up to 50 km per decade, much faster than most recorded shifts of terrestrial species (Helmuth *et al.*, 2006; Poloczanska *et al.*, 2013, see also Box 18-3). However, distinguishing the response of these communities to climate change from those due to other natural and anthropogenic causes is challenging. Weak warming, overriding effects of confounding factors or biogeographic barriers can explain the fact that geographical distribution of some species did not change over the past decades (Helmuth *et al.*, 2002; Rivadeneira and Fernández, 2005; Helmuth *et al.*, 2006; Poloczanska *et al.*, 2011).

Ocean warming has contributed to observed range shifts in vegetated coastal habitats such as coastal wetlands, mangrove forests and seagrass meadows (5.4.2.3). Poleward expansion of mangrove forests, consistent with expected behavior under climate change, has been observed in the Gulf of Mexico (Perry and Mendelssohn, 2009; Comeaux *et al.*, 2012; Raabe *et al.*, 2012), and New Zealand (Stokes *et al.*, 2010). High temperatures have impacted seagrass biomass in the Atlantic Ocean (Reusch *et al.*, 2005; Díez *et al.*, 2012; Lamela-Silvarrey *et al.*, 2012), the Mediterranean Sea (Marbà and Duarte, 2010) and Australian waters (Rasheed and Unsworth, 2011). Extreme weather events also contributed to the overall degradation of seagrass meadows in a Portuguese estuary (Cardoso *et al.*, 2008).

Decline in kelp populations attributed to ocean warming has occurred off the north coast of Spain (Fernández, 2011), as well as in southern Australia, where the poleward range expansion of some herbivores have also contributed to observed kelp decline (Ling, 2008; Ling *et al.*, 2009; Ling *et al.*, 2009; Johnson *et al.*, 2011; Wernberg *et al.*, 2011; Wernberg *et al.*, 2011). The spread of subtropical invasive macroalgal species (e.g., Lima *et al.*, 2007) may be adding to the stresses temperate seagrass meadows experience from ocean warming. Extreme temperature events can alter marine and coastal communities, as shown e.g. for the European heatwave 2003 (Garrabou *et al.*, 2009), and the early 2011 heat wave off the Australian West Coast (Wernberg *et al.*, 2012).

In summary, there is *high confidence* in the detection of the impact of climate change on the abundance and distribution of a range of coastal species and *medium confidence* that climate change has played a major role in many cases. In specific cases, such as the decline of salt marshes and mangroves, the impact of climate change has been detected with *very low confidence* due to the overriding effect of land use changes, pollution, and other factors unrelated to climate change.

18.3.3.3. Coastal Settlements and Infrastructure

Total damages from coastal flooding have increased globally over the last decades (*high confidence)* however, with exposure and subsidence constituting the major drivers, confidence in detection of a climate change impact is *very low* (Seneviratne *et al.*, 2012, see also 5.4.3.2, 5.4.4). Recent global (e.g., Menéndez and Woodworth, 2010; Woodworth *et al.*, 2011) and regional studies (e.g., Marcos *et al.*, 2009; Haigh *et al.*, 2010; Haigh *et al.*, 2011) have found increases in extreme sea levels consistent with mean sea level trends (see also Table 5-2), indicating that the increasing frequency of extreme water levels affecting coastal infrastructures observed so far is related to rising mean sea level rather than to changes in the behaviour of severe storms. While vulnerability of coastal settlements and infrastructure to future climate change, in particular sea level rise and coastal flooding, is widely accepted and well-documented (see 5.5), there is a shortage of studies discussing the role of climate change in observed impacts on coastal systems.

Increases in saltwater intrusion and flooding have been observed in low-lying agricultural areas of deltaic regions and small islands, but the contribution of climate change to this is not clear (e.g., Rahman *et al.*, 2011, see also 5.4.3.3, 5.4.2.5). While both climate change impacts on physiological and ecological properties of fish (e.g., Barange and Perry, 2009, see also 18.3.4), and vulnerability of coastal communities and fisherfolks to climate fluctuations and change (Badjeck *et al.*, 2010; Cinner *et al.*, 2012) are well established in the literature, there is *limited evidence* for observed effects of climate change on coastal fishery operations (see also 18.4.1.2).

_____ START BOX 18-2 HERE _____

Box 18-2. Attribution of Mass Coral Bleaching Events to Climate Change

A critical source of energy for the maintenance and growth of coral is provided by symbiotic brown algae. Coral bleaching occurs when these symbionts leave their host. Bleaching events have deleterious impacts on corals and, depending on their severity and duration, can cause death. It is known that thermal stress can trigger coral bleaching (Muscatine, 1986; Hoegh-Guldberg and Smith, 1989; Jones *et al.*, 1998). Mass bleaching events that affect entire reefs or coastal regions can occur when local or regional temperatures exceed the typical summer maximum for a period of a few weeks (Hoegh-Guldberg, 1999; Baker *et al.*, 2008; Strong *et al.*, 2011). The effect of elevated temperature is exacerbated by strong solar irradiance (Hoegh-Guldberg, 1999).

Since 1980, mass coral bleaching events have occurred throughout the tropics and sub-tropics at a rate without precedent in the literature (see also CC-CR, CC-OA, 5.4.2.4). These events have often been followed by mass mortality (Hoegh-Guldberg, 1999; Baker *et al.*, 2008). In the very warm year of 1998, for example, mass bleaching occurred in almost every part of the tropics and sub-tropics and resulted in the loss of a substantial fraction of the world's corals (Wilkinson *et al.*, 1999). A large-scale bleaching event also occurred in the Caribbean during 2005 (Eakin *et al.*, 2010).

Declining water quality, coastal development, increased fishing, and even tourism have also been implicated in the decline of coral communities over the past 50 years (Bryant *et al.*, 1998; Gardner *et al.*, 2003; Bruno and Selig, 2007; Sheppard *et al.*, 2010; Burke *et al.*, 2011; De'ath *et al.*, 2012). However, given the scope of recent mass bleaching events, their co-occurence with elevated temperatures, and a physiological understanding of the role of temperature in bleaching, there is *very high confidence* in the detection of the impact of climate change, and *high confidence* in the finding that climate change has played a major role.

_____ END BOX 18-2 HERE _____

18.3.4. Oceans

Since 1970, ocean temperatures have increased by around 0.1 °C $decade^{-1}$ in the upper 75 m and approximately 0.015 °C $decade^{-1}$ at 700m (see 30.3.1.1). It is *very likely* that the increase in global ocean heat content observed in the upper 700 m since the 1970s has a substantial contribution from anthropogenic forcing (WGI AR5 Chapter 10.4.1). The increased flux of CO_2 from the atmosphere to the ocean has reduced the average pH of sea water by about 0.1 pH units over the past century, with the greatest reduction occurring at high latitudes (see also Box CC-OA). These changes have been attributed to increases in the atmospheric concentration of greenhouse gases as result of human activities (*very high confidence*, WGI AR5 Chapter 10.4.4). Changes in wind speed, upwelling, water column stratification, surface salinity, ocean currents, sand oxygen depth profile have also been been detected with at least *medium confidence* (WGI AR5 Chapter 3; Figure 30-5, 30-6).

Changes in the physical and chemical nature of ocean environments are predicted to have impacts on marine organisms and ecosystems, with many already having been observed across most ocean regions (6.2, 6.3, 30.4, 30.5). However, the detection of these predicted changes and the assessment of the role of climate change in them are complicated by the influence of long-term variability such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO). The fragmentary nature of ocean observations and the influence of confounding factors such as fishing, habitat alteration and pollution also represent significant challenges to detection and attribution (Hoegh-Guldberg *et al.*, 2011; Parmesan *et al.*, 2011, see also Box 18-3).

18.3.4.1. Impacts on Ocean System Properties and Marine Organisms and Ecosystems

Greater thermal stratification in many regions has reduced ocean ventilation and mixing depth. As this reduces the availability of inorganic nutrients, it can reduce primary productivity in surface layers. However, trends in primary production from different observational methods disagree (6.1.1, 6.3.4, Box CC-PP). Coastal upwelling has increased in some regions bringing greater concentrations of nutrients to surface waters, boosting productivity and enhancing fisheries output (see 30.5.5). Increases in productivity also occurred with warming and sea ice loss at high latitude (Table 18-1, *medium confidence*).

Poleward shifts in the distributions of zooplankton, fish, seabirds and benthic invertebrates related to climate change have been detected with *high confidence* in the well-studied NE Atlantic. There is also *high confidence* that climate change has played a *major role* in these shifts (Box 6-1, 6.3, 30.5.1). In many regions, temperature exerts the strongest influence on ecosystems and the responses of ecological systems to changing temperature are well-studied. However, it is often difficult to clearly identify the interaction of temperature with other factors (6.3.5). Some studies have found changes in the abundance of fish species that are consistent with regional warming, with differences in response between species, in line with differential specializations of coexisting species (6.2, 6.3.1, see also Pörtner, 2012). Anthropogenic influences modulate responses to climate, e.g., due to exploitation status (Tasker, 2008; Belkin, 2009; Overland *et al.*, 2010; Schwing *et al.*, 2010), with more heavily exploited species being more sensitive to environmental variability in general, including temperature trends and extremes (Hsieh *et al.*, 2005; Stige *et al.*, 2006; Hsieh *et al.*, 2008).

Laboratory experiments have shown that a broad range of marine organisms (e.g. corals, fish, pteropods coccolithophores, and macroalgae), physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth and neural function), and ecosystems processes (e.g., productivity, reef building and erosion) are sensitive to changes in pH and carbonate chemistry of seawater (6.2, Box CC-OA). However, few field studies have been able to detect specific changes in marine ecosystems to ocean acidification due to the inability to identify the effect of ocean acidification from ocean warming or local factors (Wootton *et al.*, 2008; De Moel *et al.*, 2009; Moy *et al.*, 2009; Bednaršek *et al.*, 2012, see also 6.3.2).

[INSERT TABLE 18-1 HERE
Table 18-1: Observed changes in ocean system properties and their effects, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role.]

There has been a substantial increase in the number of studies documenting significant changes in marine species and processes since the AR4. A new meta-analysis using a database of long-term observations from peer-reviewed studies of biological systems, with nearly half of the time series extending prior to 1960, shows that more than 80% of observed responses are consistent with regional climate change (see 30.4, Box CC-MB). Poloczanska *et al*. (2013) argue that the high consistency of marine species' responses across geographic regions (coastal to open ocean, polar to tropical), taxonomic groups (phytoplankton to top predators), and types of responses (distribution, phenology, abundance) reported in their analysis support the detection of a widespread impact of climate change on marine populations and ecosystems (see 30.4 and 30.5 for more detail). Table 18-2 gives examples of the manifestation of climate change on marine species and ecosystems.

[INSERT TABLE 18-2 HERE
Table 18-2: Observed changes in marine species and ecosystems, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role (see also 6.2, 6.3, 30.4, Box CC-MB).]

18.3.4.2. Observed Climate Change Effects across Ocean Regions

Climate change has affected physical properties across the ocean, with regional variations (Table 30-1; Figures 30-2 to 30-5; WGI AR5 Chapter 3). Confidence in the detection and attribution of these impacts also varies regionally, reflecting differences in system understanding, data availability, influence of long term natural variability and the impact of factors unrelated to climate change. The attribution of changes in heat content to climate change is less certain regionally than globally, but warming has been detected with *high confidence* in all basins except Eastern boundary upwelling systems (Table 30-1, Figure 30-2), Recent research shows declining oxygen levels *(medium confidence*, 30.3.2.3) and deep penetration of warming in some regions. Regional estimates of CO_2 uptake are in line with global estimates, and ocean acidification has been detected with *high confidence* in most regions (WGI AR5 Chapter 3.8.2, 30.3.2.2).

The high latitude spring bloom systems of the Northern Hemisphere show strong warming and associated effects (see above). In the North Pacific, the Bering Sea has undergone major changes in recent decades as a result of climate variability, climate change and fishing impacts (Litzow *et al.*, 2008; Mueter and Litzow, 2008; Jin *et al.*, 2009; Hunt *et al.*, 2010). Loss of sea ice has led to the retreat of the cold pool in the Bering Sea, and northward expansion of productivity.

Marginal seas such as the East China Sea are also warming rapidly, with subsequent impacts such as declining primary productivity and fisheries yields as well as other ecological changes (30.5.4.1). However, other human pressures including over-fishing, habitat alteration, and nutrient loading are important contributing factors and it is difficult to disentangle these from the impacts of climate change.

Semi-enclosed seas such as the Black and Baltic Seas and the Arabian / Persian Gulf show differing patterns of change over the past decades (30.5.3.1). Expansions of hypoxic zones in the Baltic and Black Seas have been detected. Although there is *high confidence* that climate change has had a role, its magnitude is difficult to assess in light of other contributing factors. Coral reefs in the Arabian / Persian Gulf and Red Seas appear to have experienced widespread bleaching in 1996 and 1998 associated with elevated temperature with *high confidence* that climate change has played a major role.

Warming of the Mediterranean has been associated with mass mortality events as well as invasions and spread of new warm water species, resulting in the 'tropicalisation' of fauna with *high confidence* in a major role for climate change (30.5.3.1.5). In many tropical regions and the subtropical gyres of the Pacific, Indian, and Atlantic, periodic heat stress related to climate change has combined with other local stresses to cause mass coral bleaching and mortality (see also Box CC-CR, 30.5).

In other regions, such as the California Current upwelling system, there is *very high confidence* in both the detection and attribution of ecological changes associated with climate change, but separating the effects of ENSO and the PDO from that of anthropogenic climate change is not possible.

In overall terms, attributing observed local and regional changes in marine species and ecosystems to climate change remains an important question for on-going research (Stock *et al.*, 2010).

_____ START BOX 18-3 HERE _____

Box 18-3. Differences in Detection and Attribution of Ecosystem Change on Land and in the Ocean

Marine and terrestrial ecosystems differ in fundamental ways. Gradients in turbulence, light, pressure and nutrients uniquely drive fundamental characteristics of organisms and ecosystems in the ocean. While the critical factor for transporting nutrients to marine primary producers is ocean mixing driven by wind, water is the primary mode for transporting nutrients to land plants. In addition to these characteristics, marine ecosystems are often more technically difficult and costly to explore than terrestrial equivalents, which explains the low number and shorter scientific studies of marine ecosystems (Hoegh-Guldberg and Bruno, 2010). The latter has restricted the extent to which changes within the Ocean can be detected and attributed.

Impacts of climate change in terrestrial and marine systems differ significantly for the same types of measures, e.g., species phenology and range shifts, leading to differences in expert's interpretations of the data and possibly divergent levels of confidence in detection and attribution. There are also fundamental differences in exposure of organisms to recent warming, their biological responses and our ability to detect change through observations. Changes in temperature of ocean systems have generally been less than those of terrestrial ecosystems over the last four decades (Burrows *et al.*, 2011). Furthermore, despite higher variability the horizontal spatial gradient of temperature change (°C km^{-1}) is generally much higher in terrestrial ecosystems than in marine ecosystems. All else being equal, the net result is that species have generally needed to move much shorter distances in terrestrial ecosystems to stay within their preferred climates, also due to the influence of the topography such as mountain ranges (Burrows *et al.*, 2011), although many marine species can potentially exploit strong vertical thermal gradients to attenuate the need for range shifts in response to warming.

Species and ecosystems may respond very differently to these climate signals in ways that influence the ability to detect change. For example, a comparison of ectotherm species (i.e., species that do not actively regulate their body temperatures such as reptiles and fish) indicates that marine species' ranges have tracked recent warming at both their poleward and equatorial range limits, while many other terrestrial species' ranges have only tracked warming at their poleward range limits (Sunday *et al.*, 2012). Biological processes influencing phenological shifts may also differ substantially between systems. For example, the effect of climate on the timing of flowering of terrestrial plants at high latitudes is only moderately influenced by confounding effects, whereas the timing of phytoplankton blooms in high latitude marine systems is highly dependant on ocean temperature and associated stratification and changes in nutrient availability.

_____ END BOX 18-3 HERE _____

18.4. Detection and Attribution of Observed Climate Change Impacts in Human and Managed Systems

Observed impacts on human systems have received considerably less attention in previous IPCC reports and the scientific literature, compared to observed impacts on natural systems. Human systems' "normal state in the absence of climate change" is almost never stationary. Confounders other than climate change have been and continue to drive the normal evolution of these systems with climate often playing a relatively minor role. Further, monitoring in many of the systems have been and continue to be inadequate. It is therefore difficult to detect and attribute the signal of climate change in the majority of human systems, food production systems constituting one noteworthy exception. There is emerging literature estimating the sensitivity to climate of many sectors within the human system (see Box 18-4), yet climate impacts are often not detectable over the impacts from non-climate confounders.

For some human systems, the clearest situations where a climate signal had a detectable and sometimes attributable impact are during extreme weather events. Impacts of extreme events, and single event attribution are therefore discussed in a separate section below, and the discussion is expanded to include responses to extreme weather for some sectors. Overall, the literature has made significant progress for certain sectors, such as food systems, since AR4. The following sections provide a synthesis of findings with regard to food systems, economic systems, human health, human security and human livelihoods and poverty, which are documented in greater detail in Chapters 7, 9, 10, 11, 12 and 13. They also incorporate evidence from regional chapters and further available literature, especially for the discussion of extreme events, human security, and observed changes in indigenous communities.

_____ START BOX 18-4 HERE _____

Box 18-4. The Role of Sensitivity to Climate and Adaptation for Impact Models in Human Systems

Impacts of climate change on a measurable attribute of a human system only occur if a) the attribute is sensitive to climate and b) a change in climate has occurred. Many studies now attempt to quantify both climate sensitivity of various systems and observed changes in climate.

Assessment of the sensitivity of an outcome such as crop yields, heat related mortality or migration,to climate relies on observed climate variability either across space (e.g., Schlenker *et al.*, 2005), time (e.g., Mann and Emanuel, 2012), or space and time (e.g., Dell *et al.*, 2012). While there are many studies using climate variability across space, the lack of long observational weather time series required for exploring climate variability across space and time have limited the opportunities for study. A number of studies have instead estimated the sensitivity of outcomes to short run fluctuations (e.g., weather) in order to project the future impacts of climate change (Deschênes and Greenstone, 2007; Deschênes and Greenstone, 2011), or attribute impacts for the past (Auffhammer *et al.*, 2006). The issue with impact studies using a weather based sensitivity measure is that they cannot provide estimates of impacts based on the sensitivity to climate. For example, farmers may respond to an unusually hot summer, which is a weather event, by applying more irrigation water. However, in the long run farmers may respond to a warmer climate by switching crops, changing irrigation technology or abandoning farming altogether. The two sensitivities and resulting magnitudes of attributable impacts due to a change in weather versus a change in climate are therefore different. In order to detect and attribute a change in a system to climate change, one needs to combine a measure of sensitivity of the outcome to climate with climate observations under climate change.

_____ END BOX 18-4 HERE _____

18.4.1. Food Production Systems

Detection and attribution of climate change impacts in food systems is challenging, given that the behavior of the system in the absence of climate change is driven by a large number of other factors (7.2.1). For cropping systems, these confounders include, but are not limited to, cultivar improvement and increased use of synthetic fertilizers, herbicides, and irrigation. These confounders are often not well measured in terms of their distribution across space and time. Further, it is difficult to quantify or model the exact relationship between these confounders and outcomes of interest (e.g., crop yield or pasture productivity). In addition, the role of farmers' behavior in response to climate change requires significant assumptions and has been shown to change over time (7.2.1). The discussion below is limited to crop systems and fisheries, as literature is scarce on observed impacts for other important sources of food.

18.4.1.1. Agricultural Crops

A significant number of studies have provided impact estimates of observed changes in climate on cropping systems over the past few decades (e.g., Auffhammer *et al.*, 2006; Kucharik and Serbin, 2008; Ludwig *et al.*, 2009; Lobell *et al.*, 2011; Tao *et al.*, 2012, see also Figure 7-2). Over the past several decades, observed climate trends have adversely affected wheat and maize production for many regions, as well as the total global production of these crops (*medium confidence* in a minor role of climate change in overall production). Climate change impacts on rice and soybean yields over this time period have been small in major production regions and globally (*medium confidence,* Figure 7-2). In some mid latitude regions, such as the United Kindom and Northeast China, warming has benefitted crop production during recent decades (*high confidence* in a minor role of climate change; 7.2.1.1, Jaggard *et al.*, 2007; Chen *et al.*, 2011). At the continental or global scale, observed trends in some climatic variables, including mean summer temperatures, attributed to anthropogenic activity (see 7.2.1.1; WGI AR5 10.3.1; Table 10-1) have had significant negative impacts on trends in yields for certain crops (Lobell and Field, 2007; You *et al.*, 2009; Lobell *et al.*, 2011).

Attributable trends have been found not only in the seasonal averages of climate variables, but also for extremes (WGI AR5 Chapter 10.6). Extreme rainfall events are widely recognized as important to cropping systems (Rosenzweig *et al.*, 2002), and global scale changes in the patterns of rainfall extremes have been attributed to anthropogenic activity (Min *et al.*, 2011). High nighttime temperatures are harmful to most crops, particularly for rice yield (Peng *et al.*, 2004; Wassmann *et al.*, 2009; Welch *et al.*, 2010) and quality (Okada *et al.*, 2009). Daytime extreme heat is also damaging and sometimes lethal to crops (Porter and Gawith, 1999; Schlenker and Roberts, 2009). At the global scale, trends in annual maximum daytime temperatures have been attributed to greenhouse gas emissions (Zwiers *et al.*, 2011), and similar observation have been made for the occurrence of very hot nights (WGI AR5 Chapter 10.6.1.1, Seneviratne *et al.*, 2012).

Changing atmospheric conditions are affecting crops both positively and negatively. It is *virtually certain* that the increase in atmospheric CO_2 concentrations since preindustrial times has improved water use efficiency and yields most notably in C_3 crops. These effects are however of relatively minor importance when explaining total yield trends (Amthor, 2001; McGrath and Lobell, 2011). Emissions of CO_2 have been associated with tropospheric ozone (O_3) precursors (Morgan *et al.*, 2006; Mills *et al.*, 2007, 7.3.2.1.2). O_3 suppresses global output of major crops, with reductions estimated at roughly 10% for wheat and soy and 3-5% for maize and rice (Van Dingenen *et al.*, 2009). Detected impacts are most significant for India and China, but can also be found for soybean production in the United States in recent decades (Fishman *et al.*, 2010; Christidis *et al.*, 2011).

18.4.1.2. Fisheries

Many new studies focus on the relationship between the dynamics of marine fish stocks and climate, suggesting a sensitivity to climate of these stocks and on the fisheries that exploit them (Hollowed *et al.*, 2001; Roessig *et al.*, 2004; Shriver *et al.*, 2006; Brander, 2007). Some fisheries and aquaculture do not show evidence of climate change impacts (e.g. aquaculture in the UK and Ireland, Callaway *et al.*, 2012), while many others do with both positive and negative changes (see also 18.3.4, 30.6.2.1, 7.2.1.1).

There is *high confidence* in the detection of a climate change impact on the spatial distributions of marine fishes (Perry *et al.*, 2005) and in the timing of events like spawning and migration (Sydeman and Bograd, 2009), with *high confidence* of a major role of climate change (see 18.3.4, CC-MB, 30.4). This distributional shift is reflected in the species composition of harvest, with the relative share of warm water species increasing (Cheung *et al.*, 2013). The impacts of ocean warming and acidification on fish stocks vary from region to region (30.6.2.1). To date, the role of climate change in change in fish stocks and fishery yields is, in most cases, minor (*high confidence*) in relation to other factors such as harvesting, habitat modification, technological development, and pollution (Brander, 2010).

18.4.2. Economic Impacts, Key Economic Sectors, and Services

18.4.2.1. Economic Growth

In low income countries, careful tracking of incomes and temperatures over an extended period, taking into account important confounders, shows that higher annual temperatures as well as higher temperatures averaged over 15 year periods result in substantially lower economic growth (Dell *et al.*, 2012). This effect is not limited to the level of per capita income, but also to its rate of growth. Declining rainfall over the 20^{th} century partly explains the slower growth of Sub-Saharan economies relative to those of other developing regions (Barrios *et al.*, 2006; Brown *et al.*, 2011). Dell *et al*. (2009) find that 1° C of warming reduces income by 1.2% in the short run, and by 0.5% in the long run. The difference is argued to be due to adaptation. Horowitz (2009) finds a much larger effect: a 3.8% drop in income in the long run for 1° C of warming. One proposed mechanism for this is the impact of heat stress on workers in the workplace (Dash and Kjellström, 2011; Dunne *et al.*, 2013). Temperature shocks have negatively affected the growth of developing countries' exports, for which 1° C of warming in a given year reduced the growth rate of its exports by 2.0-5.7% (Jones and Olken, 2010). The export sectors most affected are agricultural and light manufacturing exports.

18.4.2.2. Energy Systems

Energy production and consumption is growing rapidly globally, with much of the growth taking place in low income and emerging economies. Various parts of the energy sector are known to be sensitive to climate change (cf. Ebinger and Vegara, 2011). Higher temperatures raise the demand for cooling and lower the demand for heating. Cooling demand is largest in the summer and in some areas peak loads during the summer months have increased, this peak being highly correlated with summer maximum temperatures (Franco and Sanstad, 2008). There are also opposing effects of warmer winters and summers on electricity and gas demand. Statistical studies have confirmed this U-shaped relationship of energy and electricity demand in temperature for the United States and elsewhere (Isaac and van Vuuren, 2009; Akpinar-Ferrand and Singh, 2010; Deschênes and Greenstone, 2011). On the supply side, sensitivity to climatic factors such as ambient temperature, wind speeds, or snow and ice is well-known for many energy technologies and part of the transmission infrastructure (see 10.2.2, 10.2.3), however, there are no studies available that discuss observed effects of climate change on the energy sector.

18.4.2.3. Tourism

Tourism is a climate sensitive economic sector and ample research has been performed to understand its sensitivity to climate change and impacts of (future) climate change on tourism, yet few studies have focused on detection and attribution of observed impacts (cf. Scott *et al.*, 2008, see also 10.6). A comparatively well-studied area is the sensitivity of the winter sports industry in lower lying areas to climate. For example, the increase in investment in artificial snow machines in the European Alps can be attributed with *high confidence* to a general decrease of snow depth, snow cover duration and snow fall days since the end of the 1980s for low-elevation mountain stations (Durand *et al.*, 2009; Valt and Cianfarra, 2010; Voigt *et al.*, 2011), which in turn has been attributed to anomalous higher winter temperatures over the past 20 years (Marty, 2008). Variability in precipitation, shrinking glaciers and milder winters have been shown to negatively affect visitor numbers in winter sports areas in Europe and North America (Becken and Hay, 2007). Another indirect effect of climate change that has been reported is a rise in popularity of destinations that are perceived to be at risk from climate change (e.g., Eijgelaar *et al*. (2010) for Antarctic glaciers, or Farbotko (2010) for Tuvalu).

18.4.3. Impacts of Extreme Weather Events

The impacts of extreme weather events depend on the frequency and intensity of the events, as well as exposure and vulnerability of society and assets. The last several decades have seen changes in the frequency and intensity of extreme weather events including extreme temperature, droughts, heavy rainfall, and tropical and extratropical cyclones with *low* to *very high confidence*, depending on the type of extreme event (IPCC, 2012, WGI AR5 Chapter 2). However, the impacts of extreme weather events also depend on the vulnerability and exposure of systems. It is possible that climate change can affect vulnerability and exposure, but typically both are primarily influenced by non-climate confounders, most notably economic development.

18.4.3.1. Economic Losses due to Extreme Weather Events

Extreme weather events can result in economic impacts related to damage to private and public assets as well as the temporary disruption of economic and social activities, long-term impacts and impacts beyond the areas affected. Some economic and especially social impacts are not readily monetizable and are thus excluded from most economic assessments (Handmer *et al.*, 2012, their chapter 4.5.1, 4.5.3).

Economic costs of extreme weather events have increased over the period 1960-2000 *(high confidence),* with insured losses increasing more rapidly than overall losses (10.7.3, Handmer *et al.*, 2012, their chapter 4.5.3.3, 4.5.4.1). This is also reflected by an increase in the frequency of extreme weather-related disasters over the same period (Neumayer and Barthel, 2011). Recent studies from Mexico and Colombia highlight both variability and positive trends in disaster frequency, (unadjusted) losses and other damage metrics (Saldaña-Zorrilla and Sandberg, 2009; Marulanda *et al.*, 2010; Rodriguez-Oreggia *et al.*, 2013). However, the greatest contributor to increased cost is rising exposure associated with population growth and growing value of assets (*high confidence;* Bouwer *et al.*, 2007; Bouwer, 2011; Barthel and Neumayer, 2012; Handmer *et al.*, 2012, their Chapter 4.2.2, Box 4.2 and 4.5.3.3).

To account for changes over time in the value of exposed assets, many studies attempt to normalize monetary losses by an overall measure of changes in asset value. A majority of studies have found no detectable trend in normalized losses (Bouwer, 2011). Studies on insured losses that in general meet higher data quality standards than data on overall losses due to thoroughly monitored payouts, have focused on developed countries including Australia, Germany, Spain, the US, (Changnon, 2007; Changnon, 2008; Changnon, 2009a; Changnon, 2009b; Barredo *et al.*, 2012; Barthel and Neumayer, 2012; Sander *et al.*, 2013, see also 10.7.3). Studies of normalized losses from extreme winds associated with hurricanes in the US (Miller *et al.*, 2008; Pielke Jr *et al.*, 2008; Schmidt *et al.*, 2010; Bouwer and Botzen, 2011) and the Caribbean (Pielke Jr *et al.*, 2003), tornadoes in the US (Brooks and Doswell, 2002; Boruff *et al.*, 2003; Simmons *et al.*, 2013) and wind storms in Europe (Barredo, 2010) have failed to detect trends consistent with anthropogenic climate change, although some studies were able to find signals in loss records related to climate variability, such as damage and loss of life due to wildfires in Australia related to El Niño Southern Oscillation and Indian Ocean dipole phenomena (Crompton *et al.*, 2010), or typhoon loss variability in the Western North Pacific (Welker and Faust, 2013). Effects of adaptation measures (disaster risk prevention) on disaster loss changes over time cannot be excluded as research is currently not able to control for this factor (Neumayer and Barthel, 2011).

In conclusion, although there is *limited evidence* of a trend in the economic impacts of extreme weather events that is consistent with a change driven by observed climate change, climate change cannot be excluded as at least one of the drivers involved in changes of normalized losses over time in some regions and for some hazards.

18.4.3.2. Detection and Attribution of the Impacts of Single Extreme Weather Events to Climate Change

Although most studies on the relationship between climate change and extreme weather events have focused on changes over time in their frequency and intensity, a few studies have focused on the contribution of climate change to specific events (WGI AR5 Chapter 10.6.2). Assessing the contribution of climate change to a specific event poses particular challenges, both in terms of methodology and communication of results (Allen, 2011; Curry, 2011; Hulme *et al.*, 2011; Trenberth, 2011). Only a few studies have attempted to evaluate the role of climate change in the impacts of individual extreme weather events. For instance, Pall *et al.* (2011) and Kay *et al.* (2011), using observational constraints on climate and hydrologic model simulations, concluded that greenhouse gas emissions have increased the probability of occurrence of a comparable flooding event in autumn 2000 over the UK.

In highly temperature-sensitive regions, such as high mountains, several extreme impact events of recent decades can be qualitatively attributed to effects of long-term warming *(high confidence)*, namely glacier lake outburst floods due to glacier recession and subsequent formation of unstable lakes (Evans and Clague, 1994; Carey, 2005; Bajracharya and Mool, 2009), debris flows from recently deglaciated areas, and rock fall and avalanches following the loss of mechanical support accompanying glacier retreat (Haeberli and Beniston, 1998; Oppikofer *et al.*, 2008; Huggel *et al.*, 2012b; Stoffel and Huggel, 2012, see also 18.3.1.3). Multi-step approaches can be used to evaluate the contributions of anthropogenic emissions to recent damaging extreme events (Hegerl *et al.*, 2010).

Irrespective of whether a specific event can be attributed in part to climate change, there is ample evidence of the severity of related impacts on people and various assets. Both low- and high-income countries have been strongly impacted by extreme weather events in recent years, but the impacts relative to economic strength have been higher in low-income countries (Handmer *et al.*, 2012). Similarly, at the national scale, poor or elderly people have been disproportionately affected, as documented for Hurricane Katrina in the US in 2005 (Elliott and Pais, 2006; Bullard and Wright, 2010) or the 2003 European heat wave (Fouillet *et al.*, 2008). Exacerbating effects of extreme weather events are mostly of non-climatic nature, including increasing exposure and urbanization, land-use changes including deforestation, or vulnerable infrastructure. Table 18-3 lists a selection of recent weather-related disasters, and lists various factors contributing to long-term changes in the risk of damage, including recent climate change.

[INSERT TABLE 18-3 HERE
Table 18-3: Illustrative selection of recent disasters related to extreme weather events, with description of the impact event, the associated climate hazard, recent climate trends relating to the weather event, and recent trends relating to the consequences of such a weather event.]

18.4.4. Human Health

IPCC AR4 (Confalonieri *et al.*, 2007) concluded that there was *weak to moderate evidence* of effects of recent observed climate change on three main categories of health exposure (ranging from *low* to *medium confidence*): vectors of human infectious diseases (changes in distribution), allergenic pollen (changes in phenology), and extreme heat exposures (trend in increased frequency of very hot days and heat wave events). Overall, there was a lack of evidence for observed effects of climate change on human health outcomes, and this generally remains the case (see Chapter 11). Evaluation of the detection and attribution of impacts on health outcomes requires disentangling the roles of changes in exposures (e.g. patterns), control measures (e.g. vaccination, drug resistance), population structures (e.g. population aging), and reporting practices.

The most direct potential health impact of climate change is through exposure to higher temperatures, as the association between very hot days and increases in mortality is very robust (11.4.1). Recent decades have seen a shift toward more frequent hot extremes and less frequent cold extremes (*high confidence;* Seneviratne *et al.*, 2012, WGI Table 2.13). However, the translation of this trend in hazard to a trend in exposure is complicated by changes in social, environmental, and behavioral factors (e.g., Carson *et al.*, 2006, Table 18-3) and interseasonal mortality relationships (Rocklöv *et al.*, 2009; Ha *et al.*, 2011). Climate change has contributed to a shift from cold-related mortality to heat-related mortality during recent decades in Australia (*medium confidence;* Bennett *et al.*, 2013). In a similar shift in England and Wales, a contribution from anthropogenic climate change has been detected (*medium confidence;* Christidis *et al.*, 2010).

For pollen production, changes in phenology have been consistently observed in mid to high latitudes with, for example, earlier onset in Finland (e.g., Yli-Panula *et al.*, 2009) and Spain (D'Amato *et al.*, 2007; García-Mozo *et al.*, 2010, see also 4.3) over the past few decades. In North America, the pollen season of ragweed (*Ambrosia* spp.) has been extended by 13-27 days since 1995 at latitudes above 44 °N (Ziska *et al.*, 2011). Allergic sensitization of humans has changed over a 25 year period in Italy, but the attribution to observed warming remains unclear (Ariano *et al.*, 2010).

There is *limited evidence* regarding the role of observed warming in changes in tick-borne disease in mid to high latitudes. While patterns of changes in tick borne encephalitis (TBE) incidence in the Czech Republic match those expected from observed warming (Kriz *et al.*, 2012), the upsurge of TBE in the 1980-90s in Central and Eastern Europe generally has been attributed to socio-economic factors (human behavior) rather than temperature (Šumilo *et al.*, 2008; Šumilo *et al.*, 2009). Changes in the latitudinal and altitudinal distribution of ticks in Europe and North America are consistent with observed warming trends (e.g., Gray *et al.*, 2009; Ogden *et al.*, 2010), but there is no evidence so far of any associated changes in the distribution of human cases of tick-borne diseases. There is *limited evidence* of a change in the distribution of rodent-borne infections in the US (plague and tularaemia) consistent with observed warming (Nakazawa *et al.*, 2007). Specifically, a northward shift of the southern edge of the distributions of the diseases (based on human case data for period 1965-2003) was observed. There was no change detected in the northern edge of the distributions though.

Globally, the dominant trend concerning malaria has been a contraction of the geographical range and a decrease in endemicity over the past century due to changes in land cover, behaviour, and health care (Gething *et al.*, 2010). Given that the mosquito vector is climate-sensitive, however, there may be specific locations where climate change matches the influence of these other factors. In the Kericho region of Kenya, both increasing incidence and warming have been observed over several decades (Omumbo *et al.*, 2011). Modelling suggests that the gradual warming is inducing an amplified non-linear response in malaria incidence (Alonso *et al.*, 2011). A detailed review concluded that decadal temperature changes have played at least a minor role in these malaria trends in the East African highlands (*low confidence;*Chaves and Koenraadt, 2010).

18.4.5. Human Security

A small number of studies have examined the connection between the collapse of civilizations and large-scale climate disruptions such as severe or prolonged drought. However, both the detection of a climate change effect and an assessment of the importance of its role can only be made with *low confidence* due to limitations on both historical understanding and data. Some studies have suggested that levels of warfare in Europe and Asia were relatively high during the Little Ice Age (Parker, 2008; Brook, 2010; Tol and Wagner, 2010; White, 2011; Zhang *et al.*, 2011), but for the same reasons the detection of the effect of climate change and an assessment of its importance can only be made with *low confidence*. There is no evidence of a climate change effect on inter-state conflict in the post-WW II period.

Most recent research in this area has focused on the relationship between interannual climate variability in temperature, precipitation, and other climate variables and civil conflict, with most studies focusing on Africa (Hsiang *et al.*, 2013, see also 12.5). A number of studies have identified statistical relationships (Miguel *et al.*, 2004; Hendrix and Glaser, 2007; Hsiang *et al.*, 2011), but the results have been challenged (Buhaug *et al.*, 2010; Theisen *et al.*, 2011; Buhaug and Theisen, 2012; Slettebak, 2012) on both technical and substantive grounds. The issue is further complicated by the focus on interannual variability – rather than climate change – and civil conflict. While a plausible argument could be made that climate change has increased interannual variability and has, therefore, contributed positively to the rate of civil conflict, this argument has not been tested in the literature. For these reasons, neither the detection of an effect of climate change on civil conflict nor an assessment of the magnitude of such an effect can currently be made with a degree of confidence.

Several studies have examined links between climate variability and small-scale communal violence (Adano *et al.*, 2012; Butler and Gates, 2012; Hendrix and Salehyan, 2012; Raleigh and Kniveton, 2012; Theisen, 2012). As with larger-scale civil conflict, this work has focused on climate variability rather than on climate change, so neither the detection of the effect of climate change nor an assessment of its magnitude can currently made with a degree of confidence.

Finally, efforts have been made to establish a link between high temperatures and violent crime (Anderson, 1987; Field, 1992; Anderson, 2001; Rotton and Cohn, 2001; Butke and Sheridan, 2010; Breetzke and Cohn, 2012; Gamble and Hess, 2012). However, the findings remain controversial with other studies identifying non-climate factors as explaining variations in the rate of violent crime (Kawachi *et al.*, 1999; Fajnzylber *et al.*, 2002; Neumayer, 2003; Cole and Gramajo, 2009). Again, the focus in this work has been on weather rather than climate and, in light of this and the equivocal nature of the results, neither the detection of a climate change effect nor an assessment of its magnitude can currently be made with a degree of confidence.

The impact of future climate change on human displacement and migration has been identified as an emerging risk (19.4.2.1). The social, economic, and environmental factors underlying migration are complex and varied (see e.g. Black *et al.*, 2011) and it has not been possible to detect the effect of observed climate change nor assess its magnitude with any degree of confidence (see also 12.4.1.1). Migration in response to climate-related events has been identified in sub-Saharan Africa (Marchiori *et al.*, 2012), with evidence from North America a subject of disagreement (Auffhammer and Vincent, 2012; Feng *et al.*, 2012; Feng and Oppenheimer, 2012).

18.4.6. Livelihoods and Poverty

The vulnerability of the world's poor to climate change, and more general the sensitivity of many livelihood aspects to climate variability has been shown in this and earlier IPCC reports (see Chapter 13). However available research about climate related effects on livelihood and poverty has focused on impacts of climate extremes or year to year climate variability rather than long term climatic trends, resulting in a paucity of evidence on observed impacts of climate change on livelihoods and poverty. Moreover, detection of changes in livelihood aspects is often difficult due to a lack of observations (13.2.1), while multiple confounding factors and lack of both adequate climate data and system understanding preclude attribution (Nielsen and Reenberg, 2010).

Table 18-4 summarizes examples of impacts on livelihoods related to climatic trends, climate variability and extreme weather events. Impacted natural assets include land, water, fish stocks and livestock (Osbahr *et al.*, 2008; Bunce *et al.*, 2010). There is growing concern about negative effects of climate change and ocean acidification on marine and coastal fisheries, and the livelihoods of fisherfolks (Cooley and Doney, 2009; Badjeck *et al.*, 2010), however there are no studies evaluating observed impacts.

[INSERT TABLE 18-4 HERE
Table 18-4: Cases of regional livelihood impacts associated with weather- and climate related extreme events, inter-annual climate variability or climate change (see also Table 18-3; 13.2.1.1).]

Climate related impacts disproportionately affect poor populations, thus increasing social and economic inequalities, both in urban and rural areas, and in low-, middle- and high-income countries (13.1.4; 13.2.1). Evidence for poor people in high-income nations being disproportionately affected by extreme weather events comes, for instance, from 2005 US Hurricane Katrina (Elliott and Pais, 2006; Bullard and Wright, 2010, see also 13.2.5.1) or severe drought in Australia (Alston, 2011). Glacial lake outburst floods in the Peruvian Andes also affected different populations depending on their degree of exposure, level of vulnerability, race, ethnicity, and socio-economic class (Carey, 2010; Carey *et al.*, 2012b). Due to gender specific roles within the household, communities, and wider socio-political and institutional networks, a gender bias has been found in observations of impacts of extreme weather events and climate variability (Carr, 2008; Arora-Jonsson, 2011; Nightingale, 2011, see also Box 13-1).

Poor people living in hazard exposed areas in Africa and Latin America were increasingly affected by floods and landslides in the 1990s and 2000s *(high confidence)*, however most of this trend was due to increased urbanization in such areas (Douglas *et al.*, 2008; Hardoy and Pandiella, 2009). There is evidence of a decline in average precipitation in West Africa since 1960 (Lacombe *et al.*, 2012) including repeated droughts (Dietz *et al.*, 2004; Armah *et al.*, 2011), which in some cases has been partly attributed to anthropogenic climate forcing (Held *et al.*, 2005; Jenkins *et al.*, 2005; Biasutti and Giannini, 2006). However, there is only *limited evidence* of changes in poverty among affected small-holder and subsistence farmers that can be attributed to climate drivers such as rainfall decline and droughts (13.2.1).

Livelihoods of indigenous people in the Arctic have been identified as among the most severely affected by climate change, including food security aspects, traditional travel and hunting, and cultural values and references (Hovelsrud *et al.*, 2008; Ford *et al.*, 2009; Ford, 2009a; Ford, 2009b; Beaumier and Ford, 2010; Pearce *et al.*, 2010; Olsen *et al.*, 2011; Eira, 2012; Crate, 2013, see also Box 18-5, Table 18-9). Impacts of rising temperatures, increased variability, and weather extremes on crops and livestock of indigenous people in highlands were reported from Tibet (Byg and Salick, 2009) and the Andes of Bolivia (McDowell and Hess, 2012).

_____ START BOX 18-5 HERE _____

Box 18-5. Detection, Attribution, and Traditional Ecological Knowledge

Indigenous and local peoples often possess detailed knowledge of climate change that is derived from observations of environmental conditions over many generations. Consequently, there is increasing interest in merging this traditional ecological knowledge (TEK)—also referred to as indigenous knowledge - with the natural and social sciences in order to better understand and detect climate change impacts (Huntington *et al.*, 2004; Parry *et al.*, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Ford *et al.*, 2011; Diemberger *et al.*, 2012). TEK, however, does not simply augment the sciences, but rather stands on its own as a valued knowledge system that can, together with or independently of the natural sciences, produce useful knowledge for climate change detection or adaptation (Agrawal, 1995; Cruikshank, 2001; Hulme, 2008; Berkes, 2009; Byg and Salick, 2009; Maclean and Cullen, 2009; Wohling, 2009; Ziervogel and Opere, 2010; Ford *et al.*, 2011; Herman-Mercer *et al.*, 2011).

Cases in which TEK and scientific studies both detect the same phenomenon offer a higher level of confidence about climate change impacts and environmental change (Huntington *et al.*, 2004; Laidler, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Gamble *et al.*, 2010; Green and Raygorodetsky, 2010; Alexander *et al.*, 2011; Cullen-Unsworth *et al.*, 2012). Evidence is available in particular from Nordic and Mountain peoples, e.g from Peru's Cordillera Blanca mountains (Bury *et al.*, 2010; Carey, 2010; Baraer *et al.*, 2012; Carey *et al.*, 2012b), Tibet (Byg and Salick, 2009), and Canada (Nichols *et al.*, 2004; Laidler, 2006; Krupnik and Ray, 2007; Ford *et al.*, 2009; Aporta *et al.*, 2011). TEK can also inspire scientists to study new issues in the detection of climate change impacts.

In one case, experienced Inuit weather forecasters in Baker Lake, Nunavut, Canada, reported that it had become increasingly difficult for them to predict weather, suggesting an increase of weather variability and anomalies in recent years. To test Inuit observations, scientists analyzing hourly temperature data over a 50 year period confirmed that afternoon temperatures fluctuated much more during springtime during the last 20 years—precisely when Inuit forecasters noted unpredictability—than they had during the previous 30 years (Weatherhead *et al.*, 2010).

Despite frequent confluence between TEK and scientific observations, there are sometimes discrepancies between them, indicating uncertainty in the identification of climate change impacts. They can arise because TEK and scientific studies frequently focus on different and distinct scales that make comparison difficult. Local knowledge may fail to detect regional environmental changes while scientific regional or global scale analyses may miss local variation (Wohling, 2009; Gamble *et al.*, 2010). Furthermore, TEK based observations and related interpretations necessarily need to be viewed within the context of the respective cultural, social, and political backgrounds (Agrawal, 1995). Therefore, a direct translation of TEK into a natural science perspective is often not feasible.

_____ END BOX 18-5 HERE _____

18.5. Detection and Attribution of Observed Climate Impacts across Regions

Since the AR4, significant new knowledge about detected impacts of recent climate change has been gained from all continents and oceans of the world, assessed in the Chapters 22-30 of this report. The tables in this section (18-5, 18-6, 18-7, 18-8, 18-9) summarize impacts in major natural and human systems, at the local to continental scale, for which assessment of the role of climate as one driver has been possible. The following paragraphs provide a summary of recent climate changes in these regions along with notes about particular challenges in the regional assessments.

For much of *Africa*, knowledge about recent climate change is limited, due to weak climate monitoring, and gaps in coverage that continue to exist. On the other hand, the low natural temperature variability over the continent allows earlier detection of warming signals. Thus there is *medium to high confidence* in regional warming, with *low to high confidence* in attribution to anthropogenic emissions. A main regional feature has been the drying of the Sahel during the decades following 1970, but that trend has halted during the most recent decade (Hoerling *et al.*, 2006; Giannini *et al.*, 2008; Greene *et al.*, 2009; Seneviratne *et al.*, 2012). African natural and human systems present challenges for the potential detection and attribution of responses to climate change. Given the weak spatial and temporal variations in temperature, there is smaller scope for migrational and phenological responses to anthropogenic climate change than in other parts of the world. High quality monitoring is relatively sparse in time and space, and is often unsuitable for detecting changes across margins and borders where responses to climate change are most expected. The dearth of studies examining attribution questions means it is currently difficult to estimate the degree to which studies are selectively published based on results, and thus to determine whether each attribution study is only indicative of local reasons for concern or if it is more generally representative of a broader domain.

Amongst all continents, *Europe* has the longest tradition in climate monitoring. Warming has been occurring across the continent in all seasons, with an associated decreasing frequency of cold extremes and increasing frequency of hot extremes (Seneviratne *et al.*, 2012). The Mediterranean basin has been getting drier, while northern areas have been getting wetter (23.2.2.1), with a general increase in the frequency of extreme wet events everywhere (Seneviratne *et al.*, 2012).

Asia spans a particularly wide range of climate types. Warming has been observed throughout the continent with northern areas amongst the fastest warming on the planet. Precipitation trends vary geographically, with a but weaker Indian monsoon (WGI AR5 Chapter 14.2.2.1), and contrasting increasing and drying trends over coastal and inland China (24.3.1).

Warming has occurred in *Australasia* during the past century, with hot extremes becoming more frequent and cold extremes becoming less frequent (25.2, Table 25-1). Winters in southern areas of Australia have become drier in the past few decades and the northwest has become wetter, and precipitation increased over the south and west of both islands of New Zealand. While there have been no significant trends in drought frequency over Australia, regional warming may have increased their hydrological intensity; and fire weather increased since 1973 in Australia (Table 25-1, Clarke *et al.*, 2012).

North America spans a wide range of climate types and observed climate changes. While the northwest has been amongst the fastest warming regions on the planet, the southeast of the USA has experienced slight cooling (26.2.2.1). Hot extremes have been becoming more frequent while cold extremes and frost days have been becoming less frequent over the past several decades. Trends in precipitation over western parts of the continent are strongly influenced by the variability of the El Niño Southern Oscillation, with a matching drying and decreasing snowpack. The intensity of precipitation events has been increasing over most of the continent, but trends in dryness are spatially heterogeneous (26.2.2.1). Intense tropical storms have increased in the North Atlantic over the past several decades (WGI AR5 Chapter 2.6.3).

Most of *Central and South America* has warmed over the past half century, except for a slight cooling over a western coastal strip (27.2.1). Precipitation over much of Central and South America is strongly influenced by the El Niño Southern Oscillation, with accompanying long-term variability. There has been a reduction in the number of dry summer months in the southern half of the continent, while trends over the Amazon are sensitive to the selection of time period (27.2.1). More frequent and severe droughts in the Amazon have been linked to warming (Marengo *et al.*, 2011a).

The areas of largest observed warming are all *Polar:* the northwest of North America, northern Asia, and the Antarctic Peninsula. The nature of Polar regions means that warming can lead to large changes in other aspects of the climate system, in particular the observed decrease in summer sea ice cover, earlier thaw, earlier spring runoff, and thawing of permafrost (28.2).

Despite the widely accepted high vulnerability of many *small islands* to climate change, there are only few formal studies on observed impacts. Detection of climate change impacts in small islands is challenging due to the strong presence of other anthropogenic drivers of local environmental change. Attribution is further challenged by the strong influence of natural variability compared to incremental changes of climate drivers, and the lack of long term monitoring, high quality data.

[INSERT TABLE 18-5 HERE
Table 18-5: Observed impacts of climate change on mountains, snow, and ice, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.]

[INSERT TABLE 18-6 HERE
Table 18-6: Observed impacts of climate change on rivers, lakes and soil moisture, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.]

[INSERT TABLE 18-7 HERE
Table 18-7: Observed impacts of climate change on terrestrial ecosystems, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change,

and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.]

[INSERT TABLE 18-8 HERE
Table 18-8: Observed impacts of climate change on coastal and marine ecosystems, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.]

[INSERT TABLE 18-9 HERE
Table 18-9: Observed impacts of climate change on human and managed systems, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.]

18.6. Synthesis: Emerging Patterns of Observed Impacts of Climate Change

18.6.1. Approach

The AR4 precursor of the current chapter (Rosenzweig *et al.*, 2007) provided a geographically distributed empirical analysis of correlations across numerous detailed and localized studies of changing systems (more elaborated later in Rosenzweig *et al.*, 2008). Rather than expand that approach, this synthesis organizes the findings on detection and attribution of observed impacts of climate change aiming at covering the full disciplinary, sectoral and geographic diversity of impacts, drawn directly from sectoral and regional assessments in this report.

A key motivation for the effort in assessing these observed changes is the possibility that observed impacts could constitute indications of future expected changes. Observed losses in glacial volume, for example, lend important additional plausibility to model-based expectations that sustained warming could result in additional ice loss. Such extrapolation faces important limitations, however. First, due to the complex nonlinear behavior of most natural and human systems, it cannot always be assumed that past impacts scale linearly to future impacts. Likewise, absence of past impacts cannot constitute evidence against the possibility of future impacts. Nonetheless, detection and attribution of observed impacts may serve as part of the foundation for a climatic risk analysis. In order to do so, the total body of observed impacts needs to undergo a synthetic assessment pointing towards any conceivable risks.

Virtually all observed impacts of climate change are of regional nature (18.5); however the occurrence of similar impacts in many regions of the world emerges more strongly with every IPCC assessment. The global pattern emerging from the sum of observed regional impacts is therefore analysed in section 18.6.2. The current body of observations provides improved evidence of major impacts in natural and human systems which have ‘cascading’ consequences for other systems – key examples for these are synthesized in section 18.6.3. Finally, section 18.6.4 aims to establish current conditions concerning the risk analysis model formulated earlier by the IPCC through the establishment of a limited number of “Reasons for Concern” (RFC) – the risk analysis itself is part of Chapter 19 of this report.

18.6.2. The Global Pattern of Regional Impacts

The global pattern of observed climate change differs strongly for the different climate variables. Broadly, more warming has occurred at higher latitudes than in the Tropics, while the pattern of rainfall changes is highly complex (WGI AR5 Chapter 2). Taken together, this provides a heterogenous pattern of climate change across the globe. In addition, some natural and human systems (and the regions in which they occur) are more vulnerable to changing climate than others. Crucially, observational records are of highly heterogenous nature: not only do low-income countries report fewer impacts than high-income countries, but there is also a significant shortage of observations from remote areas such as the deep Sea or sparsely populated mountains and deserts. Taken together, it is therefore natural to expect an uneven distribution of detected impacts (Figure 18-3).

The outstanding finding about the global pattern of observed impacts is that, on all continents and across major ocean regions, significant impacts have now been observed. Many of these concern systems affected directly by warming (the cryosphere, marine systems), but a growing number of observed impacts have been shown to be the result of a combination of changing temperature and precipitation (agricultural and hydrological systems).

The global distribution of observed impacts shown in Figure 18-3 demonstrates that analyses can now detect impacts in systems strongly influenced by confounding factors and hence where climate change plays only a minor role. The most outstanding examples for this are agricultural systems where impacts now emerge in a number of places. An identified minor role of climate for some impact does not imply that this role is less important. New studies now identify more clearly such roles even when they are masked by stronger confounding factors such as environmental degradation or improved technology. Examples for such studies include, assessments of mangrove degradation, caused by both warming and pollution (Giri *et al.*, 2011), or changes in Inuit livelihoods, influenced by both warming and social changes (Ford *et al.*, 2009). Enhanced research efforts would probably add additional observations of impacts with a minor, but important, role of climate to the global map.

[INSERT FIGURE 18-3 HERE
Figure 18-3: Global patterns of observed climate change impacts. Each colored symbol in the top panels indicates a class of systems for which climate change has played a major role in observed changes in at least one measure of that class across the respective region, and the range of confidence in attribution. Regional-scale impacts where climate change has played a minor role are shown by colored open symbols in a box in the respective region. Localized impacts are indicated with symbols on the map, placed in the approximate area of their occurrence. Impacts on physical (blue), biological (green) and human (red) systems are differentiated by color. This map represents a graphical synthesis of Tables 18-5, 18-6, 18-7, 18-8 and 18-9.]

18.6.3. Cascading Impacts

Many impacts of climate change are direct cause-effect relationships, such as reduction of glacier volume following higher temperatures. Others may be mediated through impacts on intermediary systems (e.g., Johnson *et al.*, 2011). Enhanced evidence of observed impacts of climate change, and improved research methodologies now allow attribution of effects at various stages along the causal impact chain (Figure 18-4). Within the cryosphere, changes in atmospheric and ocean properties of the climate have driven changes in the cryosphere on the land surface, the land subsurface, and the ocean surface. These changes have in turn led to changes in multiple aspects of hydrology and ecosystems, and in some regions (e.g., the Arctic) changes in these systems have impacted human livelihoods (Xu *et al.*, 2009). Within most ocean regions, warming has lead to a number of observed impacts on biota, some of which are mediated through the effect of warming on the ocean’s thermal stratification or on sea ice. Impacts tend to propagate up the food chain, eventually affecting large mammals, birds, reptiles and humans. In forests and woodlands, climate change impacts on trees have been transmitted through pests, fire, and drought, while impacts on forests have also been observed to affect the forest fauna. In all these cases, confidence in detection and attribution to observed climate change decreases for effects further down each impact chain.

[INSERT FIGURE 18-4 HERE
Figure 18-4: Major systems where new evidence indicates interconnected, ‘cascading’ impacts from recent climate change through several natural and human subsystems. Bracketed text indicates confidence in the detection of a climate change effect and the attribution of observed impacts to climate change. The role of climate change can be major (solid arrow) or minor (dashed arrow). Confidence is assessed in 18.3, 18.4, 18.5, and 18.6.]

18.6.4. Reasons for Concern

In order to synthesize its findings in support of a risk analysis the Third Assessment Report of the IPCC (TAR) developed the "Reasons for Concern" (RFC) concept (Smith *et al.*, 2001), which was adopted for a second time in IPCC-AR4 (IPCC, 2007), and elaborated in Smith *et al*. (2009). It is further developed in Chapter 1 of this report and employed extensively in Chapter 19 for the risk framing approach of WGII AR5. In this chapter, the goal is to establish, qualitatively, the evidence of impacts already observed that are relevant to these categories (names of categories have been adapted for consistency across Chapters 1, 18 and 19, see sections below). The broad definitions of the RFC continue to imply significant overlap; hence some observed impacts are referred to under more than one RFC.

The RFC *Risks to Unique and Threatened Systems* is concerned with the potential for increased damage to, or irreversible loss of, systems such as physical systems, ecosystems, and human livelihoods, all of which are known to be highly sensitive to temporal and/or spatial variations in climate. Figure 18-5 displays confidence levels in the current evidence derived from detection and attribution studies of such observed impacts. Changes in the three indicated main natural systems (physical systems, marine and terrestrial ecosystems) have at least *high confidence* in attribution of a major role of climate change, with regional assessments also tending to have similar confidence. There is at least *medium confidence* in attribution of a major role for at least one each of ecosystems, physical systems, and human systems.

The unique and threatened systems with strongest detection and attribution evidence cover the Arctic, warm-water coral reefs, and mountains. In the Arctic, climate change has played a major role in observed impacts on glaciers, permafrost, the tundra, marine ecosystems, and livelihoods of indigenous peoples (at least *medium confidence*), reflecting large-scale changes across both natural and human systems and across the physical and ecological subregions. Evidence for the detection and attribution of shrinkage and recession of glaciers comes from all continents, while evidence for attribution of coral bleaching spans a similarly broad area of the tropical oceans (see Figure 18-5).

[INSERT FIGURE 18-5 HERE
Figure 18-5: Confidence in detection and attribution of observed impacts on "Unique and Threatened Systems" as a result of recent climate change. Global assessments (large upper case) and regional assessments (small lower case) are discussed in 18.3.1.1, 18.3.2.4, Box 18-2, and Tables 18-2 and 18-5 through 18-9. Attribution assessments are for a minor (open font) or major (bold) role of climate change, as indicated.]

The RFC *Risks Associated with Extreme Weather Events* "tracks increases in extreme events with substantial consequences for societies and natural systems" (Smith *et al.*, 2009). Besides episodic (e.g., coral bleaching) and chronic (e.g., erosion) impacts of extreme weather events, this RFC also considers increased frequency of extreme impact events (e.g., floods), even if their climate drivers are not wholly episodic in nature. A change in the risk of impacts of extreme weather events could be caused by a change in the probability, intensity, or sequencing of the weather event itself (which are manifestations of recent climate change), or by a change in exposure, vulnerability, or the resilience of the impacted system.

Trends have been noted for extreme weather hazards. Temperature extremes have changed in most regions over the past half century, with more frequent hot events and less frequent cold events (*high confidence;* Hansen *et al.*, 2012; Seneviratne *et al.*, 2012, WGI AR5 Chapter 2.6.1; Coumou *et al.*, 2013). Some regions have also experienced increasingly frequent periods of heavy precipitation events (*medium confidence;* Min *et al.*, 2011), while other regions have experienced positive or negative trends in measures of dry spells (Seneviratne *et al.*, 2012). Current evidence does not, however, indicate sustained global trends in tropical cyclone or extratropical cyclone activity (Seneviratne *et al.*, 2012, WGI AR5 2.6.3).

Table 18-10 summarizes new evidence concerning this RFC. Generally, the strongest evidence of detected impacts related to extremes concerns warm water corals where bleaching has been linked directly to high temperature spells (Box 18-2, Baker *et al.*, 2008; Strong *et al.*, 2011). Outside of these coral reef systems, however, evidence for extreme event impacts is *limited* and mostly local. Overall, a number of trends in observed impacts on natural systems have been documented which indicate changing risks driven by changes in extreme weather (*medium confidence*), but any similar trends in human systems have not been detected against large shifts in exposure, vulnerability and resilience.

[INSERT TABLE 18-10 HERE
Table 18-10: Confidence in detection and attribution of observed trends in natural disasters related to extreme weather. The assessment is for the impacts on various systems, in attribution of those trends to climate change, and in the existence of observed trends in that extreme weather. The assessment of confidence in detection is against the specified reference behaviour, while the assessment for attribution is for the indicated minor or major role of observed climate trends. The confidence statements refer to a globally balanced assessment.]

The RFC *Risks Associated with the Distribution of Impacts* focuses on the disparities of impacts between regions, countries, and populations. The survey of recent studies presented in 18.5 indicates that, while evidence for detected impacts is still more exhaustive from Europe and North America, considerable confidence in conclusions has been developed elsewhere since the AR4, particularly in Central and South America and Australasia (Figure 18-3). It is no longer the case that higher confidence levels of detected impacts are restricted to any particular region (Figure 18-6).

The qualitative conclusion that observed impacts on human and managed systems have now been detected with at least *medium confidence* on all inhabited continents is new and noteworthy. However, the number of systems with detectable impacts is only an indicative metric of coverage, because many options exist for aggregation and disaggregation of evidence. Thus this synthesis of detection and attribution studies does not, at this time, provide evidence of differing severity of impacts between continents. Throughout its assessments, the IPCC has repeatedly noted the significant disparity between the vulnerability of countries, regions, and social groups, related to differences in adaptive capacity (e.g., Wilbanks *et al.*, 2007). Nevertheless, additional coverage of detection and attribution studies is required for broad evaluation of social disparities in impacts.

[INSERT FIGURE 18-6 HERE
Figure 18-6: Confidence in detection of observed climate change impacts in physical natural systems, biological systems, and human and managed systems across regions, and confidence in attribution of such trends to observed climate change as a major or minor driver. Based on assessments developed in Tables 18-5 - 18-9.]

The original intent of the category now labeled as *Risks Associated with Aggregate Impacts* was to assess those economic impacts, damages, and risks that are specifically driven by climate change at a globally aggregated level, using unified monetary metrics. Recognizing the limits of calibrated monetarization of impacts, the scope of this RFC has been expanded over time to also include non-monetary metrics (Smith *et al.*, 2009). Table 18-11 lists various aggregate systems of near-global extent for which the following two conditions apply: there is some form of calibrated metric for comparison of impacts across space and subsystems, and the evidence for detection and attribution of the impacts has sufficient geographical coverage to count as spatially representative sample.

Confidence in such large-scale detection is, again, highest in cryospheric systems (expressed in glacier volume or permafrost active layer thickness), but climate change has also affected ecosystems (expressed as net productivity or carbon stocks, ranging from *medium to high confidence*) and some human systems (crop yields, losses due to extreme events, ranging from *low to medium confidence*) according to the listed aggregate measures. Thus, several globally aggregated impacts of recent climate change have now been identified.

[INSERT TABLE 18-11 HERE
Table 18-11: Confidence in detection of impacts on aggregate impact measures against the specified reference behaviour and confidence in attribution of the specified role of climate change in those observed changes.]

The RFC *Risks Associated with Large-Scale Singular Events* "represents the likelihood that certain phenomena (sometimes called singularities or tipping points) would occur, any of which may be accompanied by very large impacts" (Smith *et al.*, 2009). Several studies have identified "tipping elements" in the Earth System that exhibit non-linear behavior with potentially strong feedbacks on the Earth system (Lenton *et al.*, 2008; Leadley *et al.*, 2010). For observed impacts, the concern translates into a question of the possible presence of "early warning signals" for discontinuities that may be derived from monitoring changes in some climate or natural systems (Collie *et al.*, 2004; deYoung *et al.*, 2008; Andersen *et al.*, 2009; Lenton, 2011).

For the Arctic region, new evidence indicates a biophysical regime shift is taking place, with cascading impacts on physical systems, ecosystems and human livelihoods. For Arctic marine biota, the rapid reduction of summer ice cover causes a tipping element which is now severely affecting pelagic ecosystems as well as ice-dependent mammals such as seals and polar bears (*high confidence;* Duarte *et al.*, 2012a;Table 18-2, 18-8; 28.2.2.1). On land, thawing of Arctic permafrost and shrub encroachment on the tundra have been driven by warming and prolongation of the growing season (*high confidence;* 18.3.2.4, Table 18-5, 18-7; Figure 4-4, 4.3.3.4; 24.4.2.2). Permafrost degradation has contributed to wide-spread hydrological changes including lake formation or disappearance within a few years' time (*high confidence*; Prowse and Brown, 2010; Callaghan *et al.*, 2013; Table 18-6), while increasing winter rains have had consequences for the tundra food webs (*medium confidence;* Post *et al.*, 2009; Callaghan *et al.*, 2013; Hansen *et al.*, 2013). Indigenous people throughout the Arctic are impacted by these changes (18.4.6, Eira, 2012; Crate, 2013). In summary, several indicators of the ongoing regime shift in the entire Arctic land-sea socio-ecological system can be interpreted as warning sign for a large-scale singular event (Post *et al.*, 2009; CAFF, 2010; Callaghan *et al.*, 2010; AMAP, 2011; Duarte *et al.*, 2012b; Figure 18-3, Tables 18-5, 18-7, 18-8, 18-9; 28.2).

Reef building corals are in rapid decline in many regions, and climate change is one of the major drivers (*high confidence,* Box 18-2). This irreversible loss of biodiversity has significant feedbacks within the marine biosphere, and significant consequences for regional marine ecosystems as well as the human livelihoods which depend on them (Hoegh-Guldberg and Bruno, 2010; Richardson *et al.*, 2012). The growing evidence for presently ongoing change and its attribution to warming gained since the AR4 strengthens the conclusion that increased mass bleaching of corals constitutes a strong warning signal for the singular event that would constitute the irreversible loss of an entire biome.

Dieback and degradation in the boreal forests as well as the Amazonian rainforest have also been identified as potential tipping elements in the Earth system, due to their large extent and the possible feedbacks with the carbon cycle (Lenton *et al.*, 2008; Leadley *et al.*, 2010; Marengo *et al.*, 2011b, see also 4.3.3.1). For the boreal forest, increases in tree mortality have been observed in many regions, including wide-spread dieback related to insect infestations and fire in North America (4.3.3.1; 26.4.2.1). Taken together, these may be seen as indicators of an ongoing regime shift in the boreal forest, but there is only *low confidence* in attribution to climate change (18.3.2.4; Figure 4-4). In the humid tropical forests of the Amazon basin, increased tree turnover (both mortality and growth) and enhanced drought risks have been observed during recent decades. However, the main reason for concern is the interaction between climate change, deforestation, and the high susceptibility of forests to fire, which together could produce positive feedbacks leading to degradation of forests in large areas of the Amazon (Malhi *et al.*, 2009). Currently, there is only *low confidence* in attribution of observed ecosystem changes in the Amazon to climate change. In conclusion, there is insufficient evidence from observed climate change impacts to support a climate-related warning sign of possible large-scale singular events in the boreal and Amazonian forest.

18.6.5. Conclusion

Detection and attribution studies evaluate the agreement between observations of change in a system and process understanding of its causes, whether these are due to climate change or other forces. This sets a higher bar for establishing confidence in the assessment of past changes than is generally applied to the projections of future changes, because observational evidence has important gaps, while the plausibility of future changes is established on the basis of process knowledge only. Despite this constraint, the body of evidence on observed impacts of recent climate change demonstrates increasing coverage of the Earth and its various subsystems, including human livelihoods. Increasingly, there is also evidence for complex changes in interconnected systems.

This analysis lends new qualitative support to four out of the RFC established by earlier IPCC assessments. Specifically, evidence is notable for risks to unique and threatened systems, risks stemming from extreme weather events, risks associated with globally aggregated impacts and – in terms of early warnings – risks associated with large-scale discontinuities. Only the spatial or social disparities covered under "risks associated with the distribution of impacts" are still insufficiently studied to permit a synthesis of available observations for the characterization of a global concern. While the Arctic stands out as a region with robust evidence of impacts across numerous systems, current detection and attribution literature does not address whether the severity of those impacts differs from other regions. The Arctic region, warm-water coral reef systems and mountain glaciers feature strongly in the observational evidence discussed for all the RFC, but there are also important observations from impacted hydrological systems and human systems including agriculture.

The evidence gathered since the AR4 on detection and attribution of observed impacts from climate change has reached a level at which it can inform evaluation of many of the aspects of present-day climate change risk as described by the RFC. In particular, the geographical distribution of studies is reaching the point where assessment of the global nature of impacts is possible:

- There is now *robust evidence* of observed changes in natural systems in all of the regional groupings used in this report. Climate change has played a major role in observed changes in various components of the cryosphere on all continents (*high confidence*). Climate change has also driven observed changes in terrestrial ecosystems on six continents (*high confidence*, the exception being *low confidence* in Central and South America) and on some small islands (*medium confidence*), and for marine ecosystems surrounding six continents and some small islands (*high confidence*, with evidence lacking for Africa).
- There is *new and stronger evidence* of the detection of impacts in human systems on the inhabited continents. There is at least *medium confidence* in detection of impacts on food production in all the inhabited continents except North America.
- While the current detection and attribution literature does not reveal observational evidence of geographical differences in the severity of climate change impacts between continents, it does indicate that the unique systems of the Arctic region and warm water coral reefs are undergoing rapid changes in response to observed warming in ways that are potentially irreversible.

18.7. Gaps, Research Needs, Emerging Issues

There are three broad areas relating to the detection and attribution of the impacts of climate change on natural and human systems that require more research. The first concerns the formulation of the relevant issues and further development of rigorous scientific methods for addressing them. At present, the terms detection and attribution are used in numerous different ways and, while there is no need for a single definition, more clarity about usage is important. Methods in this area are closely linked to specific formulations of these terms and there is a parallel need to develop, refine, and evaluate them in light of this. For example, statistical methods are commonly used to detect the impact of variations in climate on human and natural systems while controlling for the effect of other factors. Such detection can be valuable in helping to predict the response of systems to projections of future climate change but a positive correlation does not necessarily imply that the system has already changed in response to historical climate change. A second example is the growing use of methods that combine information from multiple systems - for example, different locations or species - to draw a conclusion about systems in general. More conceptual work is needed to develop the basis for such ecological meta-analysis and the interpretation of its results.

A second area in which more work is needed is data collection and monitoring. Globally, environmental data are still insufficient for monitoring the impacts of climate change. In addition, developed countries are typically over-represented in impact studies because of their comparable wealth in socioeconomic data. Because the level of economic development is extremely important in determining the impacts of climate change, this over-representation probably gives rise to a distorted picture of the global impacts of climate change.

Finally, this chapter has stressed the need to base detection and attribution studies on a scientific understanding of the system in question and the way in which climate change (and other factors) might affect it rather than on relatively simple correlational analysis. This is particularly important for human systems and at least some natural systems in which the combined effect of climate change and other factors is complex and historical adaptation to climate change must be expected. Further development, refinement, and evaluation of both conceptual and process-based models of the human-environment system will be essential for improved conclusions about detection and attribution.

Frequently Asked Questions

FAQ 18.1: Why are detection and attribution of climate impacts important? *[to remain at the end of the chapter]*
To respond to climate change, it is necessary to predict what its impacts on natural and human systems will be. As some of these predicted impacts are expected to already have occurred, detection and attribution provides a way of validating and refining predictions about the future. For example, one of the clearest predicted ecological impacts of climate is a poleward shift in the ranges of plant and animal species. The detection in historical data of a climate-related shift in species ranges would lend credence to this prediction and the assessment of its magnitude would provide information about the likely magnitude of future shifts.

FAQ 18.2: Why is it important to assess impacts of all climate change aspects, and not only impacts of anthropogenic climate change? *[to remain at the end of the chapter]*
Natural and human systems are affected by both natural and anthropogenic climate change, operating locally, regionally and/or globally. In order to understand the sensitivity of natural and human systems to expected future climate change, and to anticipate the outcome of adaptation policies, it is less important whether the observed changes have been caused by anthropogenic climate change or by natural climate fluctuations. In the context of this chapter, all known impacts of climate change are assessed.

FAQ 18.3: What are the main challenges in detecting climate change impacts?
[to remain at the end of the chapter]
The detection of climate change impacts addresses the question of whether a system has changed beyond its expected behavior in the absence of climate change. This requires an understanding of both the external and internal factors that affect the system. External factors that can affect natural systems include exploitation, land-use changes, and pollution. Even in the absence of changes in external factors, many natural systems exhibit substantial internal variability – such as booms and busts in wild populations – that can last for long periods. For example, to detect the impact of climate change on wild fish stocks, it is necessary to understand the effects of fishing, habitat alteration, and possibly pollution, as well as the internal stock dynamics. In the same way, human systems are affected by social and economic factors that are unrelated to climate change. For example, to detect the impact of climate change on human health, it is necessary to understand the effects of changes in public health measures such as improved sanitation.

FAQ 18.4: What are the main challenges in attributing changes in a system to climate change?
[to remain at the end of the chapter]
Whereas the detection of climate change impacts addresses the question only of whether or not a system has changed as a result of climate change, attribution addresses the magnitude of the contribution of climate change to such changes. Even when it is possible to detect the impact of climate change on a system, more detailed understanding can be needed to assess the magnitude of this impact in relation to the influences of other external factors and natural variability.

FAQ 18.5: Is it possible to attribute a single event, like a disease outbreak or the extinction of a species, to climate change? *[to remain at the end of the chapter]*
It is possible to detect trends in the frequency or characteristics of a class of a class of weather events like heat-waves. Similarly, trends in a certain kind of impact of that class of events can also be detected and attributed, although the influence of other drivers of change, such as policy decisions and increasing wealth, can make this challenging. However, any single impact event also results from the antecedent conditions of the impacted system. Thus while damage from a single extreme weather event may occur against the background of trends in many influencing factors, including climate change, there is always a contribution from random chance.

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Table 18-1: Observed changes in ocean system properties and their effects, with confidence levels for the detection of the effect of climate change and an assessment of the magnitude of its role.

Process	**confidence in**		**role**	**context**	**Ref**
	detection	**attribution**			
Impacts of ocean acidification on pelagic marine biota	*low*	*very low*	minor	e.g., reduction in foraminiferan, coccolithophores and pteropod shell weight. Attribution supported by experimental evidence and physiological knowledge	[1]
Expansion of midwater hypoxic zones	*medium*	*low*	minor	oxygen minimum zones (OMZs) caused by enhanced stratification and bacterial respiration due to effects of warming	[2]
Regional and local impacts of expanding hypoxic zones	*medium*	*low*	minor	reduction of biodiversity, compression of oxygenated habitat for intolerant species, range expansion for tolerant taxa	[3]
Direct temperature effects on marine biota related to limited physiological tolerance ranges	*very high*	*high*	major	e.g., large scale latitudinal shifts of species distribution, changes in community composition; attribution supported by experimental and statistical evidence as well as physiological knowledge	[4]
Increase in net primary production at high latitudes	*medium*	*medium*	major	At higher latitudes, NPP is increasing due to sea ice decline and warming. At global scale, estimates vary regionally, and there is a discrepancy between satellite observations and open ocean time-series sites	[5]
Changes in microbial processes	*low*	*very low*	minor	limited understanding of microbial processes, drivers and interactions, and subsequently of large scale shifts in biogeochemical pathways such as oxygen production, carbon sequestration and export production and nitrogen fixation	[6]

Key references and further related information for the assessment above:[1] (Wootton *et al.*, 2008; De Moel *et al.*, 2009; Moy *et al.*, 2009; Bednaršek *et al.*, 2012); 6.3.2, Box CC-OA,; [2] (Stramma *et al.*, 2008; Stolper *et al.*, 2010); 6.1.1.3, 6.3.3; [3] (Levin *et al.*, 2009; Ekau *et al.*, 2010; Stramma *et al.*, 2010; Stramma *et al.*, 2012), 6.3.3, 6.3.5, 30.5; [4] (Merico *et al.*, 2004; Perry *et al.*, 2005; Pörtner and Farrell, 2008; Beaugrand *et al.*, 2010; Alheit *et al.*, 2012); 6.3.1; [5] (Behrenfeld *et al.*, 2006; Saba *et al.*, 2010; Arrigo and Van Dijken, 2011), 6.3.4; Box CC-PP [6] 6.3.1.2, 6.3.2.2, 6.3.3.2, 6.3.5.2

Table 18-2: Observed changes in marine species and ecosystems, with confidence levels for the dection of the effect of climate change and an assessment of the magnitude of its role (see also 6.2, 6.3, 30.4, Box CC-MB).

Process	**confidence in**		**role**	**Context**	**Ref**
	detection	**attribution**			
Range shifts of fish and macroalgae	*high*	*high*	major	changes in species biogeographical ranges to higher latitudes or greater depths	[1]
Changes in community composition	*high*	*high*	major	due to effects of warming, hypoxia, and sea ice retreat	[1]
Changes in abundance	*high*	*medium*	major	observed in fish, corals and intertidal species	[1]
Impacts on large non-fish species, e.g. walruses, penguins, and other sea-birds	*high*	*high*	major	observed effects include changing abundance, phenology, species distribution and turtle sex ratios, and are mostly mediated through changes in resource availability including prey	[2]
Impacts on reef-building corals	*very high*	*high*	major	effects mostly attributed to warming and rising extreme temperatures, though ocean acidification may contribute	[3]
Changes in fish species richness in temperate and high latitude zones	*high*	*medium*	major	effect associated with loss of sea ice and latitudinal species shifts due to warming trends	[4]

Key references and further related information for the assessment above: [1] (Müller *et al.*, 2009; Stige *et al.*, 2010); 6.3.1, 30.4, Box CC-MB; [2] (Grémillet and Boulinier, 2009; McIntyre *et al.*, 2011),6.3.7 [3] (Hoegh-Guldberg, 1999; Hoegh-Guldberg *et al.*, 2007; Baker *et al.*, 2008; Veron *et al.*, 2009), 6.3.1.4, 6.3.1.5, Box CC-CR ; [4] (Hiddink and ter Hofstede, 2008; Beaugrand *et al.*, 2010); Box 6-1, 6.3.1.5.

Table 18-3: Illustrative selection of recent disasters related to extreme weather events, with description of the impact event, the associated climate hazard, recent climate trends relating to the weather event, and recent trends relating to the consequences of such a weather event.

Date and locale	**Impact event**	**Associated climate hazard**	**Trends relating to likelihood of climate hazard**	**Trends relating to consequence of climate hazard**
France, summer 2003	Approximately 15 000 excess deaths (Hémon and Jougla, 2003; Fouillet *et al.*, 2006)	Record hot days / heatwave (Hémon and Jougla, 2003; Fouillet *et al.*, 2006)	Increasingly frequent hot days and heat waves in recent decades (Perkins *et al.*, 2012; Seneviratne *et al.*, 2012) (*high confidence*)	Aging population, increasing population, trends in marital status (Hémon and Jougla, 2003; Prioux, 2005; Fouillet *et al.*, 2006; Rey *et al.*, 2006) Difficulties staffing health services, undeveloped early warning system (Lalande *et al.*, 2003; Fouillet *et al.*, 2008)
Altantic and Gulf coasts of the United States, 2005	Over 1000 deaths and over US$100 billion in damage (Beven *et al.*, 2008)	Record number of tropical storms, hurricanes, and category 5 hurricanes (Bell *et al.*, 2006)	Recent increase in frequency but no clear century-scale trends in US landfalling tropical storms or hurricanes (WGI AR5 2.6.3, Knutson *et al.*, 2010) (*high confidence*)	More population, settlement, and wealth in coastal areas (Pielke Jr *et al.*, 2008; Schmidt *et al.*, 2010) Strengthening of building codes (IntraRisk, 2002)
Mozambique, early 2007	Over 100 000 people displaced by flooding (Foley, 2007; Artur and Hilhorst, 2012)	High rainfall in upper Zambezi Basin in preceding months, passage of Cyclone Favio (Thiaw *et al.*, 2008)	Warming and decreasing rainfall leading to lower discharge of the Zambezi (Dai *et al.*, 2009) (*low confidence*) Decreasing frequency of tropical cyclones in the Mozambique Channel during past 50 years (Mavume *et al.*, 2009) (*medium confidence*)	Increased settlement of Zambezi flood plain following dam construction (Foley, 2007) Development of emergency response plans (Cosgrave *et al.*, 2007; Foley, 2007)
Colombia, October-December 2010	Floods affecting 4 million people, US$7.8 billion total damage (Hoyos *et al.*, 2013)	Wettest year since records began 40 years ago (Martinez *et al.*, 2011)	No clear trend in discharge of rivers in flood-affected areas since 1940 (Hoyos *et al.*, 2013) (*low confidence*)	Rapid urbanisation, with high concentration of residential areas in flood-prone areas (UNISDR, 2013; Álvarez-Berríos *et al.*, 2013) Increasing vulnerability of rural population over the past decades and highly fragile urban systems (e.g. water and gas) (UNISDR, 2013)
Pakistan, July-September 2010	Flooding leading to 2000 deaths, 20 million affected, total loss US$10 billion (NDMA, 2011)	Exceptionally high monsoon rainfall over northern Pakistan during July and August (Houze Jr *et al.*, 2011; Rajeevan *et al.*, 2011; Webster *et al.*, 2011)	No substantial trend in heavy rainfall event frequency in northern Pakistan in past several decades (Wang *et al.*, 2011c; Webster *et al.*, 2011) (*low confidence*)	Rapid population growth and expansion of formal and informal human settlements (Oxley, 2011) Decreased risk through development of flood and disease warning systems and disaster planning (NDMA, 2011) Increased risk from deforestation on mountainous slopes (Ali *et al.*, 2006) Recent unrest in north constrains ability of institutions to deliver basic services (WorldBank/ADB, 2010)

European Russia, July-August 2010	Burned area > 12 500 km (Müller, 2011)	Record hot days (Barriopedro *et al.*, 2011; Müller, 2011) Unusually dry June-August (Bulygina *et al.*, 2011)	Trends in temperature, precipitation, humidity, soil moisture, and snow cover toward less conducive climatic conditions for fire (Groisman *et al.*, 2007) (*medium confidence*)	Increased risk from draining of peat bogs in 1960s and earlier (GFMC, 2010; Müller, 2011) Increased risk from poorly implemented devolution of forest management and forest fire protection in 2007 to regional administrations (GFMC, 2010)
Russia, summer 2010	Grain harvest 30% lower than forecast (Wegren, 2011)	Hottest June-August in at least 130 years, unusually dry June-August (Bulygina *et al.*, 2011)	~1°C summer warming trend over last 70 years (Gruza and Mescherskaya, 2008; Bulygina *et al.*, 2011) (*very high confidence*)	Increase in grain production partially due to government support programs (Wegren, 2011)
Southeast Queensland, Australia, January 2011	Floods affecting >200 000 people, >30 000 homes flooded, damages and cost to economy of US$2.5-10 billion (Hayes and Goonetilleke, 2012)	2010 was wettest year since 1974, with landfall of tropical cyclone in December and wet start to January resulting in highest flood since 1974 (Van den Honert and McAneney, 2011; Hayes and Goonetilleke, 2012)	Decreasing frequency of intense floods since 1840 (Van den Honert and McAneney, 2011) (*medium confidence*)	Increased development in flood-prone urban areas (Van den Honert and McAneney, 2011) Lack of development of riverine flood insurance (Van den Honert and McAneney, 2011; Ma *et al.*, 2012)
Thailand, 2011	Prolonged inundation of urban and industrialized areas, manufacturing losses of about US$32 billion (WorldBank, 2012)	One of the wettest monsoon seasons on record in middle and upper Chao Phraya Basin, resulting in flooding (Komori *et al.*, 2012; Van Oldenborgh *et al.*, 2012)	No detectable change in preciptation over the basin (Van Oldenborgh *et al.*, 2012) (*low confidence*)	Economic development focused on large industrial estates built in flood plains (Chongvilaivan, 2012; Courbage *et al.*, 2012) Recent spell of political instability (Courbage *et al.*, 2012) Subsistence from groundwater pumping (Phien-Wej *et al.*, 2006)
Contiguous United States, summer 2012	Agricultural drought, with 57% of cropland and 43% of farms experiencing at least severe drought (Crutchfield, 2013)	Second warmest summer and warmest month (July) in the contiguous U.S., and one of the driest March-July periods in the central U.S. in the 118-year record (Crouch *et al.*, 2013; Kumar *et al.*, 2013)	~0.5ºC warming in summer over the last century (Menne *et al.*, 2009) (*very high confidence*) No substantial long-term trend in drought occurrence (Peterson *et al.*, 2013) (*medium confidence*)	Significant growth in area dedicated to soy and maize (FAOSTAT, 2013)

Table 18-4: Cases of regional livelihood impacts associated with weather- and climate related exevents, inter-annual climate variability or climate change (see also Table 18-3;13.2.1.1).

Impacted Population	Climate-related driver	Impact on livelihood	Reference
Small-scale farmers, Ghana	Drought (past 20-30 years)	Landscape transformation causing emotional distress, sense of loss of belonging	Tschakert *et al.* (2013)
Middle-class farmers, Australia	Drought (2000s)	Landscape transformation, income loss from agriculture, social conflict, poverty	Alston (2011)
Arctic indigenous peoples	Warming (past decades)	Changing ice and snow conditions, dwindling access to hunting grounds	28.2.4; Table 18-9; Hovelsrud *et al.* (2008); Ford (2009a); Brubaker *et al.* (2011); Arctic Council (2013); Crate (2013)
Urban populations in Maputo, Accra, Nairobi, Lagos, Kampala	Flood frequency and severity increase (1990s and 2000s)	Direct impacts on people and loss of physical assets (e.g. housing)	Douglas *et al.*(2008); Adelekan (2010)
Industry workers in India	Temperature variability and heat waves (1960s to present)	Decrease of fully workable days since 1960Limited ability to carry out physical work, health impacts	Ayyappan *et al.* (2009); Balakrishnan *et al.*(2010); Dash and Kjellström (2011)
Farmers in Subarnabad, Bangladesh	Sea-level rise (~1980s to present)	Salt water intrusion, shift from agriculture to shrimp farming, loss of agricultural livelihoods	Pouliotte *et al.* (2009)
Women farmers, Ghana	Rainfall-related climate variability (~1990s and 2000s)	Adaptation practices in agriculture produce gender inequalities	Carr (2008)
Cambodian rice farmers	Warming, rainfall-related climate variability (1980s to present)	Shift in income generation patterns between men and women	Resurreccion (2011)
Poor children in Africa and Latin America	Weather and climate-related events (1980s to present)	Food price shocks, reduced caloric intake, physical stunting, long-term effects such as reduced lifetime earnings	Alderman (2010)
Smallholder farmers in highlands of Bolivia	Locally perceived changes in temperature means and extremes, and rainfall seasonality (~1990s and 2000s)	Stress on household resources due to need to respond to increasing plant pests, switching to other crop types or livestock	McDowell and Hess (2012)

Table 18-5: Observed impacts of climate change on mountains, snow, and ice, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.

	Mountains, snow and ice	**conf. detect.**	**role of climate**	**climate driver**	**reference behaviour**	**conf. attrib.**
Africa	**Retreat of tropical highland glaciers in East Africa** [Table 22-3; (Mölg *et al.*, 2008; Taylor *et al.*, 2009; Mölg *et al.*, 2012)]	*very high*	major	warming, drying	no change	*high*
Europe	**Retreat of Alpine, Scandinavian and Icelandic glaciers** [WGI AR5 Chapter 4.3.3; (Bauder *et al.*, 2007; Björnsson and Pálsson, 2008; Paul and Haeberli, 2008; WGMS, 2008; Zemp *et al.*, 2009; Andreassen *et al.*, 2012; Marzeion *et al.*, 2012; Gardner *et al.*, 2013)]	*very high*	major	warming	no change	*high*
	Increase in rock slope failures in Western Alps [18.3.1.3; 23.3.1.4, (Fischer *et al.*, 2012; Huggel *et al.*, 2012a)]	*high*	major	warming	no change	*medium*
Asia	**Permafrost degradation in Siberia, Central Asia, and the Tibetan Plateau** [WGI AR5 Chapter 10.5.3; Box 3-2; 24.4.2.2; (Romanovsky *et al.*, 2010; Yang *et al.*, 2013)]	*high*	major	warming	no change	*high*
	Shrinking mountain glaciers across Asia [WGI AR5 Chapter 4.3.2,4.3.3; Box 3-1; 24.4.1.2; (Bolch *et al.*, 2012; Cogley, 2012; Gardelle *et al.*, 2012; Kääb *et al.*, 2012; Yao *et al.*, 2012; Gardner *et al.*, 2013; Stokes *et al.*, 2013)]	*high*	major	warming	no change	*medium*
Australasia	**Substantial reduction in ice and glacier ice volume in New Zealand** [WGI AR5 Chapter 4.3.3; Table 25-1; (Nicholls, 2006; Chinn *et al.*, 2012)]	*high*	major	warming	no change	*medium*
	Significant decline in late-season snow depth at three out of four alpine sites in Australia (1957-2002) [Table 25-1; (Hennessy *et al.*, 2008)	*high*	major	warming	no change	*medium*
North America	**Shrinkage of glaciers across western and northern North America** [WGI AR5 Chapter 4.3.3; (Gardner *et al.*, 2013)]	*high*	major	warming	no change	*high*
	Decreasing amount of water in spring snowpack in western North America (1960-2002) (Stewart *et al.*, 2005; Mote, 2006)	*high*	major	warming	no change	*high*
South and Central America	**Shrinkage of Andean glaciers** [WGI AR5 Chapter 4.3.3; 27.3.1.1, Table 27-3; (Vuille *et al.*, 2008; Bradley *et al.*, 2009; Jomelli *et al.*, 2009; Poveda and Pineda, 2009; Marzeion *et al.*, 2012; Gardner *et al.*, 2013; Rabatel *et al.*, 2013)]	*high*	major	warming	no change	*high*
Polar Regions	**Decreasing Arctic sea ice cover in summer** [WGI AR5 Chapter 4.2.2.1; (ACIA, 2005; AMAP, 2011)]	*very high*	major	air and ocean warming, Δ ocean circulation	no change	*high*
	Reduction in ice volume in Arctic glaciers [WGI AR5 Chapter 4.3.3; (ACIA, 2005; Nuth *et al.*, 2010; AMAP, 2011; Gardner *et al.*, 2011; Moholdt *et al.*, 2012; Gardner *et al.*, 2013)]	*very high*	major	warming	no change	*high*
	Decreasing snow cover across the Arctic [28.2.3.1.2; (AMAP, 2011; Callaghan *et al.*, 2011)]	*high*	major	warming	no change	*medium*
	Widespread permafrost degradation, especially in the southern Arctic [28.2.1.1; (AMAP, 2011; Olsen *et al.*, 2011)]	*high*	major	warming	no change	*high*
	Ice mass loss along coastal Antarctica [WGI AR5 Chapter 4.2.3,4.4, 4.6; 10.5.2.1; (Gardner *et al.*, 2013; Miles *et al.*, 2013)]	*medium*	major	warming	no change	*medium*

Table 18-6: Observed impacts of climate change on rivers, lakes and soil moisture, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.

	Rivers, lakes and soil moisture	**conf. detect.**	**role of climate**	**climate driver**	**reference behaviour**	**conf. attrib.**
Africa	**Reduced discharge in West African rivers** (d'Orgeval and Polcher, 2008; Dai *et al.*, 2009; Di Baldassarre *et al.*, 2010)	*medium*	major	reduced precipitation	no change	*low*
	Lake surface warming and water column stratification increases in the Great Lakes and Lake Kariba [22.3.2.2; (Tierney *et al.*, 2010; Ndebele-Murisa *et al.*, 2011; Powers *et al.*, 2011)]	*high*	major	warming	no change	*high*
	Increased soil moisture drought in the Sahel since 1970, partially wetter conditions since 1990 [22.2.2.1, 22.2.3; (Hoerling *et al.*, 2006; Giannini *et al.*, 2008; Greene *et al.*, 2009; Seneviratne *et al.*, 2012)]	*medium*	major	precipitation	no change	*medium*
Europe	**Changes in the occurrence of extreme river discharges and floods** [23.2.3; (Schmocker-Fackel and Naef, 2010; Beniston *et al.*, 2011; Cutter *et al.*, 2012; Vorogushyn and Merz, 2012; Kundzewicz *et al.*, 2013)]	*low*	minor	precipitation, extreme precipitation	no change	*very low*
Asia	**Changes in water availability in many Chinese rivers** (Casassa *et al.*, 2009; Li *et al.*, 2010; Shrestha and Aryal, 2011)	*high*	minor	precipitation	changes due to land use	*low*
	Increased flow in many rivers due to shrinking glaciers in the Himalayas and Central Asia [Box 3-1;(Casassa *et al.*, 2009; Li *et al.*, 2010; Shrestha and Aryal, 2011; Zhang *et al.*, 2011)]	*high*	major	warming, snow	no change	*high*
	Earlier timing of maximum spring flood in Russian rivers [28.2.1.1; (Shiklomanov *et al.*, 2007; Tan *et al.*, 2011)]	*high*	major	warming	no change	*medium*
	Reduced soil moisture in North Central and NE China 1950-2006 [24.3.1, 24.4.1.2; (Sheffield and Wood, 2007; Wang *et al.*, 2011a; Seneviratne *et al.*, 2012)]	*medium*	major	warming, precipitation	no change	*medium*
	Surface water degradation in parts of Asia [24.4.1.2; (Prathumratana *et al.*, 2008; Delpla *et al.*, 2009; Huang *et al.*, 2009)]	*medium*	minor	warming, precipitation	changes due to land use	*medium*
Australasia	**Intensification of hydrological drought due to regional warming in South East Australia** [Table 25-1; (Nicholls, 2006; Cai *et al.*, 2009)]	*low*	minor	warming	no change	*low*
	Reduced inflow in river systems in south-western Australia (since the mid 1970s) [Table 25-1; 25.5.1; (Cai and Cowan, 2006; Nicholls, 2010)]	*high*	major	precipitation, warming	no change	*high*
North America	**Shift to earlier peak flow in snow dominated rivers in western North America** [WGI AR5 Chapter 2.6.2; (Barnett *et al.*, 2008)]	*high*	major	warming, snow	no change	*high*
	Runoff increases in the Midwestern and Northwestern US, decreases in Southern states (Georgakakos *et al.*, 2013)	*high*	minor	precipitation, warming	no change	*medium*

South and Central America	**Changes in extreme flows in Amazon River** [27.3.1.1; (Rodríguez-Morales *et al.*, 2010; Butt *et al.*, 2011; Wang *et al.*, 2011b; Espinoza *et al.*, 2013)]	*high*	major	precipitation, extreme precipitation	no change	*medium*
	Changing discharge patterns in rivers in the Western Andes; for major river basins in Colombia discharge has decreased during the last 30-40 years [27.3.1.1, Table 27-3; (Vuille *et al.*, 2008; Bradley *et al.*, 2009; Jomelli *et al.*, 2009; Poveda and Pineda, 2009; Rabatel *et al.*, 2013)]	*medium*	minor	warming	no change	*medium*
	Increased streamflow in sub-basins of the La Plata River [27.3.1.1; (Pasquini and Depetris, 2007; Krepper *et al.*, 2008; Saurral *et al.*, 2008; Conway and Mahé, 2009; Krepper and Zucarelli, 2010; Doyle and Barros, 2011)]	*high*	major	precipitation	increase due to land use	*high*
Polar Regions	**Increased river discharge for large circumpolar rivers (1997–2007)** [28.2.1.1; (Overeem and Syvitsky, 2010)]	*high*	major	warming, precipitation, snow cover	no change	*low*
	Winter minimum river flow increase in most sectors of the Arctic [28.2.1.1; (Tan *et al.*, 2011)]	*high*	major	warming, snow cover	no change	*medium*
	Increasing lake water temperatures 1985–2009, prolonged ice-free seasons [28.2.1.1; (Callaghan *et al.*, 2010; Schneider and Hook, 2010)]	*medium*	major	warming	no change	*medium*
	Thermokarst lakes disappear due to permafrost degradation in the low Arctic, new ones created in areas of formerly frozen peat [28.2.1.1; (Riordan *et al.*, 2006; Marsh *et al.*, 2008; Prowse and Brown, 2010)]	*high*	major	warming	no change	*high*
Small Islands	**Increased water scarcity in Jamaica** [(Gamble *et al.*, 2010; Jury and Winter, 2010)]	*low*	minor	precipitation	increase due to water use	*very low*

Table 18-7: Observed impacts of climate change on terrestrial ecosystems, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.

	Terrestrial ecosystems	**conf. detect.**	**role of climate**	**climate driver**	**reference behaviour**	**conf. attrib.**
Africa	**Tree density decreases in Sahel and semi-arid Morocco** [22.3.2.1; (Gonzalez *et al.*, 2012; Le Polain de Waroux and Lambin, 2012)]	*medium*	major	precipitation	changes due to land use	*medium*
	Range shifts of several southern plants and animals: South African bird species polewards; Madagascan reptiles and amphibians upwards; Namib aloe contracting ranges [Table 22-3,(Foden *et al.*, 2007; Raxworthy *et al.*, 2008; Hockey and Midgley, 2009; Hockey *et al.*, 2011)]	*high*	major	warming	changes due to land use	*medium*
	Wildfires increase on Mt. Kilimanjaro [Table 22-3, (Hemp, 2005)]	*medium*	major	warming, drying	no change	*low*
Europe	**Earlier greening, earlier leaf emergence and fruiting in temperate and boreal trees** [4.3.2.1; (Menzel *et al.*, 2006)]	*high*	major	warming	no change	*high*
	Increased colonization of alien plant species in Europe [4.2.4.6; Table 23-6; (Walther *et al.*, 2009)]	*medium*	major	warming	some invasion	*medium*
	Earlier arrival of migratory birds in Europe since 1970 [4.2.4.6; Table 23-6; (Møller *et al.*, 2008)]	*medium*	major	warming	no change	*medium*
	Upward shift in tree-line in Europe [18.3.2.3; Table 23-6; (Gehrig-Fasel *et al.*, 2007; Lenoir *et al.*, 2008)]	*medium*	major	warming	changes due to land use	*low*
	Increasing burnt forest areas during recent decades in Portugal and Greece [Table 23-6; (Camia and Amatulli, 2009; Hoinka *et al.*, 2009; Costa *et al.*, 2011; Koutsias *et al.*, 2012)]	*high*	major	warming, precipitation	some increase due to land use	*high*
Asia	**Changes in plant phenology and growth in many parts of Asia** (earlier greening), particularly in the North and the East [4.3.2.1; Figure 4-5; 24.4.2.2; (Ma and Zhou, 2012; Panday and Ghimire, 2012; Shrestha *et al.*, 2012; Ogawa-Onishi and Berry, 2013)]	*high*	major	warming	no change	*medium*
	Distribution shifts in many plant and animal species, particularly in the North of Asia, upwards in elevation or polewards [4.3.2.5; Figure 4-5; 24.4.2.2; (Moiseev *et al.*, 2010; Chen *et al.*, 2011; Jump *et al.*, 2012; Ogawa-Onishi and Berry, 2013)]	*high*	major	warming	no change	*medium*
	Invasion of Siberian larch forests by pine and spruce during recent decades, growth decline in Mongolian larches [24.4.2.2.; (Kharuk *et al.*, 2010; Dulamsuren *et al.*, 2011; Lloyd *et al.*, 2011)]	*medium*	major	warming	no change	*low*
	Advance of shrubs into the Siberian tundra [4.3.3.4; 24.4.2.2., 28.2.3.1; (Henry and Elmendorf, 2010; Blok *et al.*, 2011)]	*high*	major	warming	no change	*high*

Australasia	**Changes in genetics, growth, distribution and phenology of many species, in particular birds, butterflies and plants in Australia** [Table 25-3; (Chambers, 2008; Chessman, 2009; Green, 2010; Kearney *et al.*, 2010; Keatley and Hudson, 2012; Chambers *et al.*, 2013b)]	*high*	major	warming	fluctuations due to variable local climates, land use, pollution, invasive species	*high*
	Expansion of some wetlands and contraction of adjacent woodlands in SE Australia [Table 25-3; (Keith *et al.*, 2010)]	*medium*	major	precipitation, warming	no change	*low*
	Expansion of monsoon rainforest at expense of savannah and grasslands in N Australia [Table 25-3; (Banfai and Bowman, 2007; Bowman *et al.*, 2010)]	*medium*	major	precipitation, increased CO_2	no change	*medium*
	Migration of glass eels advanced by several weeks in Waikato River, New Zealand [Table 25-3; (Jellyman *et al.*, 2009)]	*medium*	major	warming	no change	*low*
North America	**Phenology changes and species distribution shifts upward in elevation and northward across multiple taxa** [26.4.1; (Parmesan and Galbraith, 2004; Parmesan, 2006; Kelly and Goulden, 2008; Moritz *et al.*, 2008; Tingley *et al.*, 2009)]	*high*	major	warming	no change	*medium*
	Increased wildfire frequency in subarctic conifer forests and tundra [28.2.3.1.4; (Mack *et al.*, 2011; Mann *et al.*, 2012)]	*high*	major	warming	no change	*medium*
	Regional increases in tree mortality and insect infestations in forests [26.4.2.1; (Van Mantgem *et al.*, 2009; Peng *et al.*, 2011)]	*medium*	minor	warming	no change	*low*
	Increase in wildfire activity, fire frequency and duration, and burnt area in boreal forest of North America [Box 26-2; (Gillett *et al.*, 2004; Westerling *et al.*, 2006; Girardin *et al.*, 2013)]	*high*	minor	warming, precipitation	changes due to land use and fire management	*medium*
South and Central America	**Increased tree mortality and forest fire in the Amazon** [4.3.3.1.3;(Phillips *et al.*, 2009)]	*medium*	minor	warming	no change	*low*
	Degrading and receding rainforest in the Amazon [18.3.2.4; 27.2.2.1, 27.3.2.1; (Etter *et al.*, 2006; Nepstad *et al.*, 2006; Oliveira *et al.*, 2007; Wassenaar *et al.*, 2007; Killeen *et al.*, 2008; Nepstad and Stickler, 2008)]	*low*	minor	warming	deforestation and land degradation	*low*
Polar Regions	**Increase in shrub cover in tundra in North America and Eurasia** [28.2.3.1.2; (Tape *et al.*, 2006; Walker *et al.*, 2006; Henry and Elmendorf, 2010; Blok *et al.*, 2011; Elmendorf *et al.*, 2012; Tape *et al.*, 2012)]	*high*	major	warming	no change	*high*
	Advance of Arctic tree-line in latitude and altitude [28.2.3.1.2; (AMAP, 2011; Hedenås *et al.*, 2011; Van Bogaert *et al.*, 2011)]	*high*	major	warming	no change	*medium*
	Loss of snow-bed ecosystems and tussock tundra [28.2.3.1.2; (Björk and Molau, 2007; Molau, 2010a; Hedenås *et al.*, 2011; Callaghan *et al.*, 2013)]	*high*	major	warming, precipitation	no change	*high*
	Impacts on tundra animals from increased ice layers in snow pack, following rain-on-snow events [28.2.3.1.3; (Callaghan *et al.*, 2013; Hansen *et al.*, 2013)]	*medium*	major	precipitation, warming	no change	*medium*

	Changes in breeding area and population size of subarctic birds, due to snowbed reduction and/or tundra shrub encroachment (Molau, 2010b; Callaghan *et al.*, 2013)	*high*	major	warming	no change	*medium*
	Increase in plant species ranges in the West Antarctic Peninsula and nearby islands over the past 50 years [28.2.3.2; (Fowbert and Smith, 1994; Parnikoza *et al.*, 2009)]	*high*	major	warming	no change	*high*
	Increasing phytoplankton productivity in Signy Island lake waters (Quayle *et al.*, 2002; Laybourn-Parry, 2003)	*high*	major	warming	no change	*high*
Small Islands	**Changes in tropical bird populations in Mauritius** [29.3.2; (Senapathi *et al.*, 2011)]	*medium*	major	precipitation	no change	*medium*
	Decline of an endemic plant in Hawai'i (Krushelnycky *et al.*, 2013)	*medium*	major	warming, precipitation	no change	*medium*
	Upward trend in tree-lines and associated fauna on high elevation islands [29.3.2; (Benning *et al.*, 2002; Jump *et al.*, 2006)]	*low*	minor	warming	no change	*low*

Table 18-8: Observed impacts of climate change on coastal and marine ecosystems, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.

	Coastal and marine ecosystems	**conf. detect.**	**role of climate**	**climate driver**	**reference behaviour**	**conf. attrib.**
Europe	**Northward shifts in the distributions of zooplankton, fish, seabirds and benthic invertebrates in the NE Atlantic** [Box 6-1; Table 6-2; 6.3.1;23.6.5, 30.5.1.1; (Beaugrand *et al.*, 2009; Philippart *et al.*, 2011)]	*high*	major	ocean warming	no change	*high*
	Northward and depth shift in distribution of many fish species across European seas [6.3.1; Table 6-2; 23.6.4; 23.6.5; 30.5.3.1;(Perry *et al.*, 2005; Pörtner *et al.*, 2008; Beaugrand *et al.*, 2009; Beaugrand *et al.*, 2010; Beaugrand and Kirby, 2010; Hermant *et al.*, 2010; Philippart *et al.*, 2011)]	*high*	major	ocean warming	no change	*medium*
	Phenology changes in plankton in the NE Atlantic [Box 6-1; 6.3.1; 23.6.5, 30.5.1.1; (Beaugrand *et al.*, 2002; Edwards and Richardson, 2004; Beaugrand *et al.*, 2009; Philippart *et al.*, 2011)]	*medium*	major	ocean warming	no change	*medium*
	Spread of warm water species into the Mediterreanean [23.6.5, 30.5.3.1.5; (Boero *et al.*, 2008; Lasram and Mouillot, 2009; Raitsos *et al.*, 2010)]	*high*	major	ocean warming	changes due to invasive species and human impacts	*medium*
Asia	**Coral reefs and large seaweeds decline in tropical Asian waters and in the coastal waters of Western Japan** [24.4.3.2; 30.5.1.4.3, (McLeod *et al.*, 2010; Krishnan *et al.*, 2011; Nagai *et al.*, 2011; Coles and Riegl, 2012)]	*high*	major	ocean warming	decline due to human impacts	*high*
	Northward range extension of coral reefs and predatory fish in the Japan Sea [24.4.3.2, (Yamano *et al.*, 2011; Tian *et al.*, 2012; Ogawa-Onishi and Berry, 2013)]	*medium*	major	ocean warming	no change	*medium*
	Shift from sardines to anchovies in the western North Pacific [6.3.1, 6.3.6;Table 6-2, (Takasuka *et al.*, 2007; Takasuka *et al.*, 2008)]	*medium*	major	ocean warming	fluctuations due to fisheries	*low*
	Increased coastal erosion in Arctic Asia [24.4.3.2**,** (Razumov, 2010; Forbes, 2011; Lantuit *et al.*, 2011)]	*medium*	major	permafrost degradation, ocean warming, sea ice	no change	*low*
Australasia	**Southward shifts in the distribution of marine species near Australia** [Table 25-3; (Ling *et al.*, 2009; Pitt *et al.*, 2010; Neuheimer *et al.*, 2011; Wernberg *et al.*, 2011; Wernberg *et al.*, 2011)]	*high*	major	ocean warming	changes due to short term env. fluctuations, fishing and pollution	*medium*
	Change in timing of migration of seabirds in Australia [25.6.2.1; (Chambers *et al.*, 2011; Chambers *et al.*, 2013a)]	*medium*	major	air and ocean warming	no change	*low*
	Increase in coral bleaching in the Great Barrier Reef and Western Australian Reefs [6.3.1.4, 6.3.1.5, Table 25-3; 25.6.2.1; (Cooper *et al.*, 2008; De'ath *et al.*, 2009; De'ath *et al.*, 2012; Moore *et al.*, 2012)]	*high*	major	ocean warming	pollution, physical disturbance	*high*

	Changes in coral disease patterns at Great Barrier Reef [25.6.2.1; Table 25-3; (Bruno *et al.*, 2007; Sato *et al.*, 2009; Dalton *et al.*, 2010)]	*medium*	major	ocean warming	pollution	*medium*
North America	**Northward shifts in the distributions of NW Atlantic fish species** [30.5.1.1; (Nye *et al.*, 2009; Lucey and Nye, 2010; Nye *et al.*, 2011)]	*high*	major	ocean warming	no change	*high*
	Changes in musselbeds along the west coast of the United States (Smith *et al.*, 2006; Menge *et al.*, 2008; Harley, 2011)	*high*	major	ocean warming,	no change	*high*
	Changes in migration and survival of salmon in the northeast Pacific (Table 6-2, Eliason *et al.*, 2011; Kovach *et al.*, 2012)	*high*	major	ocean warming	no change	*high*
	Increased coastal erosion in Alaska and Canada [18.3.1.1; 18.3.3.1; (Mars and Houseknecht, 2007; Forbes, 2011; Lantuit *et al.*, 2011)]	*high*	major	permafrost degradation, ocean warming, sea ice	no change	*medium*
South and Central America	**Increase in coral bleaching in the western Caribbean** [27.3.3.1; (Guzman *et al.*, 2008; Manzello *et al.*, 2008; Carilli *et al.*, 2009; Eakin *et al.*, 2010)]	*high*	major	ocean warming	pollution, physical disturbance	*high*
	Mangrove degradation on north coast of South America [27.3.3.1; (Alongi, 2008; Lampis, 2010; Polidoro *et al.*, 2010; Giri *et al.*, 2011)]	*low*	minor	ocean warming	degradation due to pollution and land use	*low*
Polar Regions	**Increased coastal erosion across the Arctic** [18.3.1.1; 18.3.3.1; 28.2.4.2; 28.3.4; (Mars and Houseknecht, 2007; Razumov, 2010; Forbes, 2011; Lantuit *et al.*, 2011)]	*medium*	major	permafrost degradation, ocean warming, sea ice	no change	*medium*
	Negative effects on non-migratory Arctic species [28.2.2.1; (Laidre *et al.*, 2008; Amstrup *et al.*, 2010; McIntyre *et al.*, 2011)]	*high*	major	atmospheric and ocean warming, circulation change, sea ice	no change	*high*
	Decreased reproductive success in Arctic seabirds [28.2.2.1.2; (Gaston *et al.*, 2009; Grémillet and Boulinier, 2009)]	*medium*	major	air and ocean warming, ocean circulation, sea ice	no change	*medium*
	Decline in Southern Ocean seals and seabirds [28.2.2.2; (Croxall *et al.*, 2002; Patterson *et al.*, 2003; Jenouvrier *et al.*, 2005; Véran *et al.*, 2007; Forcada *et al.*, 2008; Trathan *et al.*, 2011; Chambers *et al.*, 2013a)]	*high*	major	ocean warming	no change	*medium*
	Reduced thickness of foraminiferal shells in the Southern Ocean [6.3.2; 28.2.2.2; (Moy *et al.*, 2009)]	*medium*	major	ocean acification	no change	*medium*
	Reduced density of krill in the Scotia Sea (Atkinson *et al.*, 2004; Trivelpiece *et al.*, 2011)	*medium*	major	ocean warming, ocean circulation, sea ice	no change	*medium*
Small Islands	**Increased coral bleaching near many tropical small islands** [29.3.1.2; (Alling *et al.*, 2007; Bruno and Selig, 2007; Oxenford *et al.*, 2008; Sandin *et al.*, 2008)]	*high*	major	ocean warming	degradation due to fishing and pollution	*high*
	Degradation of mangroves, wetlands and seagrass around small islands [29.3.1.2; (McKee *et al.*, 2007; Gilman *et al.*, 2008; Schleupner, 2008; Krauss *et al.*, 2010; Marbà and Duarte, 2010; Rankey, 2011)]	*low*	minor	sea level rise, atmospheric and ocean warming	degradation due to other disturbances	*very low*

	Inreasing flooding and erosion [29.3.1.1; (Webb, 2006; Webb *et al.*, 2007; Yamano *et al.*, 2007; Cambers, 2009; Novelo-Casanova and Suarez, 2010; Storey and Hunter, 2010; Ballu *et al.*, 2011; Rankey, 2011; Ford, 2012; Romine *et al.*, 2013)]	*low*	minor	sea level rise	erosion due to human activities, natural erosion and accretion	*low*
	Degradation of groundwater and freshwater ecosystems due to saline intrusion [29.3.2; (White *et al.*, 2007a; White *et al.*, 2007b; Ross *et al.*, 2009; Carreira *et al.*, 2010; Terry and Falkland, 2010; White and Falkland, 2010; Goodman *et al.*, 2012)]	*low*	minor	sea level rise	degradation due to pollution, groundwater pumping	*low*

Table 18-9: Observed impacts of climate change on human and managed systems, over the past several decades, across major world regions, with descriptors for: i) the confidence in detection of a climate change impact, ii) the relative contribution of climate change to the observed change, compared to that of non-climatic drivers, iii) the main climatic driver (s) causing the impacts, iv) the reference behavior of the system in the absence of climate change, and v) the confidence in attribution of the impacts to climate change. References to related chapters in this report are given as well as key references to other IPCC reports and the scientific literature.

	Human and managed systems	**conf. detect.**	**role of climate**	**climate driver**	**reference behaviour**	**conf. attrib.**
Africa	**Adaptative responses to changing rainfall by South African farmers [**13.2.1.1; (Thomas *et al.*, 2007)]	*low*	major	precipitation	changes due to economic conditions	*very low*
	Decline in fruit-bearing trees in Sahel (Wezel and Lykke, 2006; Maranz, 2009)	*medium*	major	precipitation	no change	*low*
	Malaria increases in Kenyan highlands [11.4.4; (O'Meara *et al.*, 2010; Alonso *et al.*, 2011; Stern *et al.*, 2011)]	*low*	minor	warming	changes due to vaccination, drug resistance, demography, livelihoods	*low*
	Reduced fisheries productivity of Great Lakes and Lake Kariba [7.2.1.2; 13.2.1.1; 22.3.2.2; (Descy and Sarmento, 2008; Hecky *et al.*, 2010; Ndebele-Murisa *et al.*, 2011; Marshall, 2012)]	*low*	minor	warming	changes due to fisheries management and land use	*low*
Europe	**Shift from cold-related mortality to heat-related mortality in England and Wales** [18.4.4; 23.5.1; (Christidis *et al.*, 2010)]	*medium*	major	warming	changes due to exposure and health care	*low*
	Impacts on livelihoods of Sámi people in Northern Europe (Eira, 2012; Mathiesen *et al.*, 2013)	*medium*	major	warming	economic and sociopolitical changes	*medium*
	Stagnation of wheat yields in some countries in recent decades [23.4.1; (Brisson *et al.*, 2010; Kristensen *et al.*, 2011)]	*high*	minor	warming	increase due to improved technology	*medium*
	Positive yield impacts for some crops mainly in Northern Europe [Figure 7-2; 23.4.1, (Jaggard *et al.*, 2007; Supit *et al.*, 2010; Gregory and Marshall, 2012)]	*high*	minor	warming	increase due to improved technology	*medium*
	Spread of bluetongue virus in sheep, and of ticks across parts of Europe [23.4.2; (Arzt *et al.*, 2010; Randolph and Rogers, 2010; Van Dijk *et al.*, 2010; Guis *et al.*, 2012; Petney *et al.*, 2012)]	*high*	minor	warming	no change	*medium*
Asia	**Impacts on livelihoods of indigenous groups in Arctic Russia** [13.2.1.2; 18.4.6; Table 18-4; 28.2.4.2; (Crate, 2013)]	*medium*	major	warming, snow cover, sea ice	economic and sociopolitical changes	*low*
	Negative impacts on aggregate wheat yields in South Asia [7.2.1; Figure 7-2; (Pathak *et al.*, 2003; Auffhammer and Vincent, 2012)]	*medium*	minor	warming, precipitation	increase due to improved technology	*medium*
	Negative impacts on aggregate wheat and maize yields in China [7.2.1; Figure 7-2; (Tao *et al.*, 2006; Tao *et al.*, 2008; You *et al.*, 2009; Chen *et al.*, 2010; Tao *et al.*, 2012)	*low*	minor	warming	increase due to improved technology	*low*
	Increases in a water-borne disease in Israel (Paz *et al.*, 2007)	*low*	minor	warming	no change	*low*

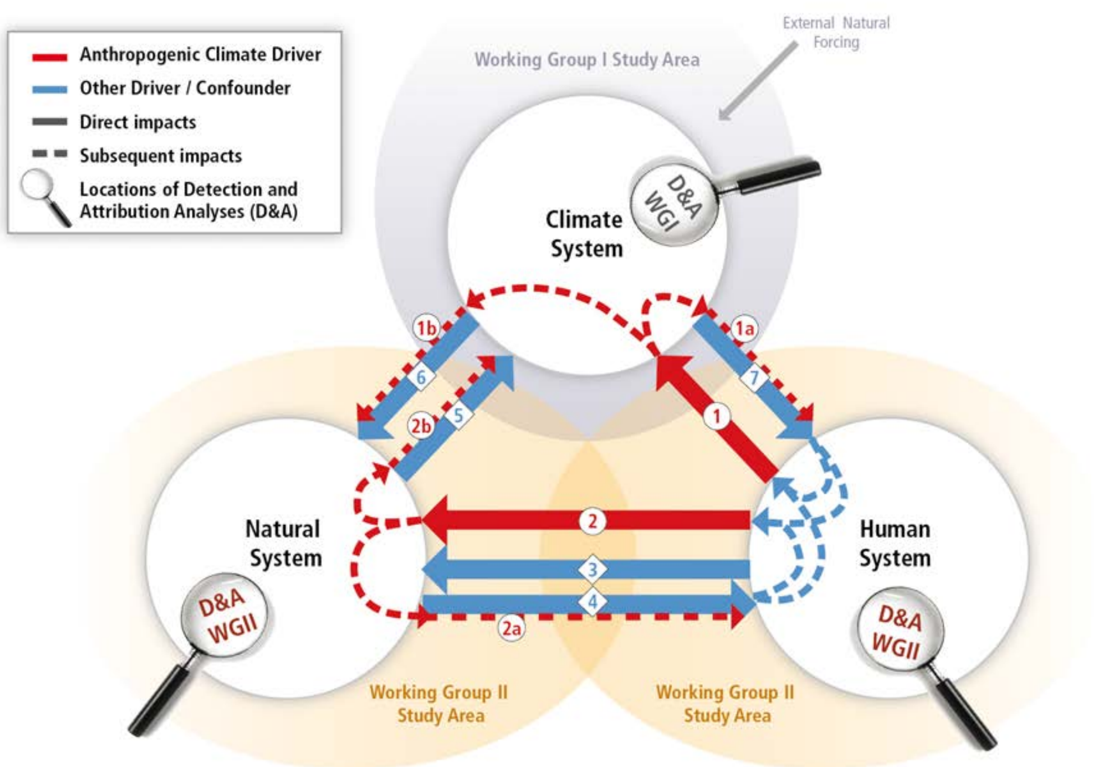
Australasia	**Advance timing of wine-grape maturation in recent decades** [Table 25-3; (Webb *et al.*, 2012)]	*high*	major	warming	advance due to improved management	*medium*
	Shift in winter vs. summer human mortality in Australia [18.4.4; 25.8.11, 11.4.1; (Bennett *et al.*, 2013)]	*medium*	major	warming	changes due to exposure and health care	*low*
	Relocation or diversification of agricultural activities in Australia [25.7.2; Box 25-5; (Gaydon *et al.*, 2010; Howden *et al.*, 2010; Park *et al.*, 2012; Thorburn *et al.*, 2012)	*medium*	minor	warming	changes due to policy, markets, and short-term climate variability	*low*
Central and South America	**More vulnerable livelihood trajectories for indigenous Aymara farmers in Bolivia**, due to water shortage [13.1.4; (McDowell and Hess, 2012)]	*high*	major	warming	increasing social and economic stress	*medium*
	Increase in agricultural yields and expansion of agricultural areas in Southeastern South America [27.3.4.1; (Magrin *et al.*, 2007; Barros, 2010; Hoyos *et al.*, 2013)]	*medium*	major	precipitation increase	increase due to improved technology	*medium*
North America	**Impacts on livelihoods of indigenous groups in the Canadian Arctic** [18.4.6; Table 18-4; 28.2.4.2; (Hovelsrud *et al.*, 2008; Ford *et al.*, 2009; Beaumier and Ford, 2010; Pearce *et al.*, 2010; Brubaker *et al.*, 2011)	*medium*	major	warming, snow cover, sea ice	economic and sociopolitical changes	*medium*
Polar Regions	**Impact on livelihoods of Arctic indigenous peoples** [18.4.6; Table 18-4; 28.2.4.2; (Hovelsrud *et al.*, 2008; Ford *et al.*, 2009; Beaumier and Ford, 2010; Pearce *et al.*, 2010; Eira, 2012; Crate, 2013; Mathiesen *et al.*, 2013)]	*medium*	major	warming, snow cover, sea ice	economic and sociopolitical changes	*medium*
	Increase of shipping traffic across the Bering Strait [28.2.6.1.3; Figure 28-4; (Robards, 2013)]	*medium*	major	warming, sea ice	no change	*medium*
Small Islands	**Increased degradation of coastal fisheries due to direct effects and effects of increased coral reef bleaching** [Box CC-CR; 18.3.3.3; 18.4.1.2; 29.3.1.2; 30.6.2.1]	*low*	minor	ocean warming	coastal fisheries degraded by overfishing and pollution	*low*

Table 18-10: Confidence in detection and attribution of observed trends in natural disasters related to extreme weather. The assessment is for the impacts on various systems, in attribution of those trends to climate change, and in the existence of observed trends in that extreme weather. The assessment of confidence in detection is against the specified reference behaviour, while the assessment for attribution is for the indicated minor or major role of observed climate trends. The confidence statements refer to a globally balanced assessment.

	Impacts and impact events				**Climate/weather drivers**		**Reference**
Observed trend	**Confidence in detection**	**Reference behaviour**	**Attribution**	**Role of climate change**	**Observed trend**	**Confidence in existence of trend**	
Earlier timing and decreasing magnitude of snowmelt floods	*medium*	no change	*medium*	major	Decreasing snow pack	*high*	3.2.7; Tables 18-5 and 18-6; WGI AR5 4.5; Seneviratne *et al.* (2012)
					Increasing heavy precipitation amounts	*medium*	
Changes in flood frequency and magnitude in non-snowmelt-fed rivers	*low*	changes due to land use	*low*	minor	Trends in extreme rainfall amounts	*medium*	Min *et al.* (2011); WGI AR5 2.5.3; 2.6.2
					Increased evapotranspiration and decreased soil moisture	*medium*	
Increased coastal erosion in low and mid latitudes	*very low*	erosion due to shoreline modification and natural processes	*very low*	minor	Increasingly frequent high storm waves and surges	*high*	18.3.3.1; 5.4.2; WGI AR5 3.7.5
Increased erosion of Arctic coasts	*medium*	no change	*medium*	major	Lack of sea ice protection from wind storms	*very high*	Table 18-8; 18.3.1.1; 24.4.3.2; 28.2.4.2; 28.3.4; Forbes (2011); WGI AR5 4.2.2
Increase in high-mountain rock slope failures	*low*	no change	*low*	major	Increasingly frequent and intense heatwaves	*medium*	Huggel *et al.* (2012a); Seneviratne *et al.* (2012); Allen and Huggel (2013), WGI AR5 2.6.1, Figure 18-2
Increased coral bleaching	*very high*	changes due to pollution, physical disturbance, and fishing	*high*	major	Increasingly frequent extreme hot surface waters	*very high*	Table 18-2; Table 18-8; 5.2.4.2; 6.3.1; Box 18-2; 24.4.3.2; 27.3.3.1; 29.3.1.2; 30.3.1.1; 30.5
Increased monetary losses	*low*	changes due to exposure and wealth	*low*	minor	Increased frequency of storms	*low*	18.4.3.1; 10.7.3, Seneviratne *et al.* (2012); WGI AR5 2.6
					Increased frequency of floods	*low*	
Increased heat related mortality	*low*	changes due to exposure and health care	*very low*	minor	Increased frequency of heat waves	*medium*	11.4.1; Seneviratne *et al.* (2012);WGI AR5 2.6.1

Table 18-11: Confidence in detection of impacts on aggregate impact measures against the specified reference behaviour and confidence in attribution of the specified role of climate change in those observed changes.

Global aggregated impact	Confidence in detection	Reference behaviour	Confidence in attribution	Role of climate change	Reference
Glacier ice volume reduction	*very high*	no change	*high*	major	3.2.2; 18.3.1.1
Permafrost degradation and increase of active layer thickness	*high*	no change	*high*	major	18.3.1.1
Increase in terrestrial net primary production and carbon stocks	*high*	changes due to nitrogen deposition, afforestation, and land management	*low*	major	18.3.2.2
Negative yield impacts on global wheat and maize yields	*medium*	changes due to technology, practice, and coverage	*medium*	minor	18.4.1.1; Figure 7-2
Increase in monetary losses due to extreme weather	*low*	changes due to exposure and wealth	*low*	minor	10.7.3;18.4.3.1



	Example of Drivers	Example of Impacts	
		Direct impacts	Subsequent impacts
1 1a 1b	Emission of CO_2	Warming	 Altered crop yield Shift in species phenology
2 2a 2b	Emission of CO_2	Carbon fertilization of plants	 Increase in forestry yield Change in humidity
3	Pollution of river catchment	Fisheries collapse	
4	Plague of crop pests	Decrease in crop yield	
5	Forest fire	Aerosol Emissions	
6	El Nino event	More wildfires	
7	El Nino event	Crop Failures	

Figure 18-1: Schematic of the subject covered in this chapter. The Earth system consists of three coupled and overlapping systems. Direct drivers of the human system on the climate system are denoted with a red arrow; some of these drivers may also directly affect natural systems. These effects can in turn influence other systems (dashed red arrows). Further influences of each of the systems on each other (confounding factors) that do not involve climate drivers are represented by blue arrows. Examples of drivers and their impacts are given in the table. Adapted from Stone *et al*. (2013).

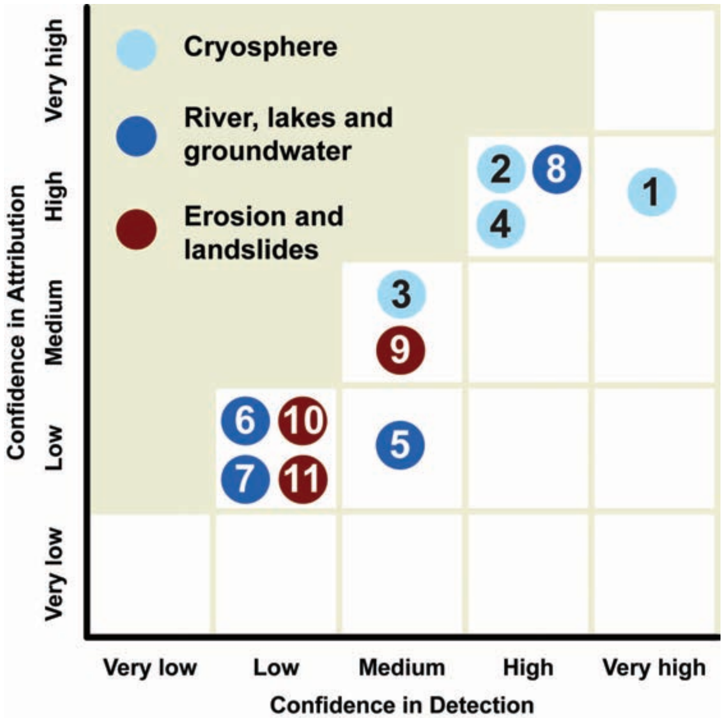


Figure 18-2: Assessment of confidence in detection of observed climate change impacts in global freshwater systems over the past several decades, with confidence in attribution of a major role of climate change, based on expert assessment contained in this section 18.3.1 and augmented by subsections of Chapter 3 as indicated. Numbered symbols refer to: Cryosphere (18.3.1.1): 1 shrinking glaciers (3.2.2), 2 changes in glacier lakes, 3 erosion and degradation of arctic coastal permafrost, 4 degradation and thaw of lowland and mountain permafrost; Rivers, lakes and groundwater (18.3.1.2): 5 groundwater storage change (3.2.4), 6 changing river flow (3.2.3), 7 changing flood frequency or intensity (3.2.3), 8 reduction in lake and river ice duration or thickness in the Northern Hemisphere; Erosion and landslides (18.3.1.3): 9 Increasing erosion (3.2.6), 10 changes in shallow landslides (3.2.6), 11 increasing frequency of high-mountain rock failures.
[Illustration to be redrawn to conform to IPCC publication specifications.]

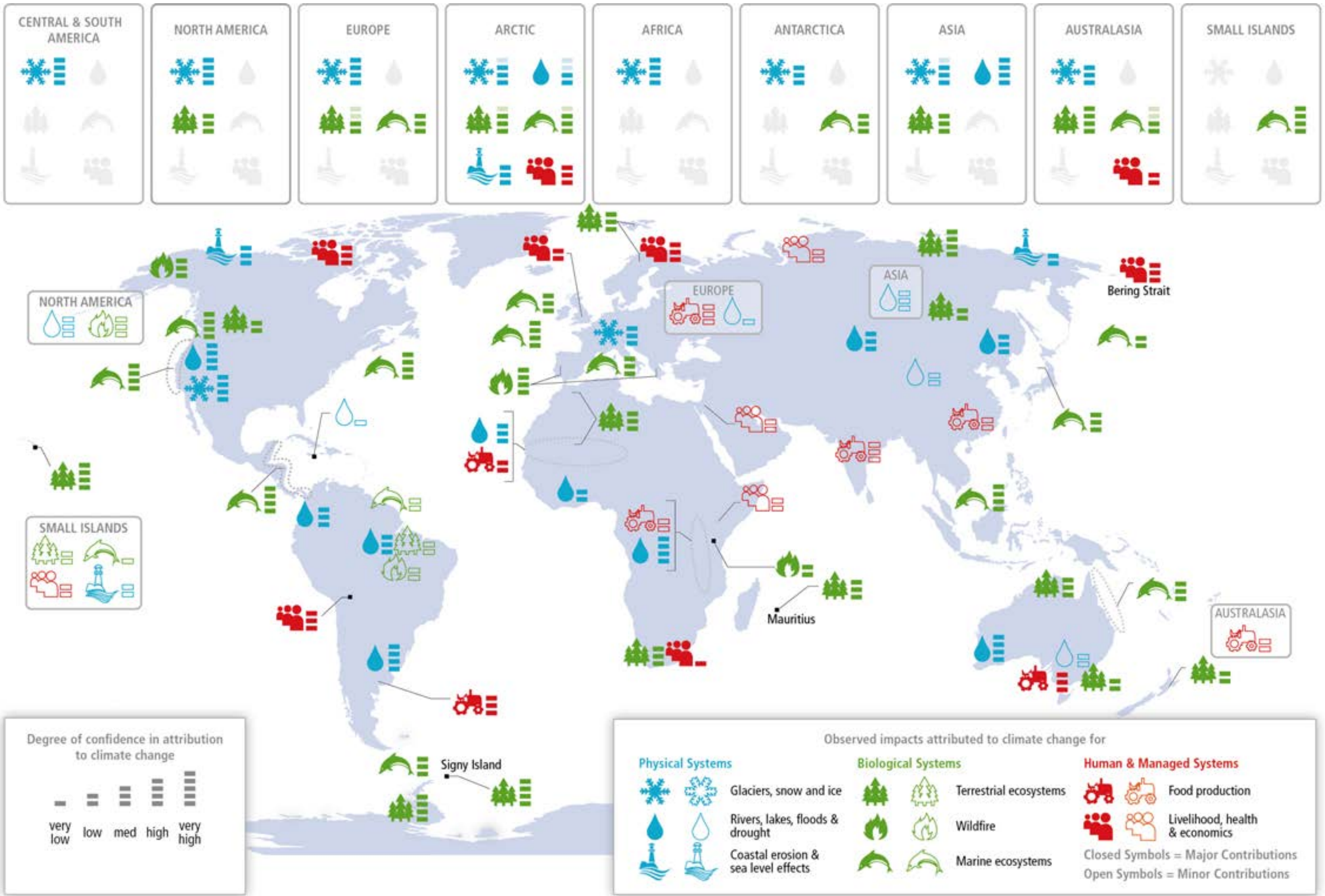


Figure 18-3: Global patterns of observed climate change impacts. Each colored symbol in the top panels indicates a class of systems for which climate change has played a major role in observed changes in at least one measure of that class across the respective region, and the range of confidence in attribution. Regional-scale impacts where climate change has played a minor role are shown by colored open symbols in a box in the respective region. Localized impacts are indicated with symbols on the map, placed in the approximate area of their occurrence. Impacts on physical (blue), biological (green) and human (red) systems are differentiated by color. This map represents a graphical synthesis of tables 18-5, 18-6, 18-7, 18-8 and 18-9.

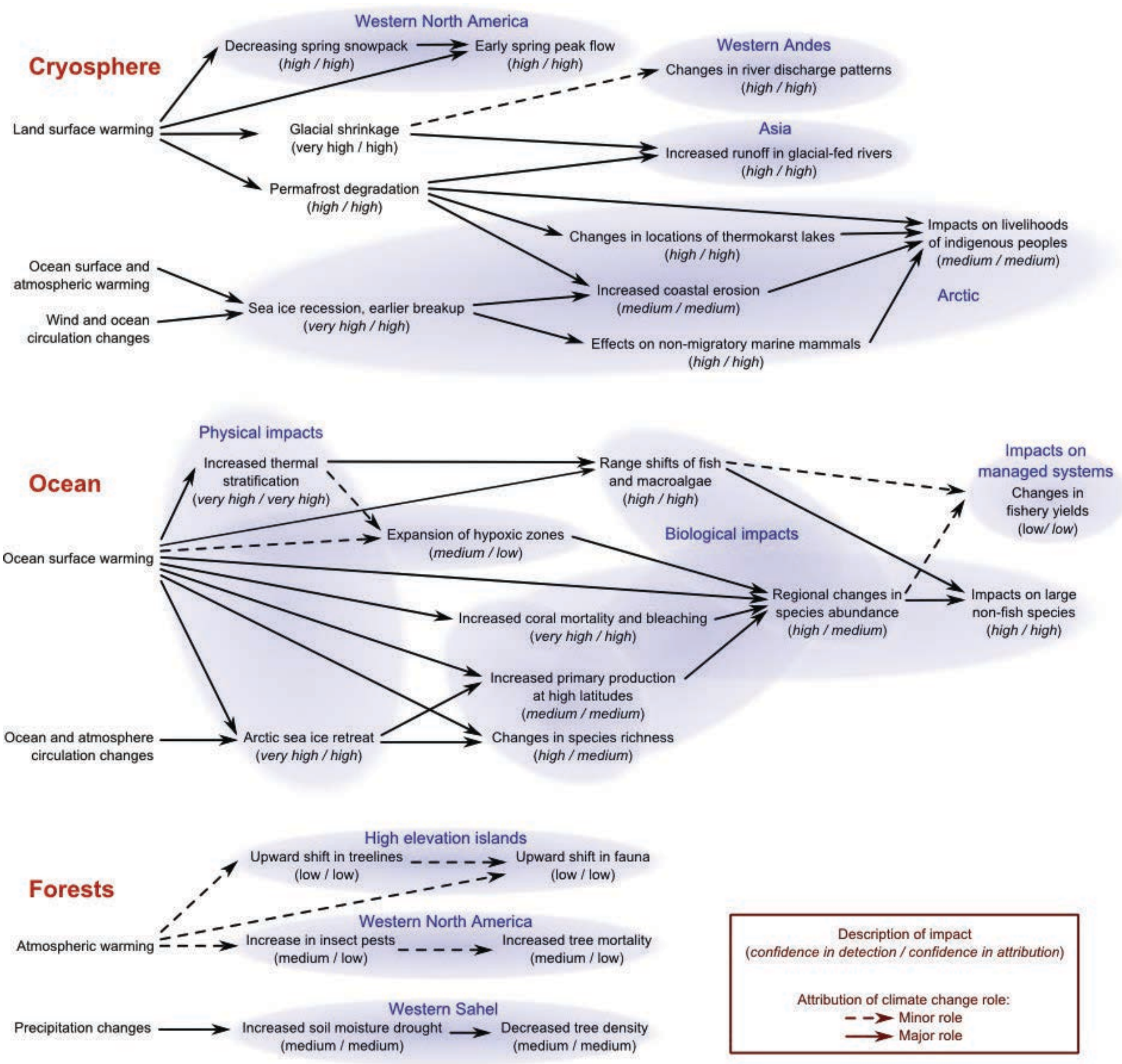


Figure 18-4: Major systems where new evidence indicates interconnected, ‘cascading’ impacts from recent climate change through several natural and human subsystems. Bracketed text indicates confidence in the detection of a climate change effect and the attribution of observed impacts to climate change. The role of climate change can be major (solid arrow) or minor (dashed arrow). Confidence is assessed in 18.3, 18.4, 18.5, and 18.6.
[Illustration to be redrawn to conform to IPCC publication specifications.]

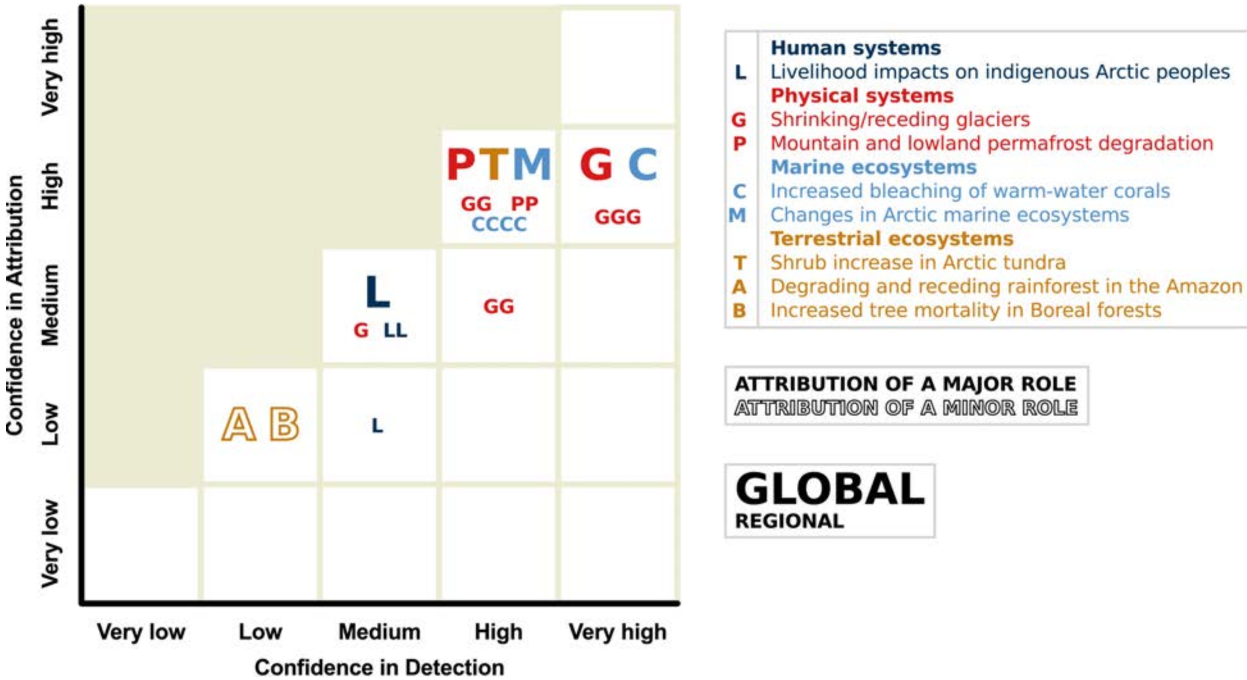


Figure 18-5: Confidence in detection and attribution of observed impacts on "Unique and Threatened Systems" as a result of recent climate change. Global assessments (large upper case) and regional assessments (small lower case) are discussed in 18.3.1.1, 18.3.2.4, Box 18-2, and Tables 18-2 and 18-5 through 18-9. Attribution assessments are for a minor (open font) or major (bold) role of climate change, as indicated.
[Illustration to be redrawn to conform to IPCC publication specifications.]

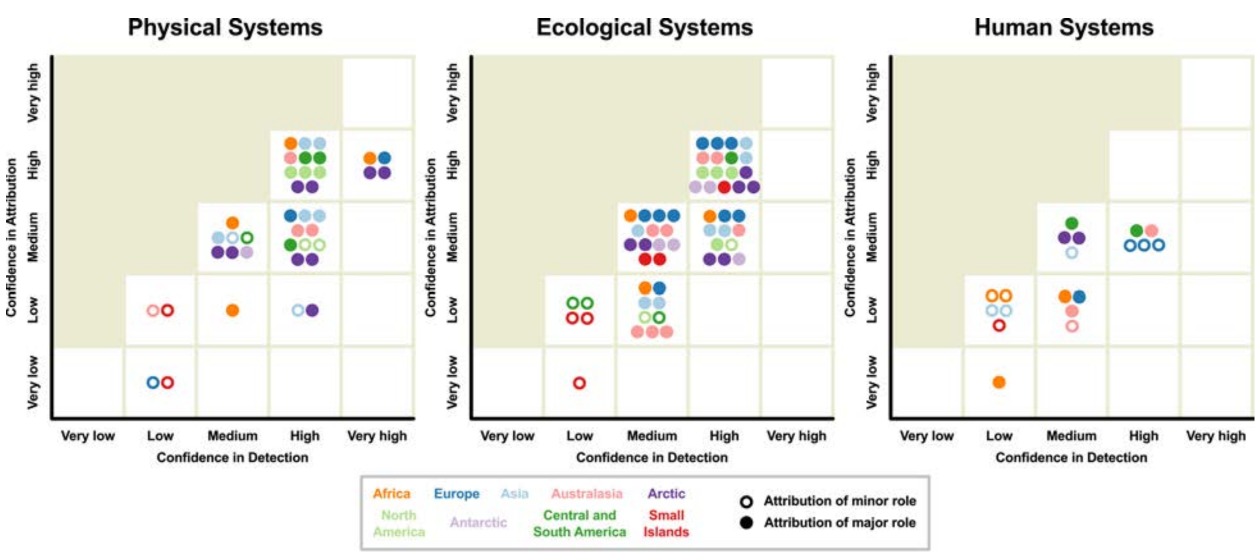


Figure 18-6: Confidence in detection of observed climate change impacts in physical natural systems, biological systems, and human and managed systems across regions, and confidence in attribution of such trends to observed climate change as a major or minor driver. Based on assessments developed in Tables 18-5 through 18-9.
[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 19. Emergent Risks and Key Vulnerabilities

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Contents

Executive Summary

This chapter assesses climate-related risks in the context of Article 2 of the UN Framework Convention on Climate Change [Box 19.1]. Such risks arise from the interaction of the evolving exposure and vulnerability of human, socioeconomic and biological systems with changing physical characteristics of the climate system [19.2]. Alternative development paths influence risk by changing the likelihood of climatic events and trends (through their

effects on greenhouse gases and other emissions) and by altering vulnerability and exposure [19.2.4, Figure 19-1, Box 19-2].

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, as well as adaptation and mitigation actions affecting the same or a different sector are generally not included or well integrated into projections of risk. However, their consideration leads to the identification of a variety of *emergent risks* [Box 19-2] that were not previously assessed or recognized [19.3, *high confidence*]**.** This chapter identifies several such complex-system interactions that increase vulnerability and risk synergistically. For example:

- **The risk of climate change to human systems (e.g., agriculture and water supply) is increased by the loss of ecosystem services which are supported by biodiversity** (e.g. water purification, protection from extreme weather events, preservation of soils, recycling of nutrients, and pollination of crops) [*high confidence*]. Studies since AR4 broadly confirm that a large proportion of species are at increased risk of extinction at all but the lowest levels of warming. [19.3.2.1, 19.5.1, 19.6.3.5]
- **Risks result from the management of water, land, and energy in the context of climate change.** For example, in some water stressed regions, as groundwater stores that have historically acted as buffers against impacts of climate variations and change are depleted, adverse consequences arise for human systems and ecosystems simultaneously undergoing alteration of regional groundwater resources due to climate change. The production of bioenergy crops to mitigate climate change leads to land conversion (e.g., from food crops and unmanaged ecosystems to energy crops; [*high confidence*]) and in some scenarios, reduced food security as well as additional greenhouse gas emissions over the course of decades or centuries. [19.3.2.2]
- **Climate change has the potential to adversely affect human health by increasing exposure and vulnerability to a variety of stresses.** For example the interaction of climate change with food security can exacerbate malnutrition, increasing vulnerability of individuals to a range of diseases [19.3.2.3, *high confidence*].
- **The risk of severe harm and loss due to climate change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones** (*high confidence*). These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure, generating new systemic risks. Cities in Asian megadeltas, where populations are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding, provide an example [19.2.3, 19.3.2.4, 19.4.2.1, 19.6.1.3.1, 19.6.2.1, 19.7.5, Table 19-4].
- **Spatial convergence of impacts in different sectors creates compound risk in many areas** (*medium confidence*). Examples include the Arctic (where thawing and sea ice loss disrupt land transportation, buildings, other infrastructure, and are projected to disrupt indigenous culture); and the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification) [19.3.2.4].

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change. Adaptive responses and mitigation measures sometimes increase such risks [19.4, *high confidence*]. Human or ecological responses to local impacts of climate change can generate harm at distant places.

- Increasing prices of food commodities on the global market due to local climate impacts, in conjunction with other stressors, decrease food security and exacerbate food insecurity at distant locations [19.4.1].
- Climate change will bear significant consequences for human migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*) [19.4.2.1].
- The effect of climate change on conflict and insecurity is an emergent risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change. In numerous statistical studies, the influence of climate variability on violent conflict is large in magnitude [*medium confidence*, 19.4.2.2].
- Many species shift their ranges in response to climate change, adversely affecting ecosystem function and services while presenting new challenges to conservation efforts [19.4.2.3*; medium confidence*].
- Mitigation measures taken in one location can have long-distance or indirect impacts on biodiversity and/or human systems. For example, the development of biofuels as energy sources can increase food prices [*high confidence*] and affect distant land use practices [19.4.1, 19.4.3].

Additional risks related to particular biophysical impacts of climate change have arisen recently in the literature in sufficient detail to permit assessment [19.5, *high confidence*].

- **Risks associated with global temperature rise in excess of 4°C relative to preindustrial levels**[1] arise from the potential for adverse impacts on agricultural production worldwide, extensive loss of ecosystem functioning, extinction of a substantial proportion of the earth's species *(high confidence)*, and traversing thresholds that lead to disproportionately large earth systems responses [19.5.1].
- **Ocean acidification poses risks to marine ecosystems and the societies that depend on them.** For example, ocean acidification is *very likely* to lead to changes in coral calcification rates. Reduced coral calcification is projected to have impacts of medium to high magnitude on some ecosystem services, including tourism and the provisioning of fishing [19.5.2].
- **There is increasing evidence in the literature that high ambient CO_2 concentrations in the atmosphere will affect human health by increasing the production and allergenicity of pollen and allergenic compounds and by decreasing nutritional quality of important food crops [19.5.3].**
- **In addition to providing potential climate change abatement benefits, geoengineering poses widespread risks to society and ecosystems.** For example, in some model experiments the implementation of Solar Radiation Management [SRM] for the purpose of limiting global warming leads to ozone depletion and reduces precipitation. In addition, the failure or abrupt halting of SRM risks rapid climate change [19.5.4].

[FOOTNOTE 1: Levels of global mean temperature change are variously presented in the literature with respect to "pre-industrial" temperatures in a specified year or period, e.g., 1850-1900. Alternatively, the average temperature within a recent period, e.g., 1986-2005, is used as a baseline. In this chapter, we use both, depending on the literature being assessed. The increase above pre-industrial (1850-1900) levels for the period 1986-2005 is estimated at 0.61°C (AR5 WGI Section 11.3.6.3). For example, using these baselines, a 2°C increase above pre-industrial levels corresponds to a 1.39°C increase above 1986-2005 levels. We use other baselines on occasion depending on the literature cited and explicitly indicate where this is the case. Climate impact studies often report outcomes as a function of regional temperature change, which can differ significantly from changes in global mean temperature. In most land areas, regional warming is larger than global warming (AR5 WGI Section 10.3.1.1.2). However, given the many conventions in the literature for baseline periods, the reader is advised to check carefully and to adjust baseline levels for consistency when comparing outcomes.]

Global, regional, and local socio-economic, environmental and governance trends indicate that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic and thus vary across temporal and spatial scales [*high confidence*]. Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socio-economic development pathways and the vulnerability and exposure of people. Changes in poverty or socio-economic status, ethnic composition, age structure and governance had a significant influence on the outcome of past crises associated with climatic hazards [19.6.1.].

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance. Studies confirm that countries that are classified as failed states and afflicted by violence are often not able to effectively reduce vulnerability. Unless governance improves in countries with severe governance failure, risk will increase as a result of climate changes interacting with increased human vulnerability [*high confidence*, 19.6.1.3.3.].

***Key risks* inform evaluation of "dangerous anthropogenic interference with the climate system," in the terminology of UNFCCC Article 2. These are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of hazards linked to climate change and the vulnerability of exposed societies and systems. Key risks were identified in this assessment based on expert judgments made by authors of the various chapters of this report in light of criteria described here [19.2.2.2] and consolidated into the following representative list (*high confidence*).** [CC-KR; 19.2.2.2, 19.6.2.1, Table 19-4, Box 19-2; Roman numerals indicate corresponding entries in Table 19-4; Notation at end of each entry indicates corresponding Reasons for Concern, discussed below.]

(i) **Risk of death, injury, and disruption to livelihoods, food supplies, and drinking water, in addition to loss of common-pool resources, sense of place, and identity due to sea level rise,** coastal flooding and storm surges affecting high concentrations of people, economic activity, biodiversity, and critical infrastructure in low-lying coastal zones and small island developing states. [*RFC 1, 2, 3, 4, and 5*]
(ii) **Risk of food insecurity and the breakdown of food systems** linked to warming, drought and precipitation variability particularly in regions that are characterized by poorer populations in urban and rural settings. [*RFC 2, 3 and 4*]
(iii) **Risk of severe harm due to inland flooding** and the limited coping and adaptive capacities of large urban populations. [*RFC 2 and 3*]
(iv) **Risk of loss of rural livelihoods and income of rural residents due to insufficient access to drinking and irrigation water,** and reduced agricultural productivity, as well as risk of food insecurity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. [*RFC 2 and 3*]
(v) **Systemic risks due to multiple interacting hazards affecting infrastructure in combination with a high dependency of people on critical services** (electricity, water supply, health and emergency services) which may break down during extreme events. [*RFC 2, 3, and 4*]
(vi) **Risk of loss of marine ecosystems and the services they provide for coastal livelihoods.** Biodiversity and coastal ecosystem services important for fishing communities in the tropics and the Arctic are especially at risk due to rising water temperature and the increase of stratification and ocean acidification. [*RFC 1, 2, 3, 4, and 5*]
(vii) **Risk of loss of terrestrial ecosystems and the services they provide for terrestrial livelihoods.** Biodiversity and terrestrial ecosystem services are important for rural and urban communities globally. These services are at risk due to rising temperatures, changes in precipitation patterns, and extreme weather events. Risks are high for communities whose livelihoods depend on provisioning services [*RFC 1, 3, and 4*].
(viii) **Risk of mortality, morbidity, and other harms during periods of extreme heat, particularly for urban populations of the elderly, infants, people with chronic diseases or compromised immune systems, and expectant mothers**. Increasing frequency and intensity of extreme heat (including exposure to the urban heat island effect and air pollution) interacts with an inability of some local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups. [*RFC 2 and 3*]

Climate change risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region and time period; both are important to understanding possible outcomes [*high confidence*]. In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a key role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services. [19.6.2.2]

Assessment of the Reasons for Concern framework pertinent to Article 2 of the UNFCCC has led to evaluations of risk being updated in light of the advances since the AR4. [19.6.3] (All temperature changes are relative to 1986-2005, i.e.,"recent"; Numbers are indicative of RFC designation in key risk enumeration, above.)

(1) Some **unique and threatened systems** are at risk from climate change at recent temperatures, with increasing numbers at risk of severe consequences at global mean warming of 1°C, and many species and systems with limited ability to adapt subject to very high risk at warming of 2°C, particularly Arctic sea ice and coral reef systems (*high confidence*) [19.6.3.2].

(2) Risk associated with **extreme events** accompanying climate change is moderate at recent temperatures based on the attribution of heat extremes to anthropogenic climate change, the attribution to climate change of impacts of extremes on a unique and threatened system, coral reefs (*high confidence*), and the current vulnerability of other exposed systems. Risk is high at 1°C warming based on the *magnitude* and *likelihood* and *timing* of the change in hazard from extreme events (*medium confidence*) [19.6.3.3].

(3) Risk associated with the **distribution of impacts** is generally greatest in low-latitude, less developed areas, but because vulnerability is unevenly distributed within countries, some populations in developed countries are highly vulnerable. Risk is moderate at recent temperatures because regionally differentiated impacts generally related to food production have been attributed to climate change *with medium to high confidence*. Based on risk to regional crop production and water resources in some countries, risk becomes high for warming above 2°C (*medium confidence*). [19.6.3.4]

(4) Risk associated with **global aggregate impacts** is determined by both economic and noneconomic metrics. For instance, the evidence for a link between increasing risk of long-term species extinction, a noneconomic metric, and increasing temperature is *robust*. Overall, global aggregate impacts become moderate between 1-2°C of warming based on model assessment that the global aggregate economic impact of climate change will become negative and significant in magnitude (*medium confidence*). Risk becomes high around 3°C, reflecting an increase in the *magnitude* and *likelihood* of both aggregate economic risks (*low confidence*) and risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*; 19.3.2.1; 19.5.1; 19.6.3.5).

(5) Risk associated with **large-scale singular events** becomes moderate between 0-1°C due to early warning signs that both coral reef and Arctic systems are experiencing irreversible regime shifts. Risk becomes high between 1-4°C with a disproportionate increase in risk as temperature increases between 1°C and 2°C due to the potential for commitment to a large and irreversible sea level rise from ice sheet loss (*medium confidence*). [19.6.3.6]

Impacts of climate change avoided under a range of scenarios for mitigation of greenhouse gas emissions are potentially large and increasing over the 21st century [19.7.1, *high confidence*]. Among the impacts assessed here, benefits from mitigation are most immediate for surface ocean acidification and least immediate for impacts related to sea level rise. Since mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades.

Only mitigation scenarios in the most stringent category (i.e. with 2100 CO_2e concentrations of 430-480ppm) maintain moderately healthy coral reefs (*medium confidence*). With respect to the Reasons for Concern, these scenarios constrain overall risks to Unique and Threatened Systems, and those associated with Extreme Weather Events to a moderate level for some stringent scenarios and to the lower end of the high range of risk for others. Such scenarios constrain the level of risk associated with all other Reasons for Concern to the moderate or neutral level *(high confidence)* [19.6.3.2, 19.6.3.3, 19.7.1].

The higher part of the range of greenhouse gas emission scenarios in the literature, i.e. those with 2100 CO_2e concentrations above 720 ppm create risks in the high range for all Reasons for Concern and in the very high range (reflecting inability to adapt) for Unique and Threatened Systems. Risks for Distribution of Impacts also approach the very high range *(high confidence)* [19.6.3.2, 19.6.3.4, 19.7.1].

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). For example, very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood [19.7.1, 19.7.2.].

The risk of crossing tipping points (critical thresholds) in the Earth system or socio-ecological systems is projected to decrease with reduced greenhouse gas emissions [19.7.3], and the risk of crossing tipping points in socio-ecological systems can also be reduced by reducing human vulnerability or by preserving ecosystem services, or both (*medium confidence*) [19.7.4]. The risk of crossing tipping points is reduced by limiting the level of climate change and/or removing concomitant stresses such as overgrazing, overfishing, and pollution, but there is *low confidence* in the level of climate change associated with such tipping points and measures to avoid them.

19.1. Purpose, Scope, and Structure of the Chapter

The objective of this chapter is to assess new literature published since the Fourth Assessment Report on emergent risks and key vulnerabilities to climate change from the perspective of the distribution of risk over geographic location, economic sector, time period, and socioeconomic characteristics of individuals and societies. Frameworks used in previous IPCC reports to assess risk in the context of Article 2 of the UN Framework Convention on Climate Change (UNFCCC) are updated and extended in light of new literature; and additional frameworks arising in recent literature are examined. A focal point of this chapter is the interaction of the changing physical characteristics of the climate system with evolving characteristics of socioeconomic and biological systems (exposure and vulnerability) to produce risk (see Figure 19-1). Given the centrality of Article 2 to this chapter, the greater emphasis is on harmful outcomes of climate change rather than potential benefits.

[INSERT FIGURE 19-1 HERE
Figure 19-1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. It underscores that risks are a product of a complex interaction between physical hazards associated with climate change and climate variability on the one hand, and the vulnerability of a society or a social-ecological system and its exposure to climate-related hazards on the other. The definition and use of “key” and “emergent” are indicated in Box 19-2 and the Glossary. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions (although changing hazard patterns also play a role, see 19.6.1.1). Changes in both the climate system (left side) and development processes (right side) are key drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk (modified version of Figure 1, IPCC 2012a).]

19.1.1. Historical Development of this Chapter

The Third and Fourth Assessment Reports (TAR and AR4, respectively) each devoted chapters to evaluating the state of knowledge relevant to Article 2 of the UNFCCC (Smith *et al.*, 2001; Schneider *et al.*, 2007; see Box 19-1). The TAR sorted and aggregated impacts discussed in the literature according to a framework called *Reasons for Concern* (RFCs), and assessed the level of risk associated with individual impacts of climate change as well as each category or “reason” as a whole, generally as a function of global mean warming. This assessment took account of the distribution of vulnerability across particular regions, countries, and sectors. AR4 furthered the discussion relevant to Article 2 by assessing new literature and developing criteria potentially useful for policy makers in the determination of *key* impacts and vulnerabilities, i.e, those meriting particular attention in respect to Article 2 (see Box 19-2 for definitions of Reasons for Concern, Key Vulnerabilities (KVs) and related terms. Some definitions go beyond those in the Glossary to provide details especially pertinent to this chapter). AR4 emphasized the differences in vulnerability between developed and developing countries but also assessed new literature describing vulnerability pertaining to various aggregations of people (such as by ethnic, cultural, age, gender, or income status) and response strategies for avoiding key impacts. The Reasons for Concern were updated and the Synthesis Report (IPCC, 2007) noted that they “remain a viable framework to consider key vulnerabilities” (AR4 WGII Section 5.2). However, their utility was limited by several factors: the lack of a time dimension (i.e., representation of impacts arising from timing and rates of climate change and climate forcing), the focus on risk only as a function of global mean temperature, lack of a clear distinction between impacts and vulnerability, and importantly, incomplete incorporation of the evolving socioeconomic context, particularly adaptation capacity, in representing impacts and vulnerability.

19.1.2. The Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

SREX (IPCC, 2012a) provides additional insights with respect to two RFC (risks associated with extreme weather events and the distribution of impacts) and particularly the distribution of capacities to adapt to extreme events across countries, communities, and other groups, and the limitations on implementation of these capacities. SREX emphasized the role of the socioeconomic setting and development pathway (expressed through exposure and vulnerability) in determining, on the one hand, the circumstances where extreme events do or do not result in extreme impacts and disasters, and on the other hand, when non-extreme events may also result in extreme impacts and disasters.

19.1.3. New Developments in this Chapter

With these frameworks already established, and a long list of impacts and key vulnerabilities enumerated and categorized in previous assessments, the current chapter has three goals: first, to recognize and assess risks which arise out of complex interactions involving climate and socioecological systems, called *emergent risks* (see Box 19-2, Table 19-4, CC-KR). In many cases, scientific literature sufficient to permit assessment of such risks has become available largely since AR4. In this chapter, we consider only those emergent risks which are relevant to interpreting Article 2 or have the potential to become relevant (see criteria in 19.2.2) as additional understanding accumulates. For example, since AR4, sufficient literature has emerged to allow initial assessment of the potential relationship between climate change and conflict. The second goal is to reassess and reorganize the existing frameworks (based on Reasons for Concern and Key Vulnerabilities) for evaluating the literature pertinent to Article 2 of the UNFCCC in order to address the deficiencies cited in section 19.1.1, particularly in light of the advances in SREX and the current report's discussions of vulnerability and human security (see Chapters 12 and 13) and adaptation (see Chapters 14-17 and 20). From this perspective, the objective stated in Article 2 may be viewed as aiming in part to ensure human security in the face of climate change. Thirdly, this chapter will assess recent literature pertinent to additional frameworks for categorizing risk and vulnerability, particularly focusing on indirect impacts and interaction and concatenation of risk, including geographic areas of compound risk (see Section 19.3).

In order to clarify the relative roles of characteristics of the physical climate system, like increases in temperature, precipitation, or storm frequency, and characteristics of the socioeconomic and biological systems with which these interact (vulnerability and exposure) to produce risks of particular consequences (the latter term used interchangeably here with "impacts" and "outcomes"), we rely heavily on a concept used sparingly in the TAR and AR4, *key risks* (see Box 19-2). Furthermore, we emphasize recent literature pointing to the *dynamic* character of vulnerability and exposure based on their intimate relationship to development.

Section 19.2 describes the framework used here for identifying key vulnerabilities, key risks, and emergent risks. We consider a variety of types of emergent risks, including in 19.3 those arising from multiple interacting systems and stresses, and in 19.4, those arising from indirect impacts, trans-boundary impacts, and impacts occurring at a long distance from the location of the climate change which causes them. One example which illustrates all of these properties is the extent to which climate change impacts on agriculture, water resources, and sea level affect human migration flows. These shifts entail both risks of harm and potential benefits for the migrants, for the regions where they originate, and for the destination regions (see 19.4.2.1 and 12.4). Associated risks include indirect impacts, like the effect of land use changes on ecosystems occurring at the new locations of settlement, which may be near the location of the original climate impact or quite distant. Such distant, indirect effects would compound the direct consequences of climate change at the locations receiving the incoming migrants. In 19.5, we discuss other risks newly assessed here, including those arising from ocean acidification. Section 19.6 assesses key risks and vulnerabilities in light of the criteria discussed here [19.2.2] and in the context of the Reasons for Concern, and section 19.7 assesses response strategies aimed at avoiding key risks.

_____ START BOX 19-1 HERE ____

Box 19-1. Article 2 of the UNFCCC

Article 2

OBJECTIVE
The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

_____ END BOX 19-1 HERE ____

____ START BOX 19-2 HERE ____

Box 19-2. Definitions

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

Vulnerability - The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

A broad set of factors such as wealth, social status, and gender determine vulnerability and exposure to climate-related risk.

Impacts (Consequences, Outcomes) - Effects on natural and human systems. In this report, the term *impacts* is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health status, ecosystems, economic, social, and cultural assets, services (including environmental), and infrastructure due to the interaction of climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as *consequences* and *outcomes*. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

Hazard - The potential occurrence of a natural or human-induced physical event or trend, or physical impact, that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Stressors - Events and trends, often not climate-related, which have an important effect on the system exposed and can increase vulnerability to climate-related risk.

Risk - The potential for consequences where something of human value (including humans themselves) is at stake and where the outcome is uncertain. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the consequences if these events occur.

Risk = (Probability of Events or Trends) X Consequences

This report assesses climate-related risks.

Key vulnerability, key risk, key impact – A vulnerability, risk, or impact relevant to the definition and elaboration of “dangerous anthropogenic interference (DAI) with the climate system,” in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policymakers in that context.

Key risks are potentially severe adverse consequences for humans and social-ecological systems due to the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered “key” due to high hazard or high vulnerability of societies and systems exposed, or both.

Vulnerabilities are considered “key” if they have the potential to combine with hazardous events or trends to result in key risks. Vulnerabilities that have little influence on climate-related risk, for instance, due to lack of exposure to hazards, would not be considered key.

Key impacts are severe consequences for humans and social-ecological systems.

Extract from Chapter 19, WGII, AR4:

Many impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them 'key'. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system, in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19-1). Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgments informed by the state of scientific knowledge.

Emergent Risk: A risk that arises from the interaction of phenomena in a complex system, for example the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region. Many of the emergent risks discussed in this report have only recently been analyzed in the scientific literature in sufficient detail to permit assessment. In this chapter, the only emergent risks discussed are those which have the potential to become key risks once sufficient understanding accumulates.

Reasons for Concern – Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be "dangerous" (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

Summary of Reasons for Concern (revised from TAR, WGII, Chapter 19; see also Chapter 1.2.3. and Chapter 18.6.4.):

"Reasons for Concern" may aid readers in making their own determination about what is a "dangerous" climate change. Each Reason for Concern is consistent with a paradigm that can be used by itself or in combination with other paradigms to help determine what level of climate change is dangerous. The reasons for concern are the relations between global mean temperature increase and:

1. Risks to unique and threatened systems
2. Risks associated with extreme weather events
3. Risks associated with the distribution of impacts
4. Risks associated with aggregate impacts
5. Risks associated with large-scale singular events

_____ END BOX 19-2 HERE _____

19.2. Framework for Identifying Key Vulnerabilities, Key Risks, and Emergent Risks

19.2.1. Risk and Vulnerability

Definitions and frameworks that systematize hazards, exposure, vulnerability, risk and adaptation in the context of climate change are multiple, overlapping, and often contested (see e.g. Burton *et al.*, 1983; Blaikie *et al.*, 1994; Twigg, 2001; Turner *et al.*, 2003a; Turner *et al.*, 2003b; UNISDR, 2004; Schröter, 2005; Füssel and Klein, 2006; Adger, 2006; Villagrán de León, 2006; Thomalla *et al.*, 2006; Tol and Yohe, 2006; Birkmann, 2006b; IPCC, 2007; Cutter *et al.*, 2008; Cutter and Finch, 2008; ICSU - LAC, 2010a; ICSU - LAC, 2010b; Cardona, 2011; Kienberger, 2012; IPCC, 2012a; Costa and Kropp, 2012; DEFRA, 2012; Birkmann *et al.*, 2013a). Today, key reports and most authors differentiate between hazards, vulnerability, risk and impacts (see e.g. Hutton *et al.*, 2011; IPCC, 2012a; Birkmann *et al.*, 2013a). The recent literature underscores that risks from climate change are not solely externally generated circumstances or changes in the climate system to which societies respond, but rather, the result of complex interactions among societies or communities, ecosystems, and hazards arising from climate change (Susman *et al.*, 1983; Comfort *et al.*, 1999; Birkmann *et al.*, 2011a; UNISDR, 2011; IPCC, 2012a; Birkmann *et al.*, 2013a). The differentiation of the various aspects of these interactions is an important improvement since AR4 because it exhibits the social construction of risk through the concept of vulnerability (IPCC, 2012a). This new framework, growing out of SREX, translates information more easily into a risk management approach that facilitates policy making (de Sherbinin, 2013). The following section advances this framework in the context of Article 2 of the UNFCCC.

We refer to the characteristics of climate change and its effects on geophysical systems, such as floods, droughts, deglaciation, sea level rise, increasing temperature and frequency of heat waves, as *hazards*. In contrast, *vulnerability* refers primarily to characteristics of human or social-ecological systems exposed to hazardous climatic (droughts, floods etc.) or non-climatic events and trends (increasing temperature, sea-level rise) (UNDRO, 1980; Cardona, 1986; Liverman, 1990; Cannon, 1994; Blaikie *et al.*, 1996; UNISDR, 2004; Cannon, 2006; Birkmann, 2006a; Thywissen, 2006; Füssel and Klein, 2006; UNISDR, 2009; IPCC, 2012a). Ecosystems or geographic areas can be classified as vulnerable, which is of particular concern if human vulnerability increases as a result of potential impairment of the related ecosystem services. The Millennium Ecosystem Assessment (MEA) for example identified ecosystem services that affect the vulnerability of societies and communities, such as provision of fresh water resources and air quality (Millenium Ecosystem Assessment, 2005). Examples in this chapter and other chapters in this report include the vulnerability of warm water coral reefs and respective ecosystem services for coastal communities (see Table 19-4 and CC-KR).

The new framework used here also underscores that the development process of a society has significant implications for exposure, vulnerability and risk. Climate change is not a risk per se; rather climate changes and related hazards interact with the evolving vulnerability and exposure of systems and therewith determine the changing level of risk (see Figure 19-1 and Table 19-4). Identifying key vulnerabilities facilitates estimating key risks when coupled with information about evolving hazards associated with climate change. This approach provides the basis for criteria developed in the following sections.

19.2.2. Criteria for Identifying Key Vulnerabilities and Key Risks

Vulnerability is dynamic and context specific, determined by human behavior and societal organization, which influences for example the susceptibility of people (e.g. by marginalization) and their coping and adaptive capacities to hazards (see IPCC, 2012a). In this regard coping mainly refers to capacities that allow a system to protect itself in the face of adverse consequences, while adaptation – by contrast – denotes a longer-term process that also involves adjustments in the system itself and refers to learning, experimentation and change (Yohe and Tol, 2002; Pelling, 2010; Birkmann *et al.*, 2013a). Perceptions and cognitive constructs about risks and adaptation options as well as cultural contexts influence adaptive capacities and thus vulnerability (Grothmann and Patt 2005; Rhomberg, 2009; Kuruppu and Liverman 2011; see section 19.6.1.4). SREX stressed that the consideration of multiple dimensions (e.g., social, economic, environmental, institutional, cultural), as well as different causal factors of vulnerability can improve strategies to reduce risks to climate change (see IPCC 2012c, p.17 and Cardona *et al*., 2012, p. 17, 67-106).

Key vulnerability and key risk are defined in Box 19-2. Vulnerabilities that have little influence on overall risk are not considered key. Similarly, the magnitude or other characteristics of climate change related hazards, such as glacier melting, sea level rise or heat waves, are not by themselves adequate to determine key risks, since the consequences of climate change also will be determined by the vulnerability of the exposed society or social-ecological system. Key vulnerabilities and key risks embody a normative component because different societies might rank the various vulnerability and risk factors and actual or potential types of loss and damage differently (see Lavell *et al*., 2012, p. 45; Schneider *et al*., 2007, p. 785). Generally, vulnerability merits particular attention when the survival of societies, communities, or ecosystems is threatened (see UNISDR 2011, 2013; Birkmann *et al.*, 2011a). Climate change will influence the nature of the climatic hazards people and ecosystems are exposed to and also contribute to deterioration or improvement of coping and adaptive capacities of those exposed to these changes. Consequently, many studies (Wisner *et al.*, 2004; Cardona, 2010; Birkmann *et al.*, 2011a) focus with a priority on the vulnerability of humans and societies as a central feature, rather than solely on the level of climatic change and respective hazards.

19.2.2.1. Criteria for Identifying Key Vulnerabilities

We reorganize and further develop criteria for identifying vulnerabilities as “key” used in AR4 based on the literature (Blaikie *et al.*, 1994; Bohle, 2001; Turner *et al.*, 2003a; Turner *et al.*, 2003b; Birkmann, 2006a; Villagrán de León, 2006; Cutter *et al.*, 2008; Cutter and Finch, 2008; ICSU - LAC, 2010a; ICSU - LAC, 2010b; UNISDR, 2011; Cardona, 2011; Birkmann, 2011a; IPCC, 2012a; Birkmann *et al.*, 2013a) and the differentiation of hazard, exposure, and vulnerability presented here. The criteria in this and succeeding sections were used to identify key vulnerabilities, key risks, and emergent risks in 19.6.2 and Table 19-4. Not all of the criteria need to be fulfilled to characterize a vulnerability or risk as key but the characterization of a phenomenon as a key vulnerability or key risk is usually supported by more than one criterion.

The following five criteria are used to judge whether vulnerabilities are key:

1) *Exposure of a society, community, or social-ecological system to climatic stressors.* While exposure is distinct from vulnerability, exposure is an important precondition for considering a specific vulnerability as key. If a system is not at present nor in the future exposed to hazardous climatic trends or events, its vulnerability to such hazards is not relevant in the current context. Exposure can be assessed based on spatial and temporal dimensions.
2) *Importance of the vulnerable system(s). Views on the importance of different aspects of societies or ecosystems can vary across regions and cultures* (see Kienberger, 2012). However, the identification of key vulnerabilities is less subjective when it involves characteristics that are crucial for the survival of societies or communities or social-ecological systems exposed to climatic hazards. Defining key vulnerabilities in the context of particular societal groups or ecosystem services also takes into account the conditions that make these population groups or ecosystems highly vulnerable, such as processes of social marginalization or the degradation of ecosystems (Leichenko and O'Brien, 2008; O'Brien *et al.*, 2008; IPCC, 2012a).
3) *Limited ability of societies, communities or social-ecological systems to cope with and to build adaptive capacities to reduce or limit the adverse consequences of climate-related hazard.* Coping and adaptive capacities are part of the formula that determines vulnerability (see IPCC, 2012a; Birkmann *et al*., 2013a). While coping describes actions taken within existing constraints to protect the current system and institutional settings, adaptation is a continuous process which encompasses learning and change of the system exposed – including changes of rule systems or modes of governance (Smithers and Smit, 1997; Pielke Jr, 1998; Smit *et al.*, 1999; Frankhauser *et al.*, 1999; Adger *et al.*, 2005; Smit and Wandel, 2006; Pelling, 2010; Kelly and Adger, 2000; Yohe, 2002; IPCC, 2012a; Pelling *et al.*, 2008; Garschagen, 2013; Tschakert and Dietrich; 2010; Birkmann *et al.*, 2013a). Severe limits of coping and adaptation provide criteria for defining a vulnerability as key, since they are core factors that increase vulnerability to climatic hazards (see e.g. Warner *et al*., 2012).
4) *Persistence of vulnerable conditions and degree of irreversibility of consequences.* Vulnerabilities are considered key when they are persistent and difficult to alter. This is particularly the case when the susceptibility is high and coping and adaptive capacities are very low due to conditions that are hard to change. Irreversible degradation of ecosystems (e.g. warm water coral reefs), chronic poverty and marginalization, and insecure land tenure arrangements are drivers of vulnerability that in combination with climatic hazards determine risks which often persist over decades (see CC-KR), for example as observed in the Sahel Zone. In this way, communities or social-ecological systems (e.g. coastal communities dependent on fishing or mountain communities dependent on specific soil conditions) may reach a tipping point (or critical threshold) that would cause a partial or full collapse of the system, including displacement (see Renaud *et al.*, 2010; section 19.4.2.1). Inability to replace such a system or compensate for potential and actual losses and damages (i.e., irreversibility) is a critical criterion for determining what is “key”.
5) *Presence of conditions that make societies highly susceptible to cumulative stressors in complex and multiple-interacting systems.* Conditions that make communities or social-ecological systems highly susceptible to the imposition of additional climatic hazards or that impinge upon their ability to cope and adapt, such as violent conflicts (e.g. during drought disaster in Somalia (see Menkhaus, 2010)) are considered under this criteria. Also, the critical dependence of societies on highly interdependent infrastructures (e.g. energy/power supply, transport and health care) (see Atzl and Keller, 2013; Rinaldi *et al*., 2001; Wang *et al*., 2012a) leads to key vulnerabilities regarding multiple-interacting systems where capacity to cope or adapt to their failure is low (see Reed *et al*., 2010; Copeland, 2005; Table 19-4).

19.2.2.2. Criteria for Identifying Key Risks

Risks are considered "key" due to high hazard or high vulnerability ("key vulnerability") of societies and systems exposed, or both. Criteria for determining key risks build on the criteria for key vulnerabilities, since vulnerability is a component of risk. As such, risk is strongly determined by coping and adaptive capacities. However, the criteria for identifying key risks also take into account the magnitude, frequency and intensity of hazardous events and trends linked to climate change to which vulnerable systems are exposed. Accordingly, the following four additional criteria are used to judge whether risks are key:

1) *Magnitude:* Risks are key if associated harmful consequences have a large magnitude, determined by a variety of metrics including human mortality and morbidity, economic loss, losses of cultural importance, and distributional consequences (see Schneider *et al.*, 2007; IPCC, 2012a). Magnitude and frequency of the hazard as well as socioeconomic factors that determine vulnerability and exposure contribute.
2) *Probability that significant risks will materialize and their timing.* Risks are considered key when there is a high probability that the hazard due to climate change will occur under circumstances where societies or social-ecological systems exposed are highly susceptible and have very limited capacities to cope or adapt and consequently potential consequences are severe. Both the timing of the hazard and the dynamics of vulnerability and exposure contribute. Risks which materialize in the near term may be evaluated differently than risks which materialize in the distant future, since the time available for building up adaptive capacities is different (Oppenheimer, 2005; Schneider *et al.,* 2007; Section 19.6.3.6*).*
3) *Irreversibility and persistence of conditions that determine risks.* Persistence of risks refers to the fact that underlying drivers and root causes of these risks, either socioeconomic (e.g. chronic poverty) or physical, cannot be rapidly reduced. The criteria for assessing key vulnerabilities include the persistence of socioeconomic conditions contributing to vulnerability that also apply here (Section 19.2.2.1, point 4). In addition, some hazards are associated with the potential for persistent physical impacts, such as loss of an ice sheet causing irreversible sea level rise or release of methane clathrates from the seabed.
4) *Limited ability to reduce the magnitude and frequency or other characteristics of hazardous climatic events and trends and the vulnerability of societies and social-ecological systems exposed.* Criterion 3 pertaining to key vulnerabilities (Section 19.2.2.1) discusses limited ability of societies to improve coping and adaptive capacities in order to manage risk. This criterion also applies here. In addition, risks are also considered to be key when societies together have very limited prospects for reducing the magnitude, frequency or intensity of the associated climate hazards. For example, risks that may be reduced or limited by greenhouse gas reductions which reduce the probability of the associated hazard are less threatening than those for which the likelihood of the hazard cannot be effectively altered (see also 19.7.1). For example, risks which are already projected to be large during the next few decades under a range of Representative Concentration Pathways (RCPs) are much more difficult to influence by reducing emissions than those projected to become large late in this century (for example, see discussion of risk from extreme heat in Section 19.6.3.3).

19.2.3. Criteria for Identifying Emergent Risks

A risk that arises from the interaction of phenomena in a complex system is defined here as an *emergent risk*. For example, feedback processes between climatic change, human interventions involving mitigation and adaptation, and processes in natural systems can be classified as emergent risks if they pose a threat to human security. Emergent risks could arise from unprecedented situations, such as the increasing urbanization of low lying coastal areas that are exposed to sea-level rise or where new pluvial flooding risk emerges due to urbanization of vulnerable areas not historically populated. Some emergent risks have been identified or discussed only recently in the scientific literature and as a result, our ability to assess whether they are key risks is limited. In this chapter, the only emergent risks discussed are those which have the potential to become key risks once sufficient understanding accumulates.

19.2.4. Identifying Key and Emergent Risks under Alternative Development Pathways

Key risks are determined by the interaction of climate-related hazards with exposure and vulnerabilities of societies or ecosystems. Development pathways describing possible trends in demographic, economic, technological, environmental, social and cultural conditions (Hallegatte *et al.*, 2011) will affect key risks because they influence both the likelihood and nature of climate-related hazards, and the societal and ecological conditions determining exposure and vulnerability. Therefore some risks could be judged to be key under some development pathways but not others. Emergent risks can depend on development pathways as well, since whether or not they become key risks may be contingent on future socio-economic conditions.

The effect of development pathways on climate-related hazards occurs through their effects on emissions and other radiative forcing factors such as land use change (see AR5 WGI Chapter 12). Components of development pathways such as economic growth, technical change, and policy will influence the rates and spatial distributions of emissions of greenhouse gases and aerosols, and of land use change, and therefore influence the magnitude, timing, and heterogeneity of hazards (see AR5 WGIII Chapter 5).

Development pathways will also influence the factors determining key vulnerabilities of human and ecological systems, including exposure, susceptibility or sensitivity to impacts, and adaptive capacity (Yohe and Tol, 2002; Füssel and Klein, 2006; Hallegatte *et al.*, 2011; O'Neill *et al.*, 2013; Birkmann *et al.*, 2013a). The magnitude of the aggregate exposure and sensitivity of socio-ecological systems will depend on population growth and spatial distribution, economic development patterns, and social systems. The particular elements of the social-ecological system that are most exposed and sensitive to climate hazards, and that are considered most important, will depend on spatial development patterns as well as on cultural preferences, attitudes toward nature/biodiversity, and reliance on climate-sensitive resources or services, among other factors (Adger, 2006; Füssel, 2009). The degree to which persistent or difficult to reverse vulnerabilities are built into social systems, as well as the degree of inequality in exposure and vulnerability across social groups or regions, also depend on characteristics of development pathways (Adger *et al.*, 2009).

19.2.5. Assessing Key Vulnerabilities and Emergent Risks

The criteria above for assessing vulnerability and risk provide a sequence of potential assessment steps. While the initial assessment phase would explore whether and how a society or social-ecological system is exposed to climate related hazards, the assessment would subsequently focus on the predisposition of societies or ecosystems to be adversely affected (vulnerability) and the potential occurrence of severe adverse consequences for humans and social-ecological systems once the hazard interacts with the vulnerability of societies and systems exposed. In addition, the importance of the system at risk and the ability of a society or system to cope and to adapt to these stressors would be assessed. Finally, the application of the criteria would also require the assessment of the irreversibility of the consequences and the persistence of vulnerable conditions. Hence, the assessment criteria for risks focus on the internal conditions of a person, a community (e.g. age structure, poverty), or a social-ecological system and the contextual conditions that influence their vulnerability (e.g. governance conditions and systems of norms), in addition to the assessment of hazards, such as storm intensity, heat waves, and sea level rise, which are directly influenced by climate change. Examples of such key vulnerabilities and key risks drawn from other chapters of this assessment are provided in section 19.6 and particularly Tables 19-4 and CC-KR.

19.3. Emergent Risk: Multiple Interacting Systems and Stresses

19.3.1. Limitations of Previous Approaches Imply Key Risks Overlooked

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, or with adaptation and mitigation actions affecting the same or a different sector are generally not included or well integrated into projections of risk (Warren, 2011). However, their consideration leads to the identification of a variety of *emergent risks* that were not previously assessed or recognized. This chapter identifies several such complex-system interactions that increase vulnerability and risk synergistically [Section 19.3, *high confidence*]. There are a very large number of potential interactions, and many important ones have not yet been quantified, meaning that some key risks have been overlooked [*high confidence*]. In some cases, literature analyzing these risks is very recent. The six interaction processes listed below, while not exclusive, are systemic and may lead to further key vulnerabilities as well as a larger number of less significant impacts. Several of these are discussed in more detail in the following sections.

- Biodiversity loss induced by climate change that erodes ecosystem services, in turn increasing vulnerability and exposure of human systems dependent on those services. (*19.3.2.1)*
- Alterations in extreme weather events induced by climate change which affect human systems and ecosystems, increasing vulnerability and exposure to the effects of mean climate change. Most impacts projections are based only on changes in mean climate (Rosenzweig and Hillel, 2008; IPCC, 2012a, Box 3-1).
- The interaction between non-climate stressors such as those related to land management, water management, air pollution (which has drivers in common with climate change) and energy production and climate change. Heretofore, mainly climate interactions with population/economic growth were assessed (*19.3.2.2).*
- Climate changes which increase human exposure and vulnerability to disease. *(19.3.2.3)*
- Locations where risks in different sectors are compounded because impacts, hazards, vulnerability, and exposure interact non-additively. (*19.3.2.4)*
- Mitigation or sectoral adaptation that has unintended consequences for the functioning of another sector. (*19.3.2.5)*

19.3.2. Examples of Emergent Risks

19.3.2.1. Emergent Risks Arising from the Effects of Degradation of Ecosystem Services by Climate Change

Biodiversity loss is linked to disruption of ecosystem structure, function and services (Cardinale, 2012; Díaz *et al.*, 2006; Gaston and Fuller, 2008; Maestre *et al.*, 2012; Midgley, 2012, Duraiappah *et al.*, 2005). Terrestrial and freshwater species face increased extinction risks under projected climate change during and beyond the 21st Century, especially as climate change interacts with other pressures (*high confidence*; Section 4.3.2.5). A large number of modelling studies project that species ranges decline in size as mean climate changes (Section 4.3.2.5), e.g., a global scale study of 50,000 species found that the range sizes of 57±6% of widespread and common plants and 34±7% of widespread and common animals are projected to decline by over 50% by the 2080s if global temperatures increase by 3.5^0C relative to pre-industrial times, when allowing for species to disperse at observed rates to areas that become newly climatically suitable (Warren *et al.*, 2013a). AR4 (Fischlin *et al*., 2007) estimated that "approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above preindustrial levels (*medium confidence*)." Evaluation of various lines of evidence including a range of modelling approaches and, since AR4, new and/or improved techniques (e.g., multi-factorial driven species distribution models, species specific population dynamics, tree-based and trait based modeling (for an overview see Bellard *et al.*, 2012, Table 1; also Staudinger *et al.*, 2012; Murray *et al.*, 2011; Dullinger *et al*., 2012; Foden *et al*., 2013), imply similar levels of risk as in AR4 with some new estimates indicating higher fractions of species at risk. However, there is *low agreement* on the completeness of these lines of evidence for assigning specific numerical values for fraction of species at risk (see Sections 19.5.1 and 4.3.2.5).

These extinction risks and possible declines in species richness are associated with change in mean climate, but ecosystems and species are also expected to be affected by projected climate-change induced increases in short-term extreme weather events and increased fire frequency in some locations (see IPCC, 2012a (SREX); AR5 WGI Table SPM.1; AR5 WGI Sections 12.4.3 and 12.4.5). Accordingly, despite the recognition of additional uncertainties in numerical estimates since AR4 (Section 4.3.2.5), the evidence for risk to a substantial fraction of species associated with increasing GMT is *robust*.

In both terrestrial and marine environments, the potential for the disruption of ecosystem functionality as a result of climate change translates into a key risk of large-scale loss of ecosystem services (Mooney *et al.*, 2009; Midgley, 2012; Table 19-4). At-risk services include water purification by wetlands, removal and sequestration of carbon dioxide by forests, crop pollination by insects, coastal protection by mangroves and coral reefs, regulation of pests and disease, and recycling of waste nutrients (Sections 4.3.4, 22.4.5.6, 27.3.2.1, Table 23-2, Box CC-WE; Chivian and Bernstein, 2008). Biodiversity loss can lead to an increase in the transmission of infectious diseases such as Lyme, Schistosoma and hantavirus in humans, and West Nile virus in birds, creating a newly identified dimension to the emergent risks resulting from biodiversity loss (Keesing *et al.*, 2010).

There are a number of examples of projected yield losses in the agricultural sector due to increased prevalence of pest species under climate change including *Fusarium graminearum* (a fungal disease of wheat), the European corn borer, the Colorado beetle, bakanae disease and leaf blights of rice, and Western corn root worm (Petzoldt and Seaman, 2006; Kocmankova *et al.*, 2010; Huang *et al.*, 2010; Chakraborty and Newton, 2011; Magan *et al.*, 2011; Aragón and Lobo, 2012); or declines in pollinators (Section 4.3.4; Rosenzweig and Hillel, 2008; Kuhlmann *et al.*, 2012; Giannini *et al.*, 2012; Abrol, 2012; Bedford *et al.*, 2012). Climate change impacts on pollinators places these valuable services at risk, and affects animals which are dependent upon the plants (see Chapter 4). Although the impacts of CO_2 fertilisation on plant-pathogen systems is not well understood (Section 7.3.2.3), these processes operate simultaneous with climate change's direct effects on yields through changing temperature, precipitation, and carbon dioxide concentrations, creating an emergent risk. Climate change has caused, or is projected to cause range expansion in weeds that have the potential to become invasive (Bradley *et al.*, 2010; Clements and Ditommaso, 2011). These can damage agriculture and threaten other species with extinction, with costs to economies being extremely high (e.g. $120 billion annually in the USA, Pimentel *et al.,* 2005; Crowl *et al.*, 2008). Although there are also examples of projected decreases in insect damage to crops, there is a tendency for risk of insect damage to plants to increase with climate change (section 7.3.2.3). Any one of the above mechanisms could result in harmful outcomes that act in synergy with existing climate change impacts on agriculture. Hence, these various susceptibilities to loss of ecosystem services comprise a key vulnerability, and in interaction with climate change, imply a potential key risk that global scale yields of a number of crops will be reduced by such interactions.

Severe decline of coral reefs (section 19.3.2.4) would result in widespread loss of income for many countries, for example $Au5.4 billion to the Australian economy from international tourism, and of US$1.6 billion to the US economy from damage to Florida's reefs (CC-CR). More generally, for many Small Island Developing States, increases in vulnerability due to loss of such ecosystem services interact with physical impacts of climate change such as sea level rise to create an emergent risk (*high confidence*).

Various studies of ecosystem services nationally or globally, illustrate the very large values that are attributed to these services (Table 19-1). Such costs are represented only very crudely in aggregate global models of the economic impacts of climate change where 'non-market impacts' are estimated very broadly if at all (Section 19.6.3.5). These costs contribute to the large magnitude of the risks to human systems resulting from loss of ecosystem services, which in some cases would be irreversible. Hence the increase in vulnerability due to loss of ecosystem services interacting with climate change hazards comprises a key risk (*high confidence*). In some regions (e.g., South America) payment for ecosystem services (PES) has been implemented to support landowners to maintain the provision of services over time (Section 27.6.2, Table 27-8). Studies on degraded ecosystems examine the cost of restoring ecosystem services. Willingness to pay to restore degraded services along the Platte River (US) (Loomis *et al.*, 2000) greatly exceeded estimated costs of restoration. A meta-analysis of 89 studies looking at the restoration of ecosystem services measured using 526 different metrics found that restoration increased the amount of biodiversity and ecosystem services by 44 and 25% respectively, but restored services were still lower than in intact ecosystems (Benayas *et al.*, 2009). Hence, restoration of damaged ecosystems may be cost-effective, but can only partially compensate for loss of services.

Concomitant stress from land use change adds to the extinction risk from climate change, increasing the projected extinction rate (e.g. Şekercioğlu *et al*., 2012) - and contributing to the emergent risk of ecosystem service loss. A synthesis of empirical studies across the globe reveals that ecosystem impacts due to land use change correlate locally with current maximum temperature and recent precipitation decline, indicating a potential for climate change to exacerbate the impacts of land use change (Mantyka-Pringle *et al.*, 2012; Chapter 4).

Land clearing releases carbon to the atmosphere and removes carbon sinks (AR5 WGI Section 6.4.3.3) such as old growth forests which would otherwise accumulate carbon (Luyssaert *et al.*, 2008). Studies that value ecosystem services have tended to underestimate the importance of carbon sinks in ecosystems, due to a tendency to consider only the carbon currently stored in the systems and not the fluxes (Anderson-Teixeira and DeLucia, 2011) and overlooking other aspects such as changes in albedo (e.g. Betts *et al.*, 2012).

[INSERT TABLE 19-1 HERE
Table 19-1: Examples of global and national ecosystem service valuation studies. This table is not intended to be comprehensive. Furthermore, it encompasses studies based on a wide range of methodologies.]

19.3.2.2. Emergent Risk Involving Non-Climate Stressors: the Management of Water, Land, and Energy

Human management of water, land, and energy interacts with climate change and its impacts, to profoundly affect risks to the amount of carbon that can be stored in terrestrial ecosystems, the amount of water available for use by humans and ecosystems, and the viability of adaptation plans for cities or protected areas. Failure to manage land, water and energy in a synergistic fashion can exacerbate climate change impacts globally (Wise *et al*., 2009; Searchinger *et al.*, 2008; Lotze-Campen *et al.*; 2010; Warren *et al.*, 2011) producing emergent risks which are also potential key risks. For example, the use of water by the energy sector, by thermo-electric power generation, hydropower and geothermal energy, or biofuel production, can contribute to water stress in arid regions (Kelic, 2009; Pittock, 2011). Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Sections 3.7.2, 7.3.2, 10.2, 10.3.4; McMahon and Price, 2011; Macknick *et al*., 2012a; Ackerman and Fisher, 2013). In irrigated agriculture, climate, crop choice and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Gerten *et al*., 2011). Recent studies address the energy, water, and land 'nexus' to explore risks to the agricultural and energy sectors (Tidwell *et al.*, 2011; Skaggs *et al.*, 2012; Smith *et al.*, 2013; Box CC-WE).

Biofuels can potentially mitigate GHG emissions when used in place of fossil fuels such as gasoline, diesel, and more carbon-intensive fuels from tar sands and heavy oil (Cherubini *et al.*, 2009). One simulation of stringent mitigation (e.g. RCP2.6, which constrains radiative forcing to 2.6 W/m^2 and therefore limits global mean temperature increase to 2°C over preindustrial levels during the 21st century) shows an increased reliance on biofuels (van Vuuren *et al.*, 2011). However, due to the potential negative consequences of its use as a mitigation strategy, bioenergy development leads to several emergent risks, which are summarized in Table 19-2. Systems that may be vulnerable to bioenergy development are food systems (*high confidence,* due to bioenergy feedstocks replacing food crops, see Table 19-2.iii, Sections 19.4.1.) and ecosystems (*high confidence*), where biofuel cropping can directly or indirectly induce land use change, displacing terrestrial ecosystems such as forests, which can otherwise also act as carbon sinks, see Table 19-2.i).

While *direct* land-use change (LUC) from impacts of biofuel development (from crop substitution and/or biofuel feedstock crop expansion, c) are a concern, *indirect* land-use change (iLUC) has received more attention in the literature – both due to the magnitude of its potential impact (twice as great as direct LUC, Mellilo *et al*., 2009) and controversy over the uncertainty in accurately quantifying it. iLUC connotes land-use change resulting from biofuel impacts on agricultural commodity markets (Fargione *et al.*, 2008; Searchinger *et al.*, 2008). Reductions of greenhouse gas emissions from biofuel production and use (compared to fossil fuels) may be offset partly or entirely for decades or centuries from iLUC-induced CO_2 emissions from deforestation and the draining of peatlands (*medium confidence,* IPCC, 2011 (SRREN), Chapter 2; Bringezu *et al.*, 2009; van Vuuren *et al.*, 2010, Miettinen *et al.*, 2012, Smith *et al.* 2013). In Brazil, further biofuel expansion would be expected to impinge upon the Cerrado, the Amazon and the Atlantic rainforest - all three of which have high levels of biodiversity (Table 19-2.v) and high levels of endemism (Lapola *et al.*, 2010). Another study of biofuel production in Brazil (Barr *et al.*, 2011) found that when pasture is accounted for, direct expansion into unexploited forest land is minor, i.e., most of additional cropland is predicted to come from conversion of pastureland. However, unless the density of livestock operations is increased in tandem, the latter can also lead to *i*LUC. To the extent that biofuel feedstock crops are grown on areas that were previously fallow or degraded, the iLUC effects might be minimized and CO_2 potentially sequestered (IPCC, 2011 (SRREN); Fargione *et al.*, 2010) – although the amount, alternative uses, and potential productivity of so-called degraded lands are still contested (Dauber *et al.*, 2012). (For more information on the effects of biofuel production on terrestrial ecosystems see 4.4.4; for more information on the effects of land acquisition for biofuel production on the poor, see 13.3.1.4)

Whether such land management dynamics confound or contribute to mitigation depends on important interactions with global emissions mitigation policies (Table 19-2.ii, Van Vuuren *et al.*, 2011). A failure to include land use change emissions within a carbon mitigation regime – for example by applying a carbon price to fossil fuel and industrial emissions only – has been projected to lead to large-scale deforestation of natural forests and conversion of many other natural ecosystems by the end of the 21st century in 450 ppmv CO_2-e and 550 ppmv CO_2-e scenarios (Wise *et al.*, 2009; Mellilo *et al.* 2009a). This dynamic is due primarily to enhanced bioenergy production without a corresponding incentive to limit the resulting land use change emissions. If, instead, an equal carbon price is applied to terrestrial carbon (which, however, presents monitoring difficulties) along with fossil and industrial carbon, deforestation could slow down or even reverse.

That said, there are many equally compelling reasons for a country to encourage biofuel production including: a means to produce downward pressure on oil prices, rural development and reduced oil imports – all of which could be prioritized over biofuels as a GHG mitigation strategy depending on the country (Cherubini *et al.*, 2009). Per-litre GHG emissions from biofuels *decrease* as agriculture is further intensified through row cropping, fertilizer and pesticide use, and irrigation, while other per-litre environmental impacts like eutrophication *increase* (Burney *et al.*, 2010; Grassini and Cassman, 2012). This creates an implicit conflict between alternative development priorities. Second-generation biofuels, such as those based on non-food crops (grasses, algae, timber) and agricultural residues, are expected to offer reduced emissions of GHG and other air pollutants compared to most first-generation biofuels. This is due primarily to their having a smaller adverse interaction with food systems resulting in less LUC and *i*LUC (Plevin, 2009; Cherubini and Ulgiati, 2010; Fargione, 2010; Sander and Murthy, 2010). Further, bioelectricity and biogas both may be more effective at mitigating GHG emissions than liquid biofuels (Power and Murphy, 2009; Campbell *et al.*, 2009).
Other emergent risks from bioenergy development are summarized in Table 19-2. Nearly all of the risks presented here are driven by the increased need for raw agricultural feedstocks. Competition for cultivable lands, irrigation resources (CC-WE), and other inputs are not unique to biofuel related issues. The approximate doubling of agricultural demand projected between 2005 and 2050 (Tilman *et al.*, 2011) similarly increases competition for land and water, and would be expected to exacerbate greenhouse gas emissions from agriculture (see also AR5 WGI Section 8.3.5).

[INSERT TABLE 19-2 HERE
Table 19-2: Emergent risks related to biofuel production as a mitigation strategy.]

Projected changes in the hydrological cycle due to climate change (AR5 WGI Section 12.4.5) combined with increasing water demand leads to an emergent, potentially key risk of water stress exacerbated by the reduction of groundwater which serves as ‘an historical buffer against climate variability’ (Green *et al.*, 2011), and potentially further exacerbated by existing governance constraints which can act as barriers to reduce vulnerability. Climate change and increasing food demand are expected to drive expansion of irrigated cropland (Wada *et al.* 2013), increasing the demand for energy intensive extraction and conveyance of (ground or desalinated sea) water for irrigation (CC-WE). If water is provided through groundwater extraction, pumping, or construction and use of de-salinisation plants, local energy demand (and greenhouse gas emissions) will increase, although advanced irrigation systems are available that minimize enhancement of emissions (Rothausen and Conway, 2011).

A further potential key risk arises from increased water stress due to unsustainable groundwater extraction, which is expected to increase as an adaptation to climate change. Groundwater extraction is generally increasing globally with particularly large extraction in India and China (Wang *et al.*, 2012b). The effects of climate change on groundwater are varied with some areas expecting decreased recharge whilst others are projected to experience increased recharge (Green *et al.*, 2011; Portmann *et al*., 2013). Where extraction rates increase or recharge decreases, water tables will be depleted with potential key risks to local ecosystems and human systems (such as agriculture, tourism and recreation), while water quality will decrease. One projection shows insufficient water availability in Africa, Latin America and the Caribbean to satisfy both agricultural demands and ideal environmental flow regulations for rivers by 2050, a situation that is exacerbated by climate change (Strzepek and Boehlert, 2010).

19.3.2.3. Emergent Risks Involving Health Effects

Climate change will act through numerous direct and indirect pathways to alter the prevalence and distribution of diseases that are climate and weather sensitive. These effects will differ substantially depending on baseline epidemiologic profiles, reflecting the level of development and access to clean and plentiful water, food and adequate sanitation and health care resources. Furthermore, the impact of climate change will differ within and between regions, depending upon the adaptive capacity of public health and medical services and key infrastructure that ensures access to clean food and water.

A principal emergent global public health risk is malnutrition secondary to ecological changes and disruptions in food production as a result of changing rainfall patterns, increases in extreme temperatures (IPCC, 2012a; Sections 7.3.2.5, 11.6.1; *high confidence*), and increased atmospheric CO_2 (Taub *et al.*, 2008; Lobell and Burke, 2010). Modeling of the magnitude of the effect of climate change on future under-nutrition in five regions in South Asia and sub-Saharan Africa in 2050 (using SRES A2 emissions scenario) suggests an increase in moderate nutritional stunting, an indicator linked to increased risk of death and poor health (Black *et al.*, 2008), of 1% to 29%, depending of the region assessed, compared to a future without climate change, and a much greater impact on severe stunting for particular regions, such as 23% for central sub-Saharan Africa and 62% for south Asia (Lloyd *et al.*, 2011). The impact of climate induced drought and precipitation changes in Mali include the southward movement of drought-prone areas which would result in a loss of critical agriculturally-productive land by 2025 and increase food insecurity (Jankowska *et al.*, 2012).

In densely populated megacities, especially those with a pronounced urban heat island effect, a principal emergent health risk results from the synergistic interaction between increased exposure to extreme heat and degraded air quality with the convergence of increasing vulnerability of an aging population and a global shift to urbanization (Sections 8.2.3.5, 8.2.4.6,11.5.3, CC-HS; *high confidence*). These trends will increase the risk of relatively higher mortality from exposure to excessive heat (Knowlton *et al.*, 2007, Luber and McGeehin, 2008, Kovats and Hajat, 2008). The health risks of such interactions include increased injuries and fatalities as a result of severe weather events including heat waves (see Section 19.6.3.3); increased aeroallergen production in urban areas leading to increases in allergic airway diseases (see Section 19.5.3); and respiratory and cardiovascular morbidity and mortality secondary to degraded air quality and ozone formation (see Section 19.6.3.3). While the association between ambient air quality and health is well established, there is an increasingly *robust* body of evidence linking spikes in respiratory diseases to weather events and to climate change. In New York City, for example, each single degree (Celsius) increase in summertime surface temperature has been associated with a 3% increase in same-day hospitalizations due to respiratory diseases, and an increase of up to 3.6% in hospitalizations due to cardiovascular diseases (Lin *et al.*, 2009). Respiratory health outcomes will be exacerbated by climate change through increased production and exposure to ground-level ozone (particularly in urban areas), wildfire smoke, and increased production of pollen (D'Amato *et al.*, 2010).

19.3.2.4. Spatial Convergence of Multiple Impacts: Areas of Compound Risk

In this chapter, we define an *area of compound risk* as a region where climate-change induced impacts in one sector affects other sectors in the same region, or a region where climate change impacts in different sectors are compounded, resulting in extreme or high-risk consequences. The frequent and ongoing spatial and temporal coincidence of impacts in different sectors in the same region has consequences that are more serious than simple summation of the sectoral impacts indicates (*medium confidence*). Such synergistic processes are difficult to identify through sectoral assessment and are apt to be overlooked in spite of their potential importance in considering key vulnerabilities and risks. For example, a large flood in a rural area may damage crop fields severely, causing food shortages (Stover and Vinck, 2008). The flood may simultaneously cause a deterioration of hygiene in the region and the spread of water borne diseases (Schnitzler, 2007; Hashizume *et al.*, 2008; Kovats and Akhtar, 2008). The coincidence of disease and malnutrition can thus create an area of compound risk for health impacts, with the elderly and children most at risk.

As a systematic approach, identification of areas of compound risk could be achieved by overlaying spatial data of impacts in multiple sectors, but this cannot indicate synergistic influences and dynamic changes in these influences quantitatively. For global analysis, certain types of integrated assessment models which allow spatial analysis of climate change impacts have been used to identify regions that are affected disproportionately by climate change (MNP, 2006; Kainuma *et al.*, 2007; Warren *et al.*, 2008; Füssel, 2010). Recent efforts attempt to collect and archive spatial data on impact projections and facilitate their public use. These have created overlays for identifying areas of compound risk with web-GIS technology (Adaptation Atlas (Resources for the Future, 2009). There are also efforts to coordinate impacts assessments adopting identical future climatic and/or socio-economic scenarios at various spatial scales (Parry *et al.*, 2004; Piontek *et al.*, 2013). Areas of compound risk identified by overlaying spatial data of impacts in multiple sectors can be used as a starting point for regional case studies on vulnerability and multifaceted adaptation strategies (Piontek *et al.*, 2013).

General equilibrium economic models (see Chapter 10) may facilitate quantitative evaluation of synergistic influences. An analysis of the EU by the PESETA project (Projections of economic impacts of climate change in sectors of Europe based on bottom-up analysis) showed sub-regional welfare loss by considering impacts on agriculture, coastal system, river floods, and tourism together in the CGE (Computable General Equilibrium) model, which is designed to represent interrelationships among economic activities of sectors. The result indicated the largest percentage loss due to climate change in Southern Europe (Ciscar *et al.*, 2011).

[INSERT FIGURE 19-2 HERE
Figure 19-2: Some examples of areas of compound risk identified in this assessment. Symbols indicate one or two of the main sectors or systems subject to compound risk but in each case, additional sectors and systems are at risk.]

The following examples illustrate different types of areas of compound risk where climate change impacts coincide and interact:

1) **Cities in deltas,** which are subject to sea level rise, storm surge, coastal erosion, saline intrusion and flooding. Extreme weather events can also disrupt access to food supplies, enhancing malnutrition risk (Ahmed *et al.*, 2009; Section 19.3.2.3). Based on national population projections, if contemporary rates of effective sea level rise (a net rate, defined by the combination of eustatic sea-level rise and local contributions from fluvial sediment deposition and subsidence and subsidence due to groundwater and hydrocarbon extraction) continue through 2050, over 6 million people would be at risk of enhanced inundation and increased coastal erosion in three megadeltas and 8.7 million in 40 deltas, absent measures to adapt (Ericson *et al.*, 2006). Examples of urbanized delta areas at risk include, for example, those where Mumbai and Dhaka are located (see Chapter 8, Chapter 24, Section 19.6.3.4, Table 19-4).
2) **The Arctic,** where indigenous people (Crowley, 2011) are projected to be exposed to the disruption, and possible destruction of, their hunting and food sharing culture (see Chapter 28). Risk arises from a combination of sea ice loss and the concomitant local extinctions of the animals dependent upon the ice (Johannessen and Miles, 2011). Thawing ground also disrupts land transportation, buildings and infrastructure whilst exposure of coastal settlements to storms also increases due to loss of sea ice. Arctic ecosystems are broadly at risk (Kittel *et al.*, 2011).
3) **Coral reefs,** which are highly threatened due to the synergistic effects of sea surface temperature rise and perturbed ocean chemistry, reducing calcification and also increasing sensitivity to other impacts such as the loss of coral symbionts (Chapter 6). The importance of reef sensitivity to climate change was recently highlighted in the near-equatorial Indo Pacific, the area of greatest reef diversity worldwide (Lough, 2012). A second highly diverse reef system at risk for warming was identified around Micronesia, Mariana Island and Papua New Guinea (Meissner *et al.*, 2012).

In Figure 19-2, these and other examples of areas of compound risk identified in this assessment are indicated on a world map. The map focuses on the key role that exposure plays in determining risk, particularly compound risk, rather than vulnerabilities per se.

19.4. Emergent Risk: Indirect, Trans-Boundary, and Long-Distance Impacts

Climate change impacts can have consequences beyond the regions in which they occur. Global trade systems transmit and mediate a variety of impacts – the most prominent example of this is the global food trade system. The competitive market forces which dominate trade do not account for considerations of justice, and thus can incidentally diminish or enhance inequality in the distribution on impacts (see 19.6.3.4). Where prices on food, land, and other resources increase, vulnerability increases, *ceteris paribus*, for those most in need and least able to pay (see section 19.6.1.2 on differential vulnerability). Additionally, both mitigation and other adaptation responses have unintended consequences beyond the locations in which they are implemented (Oppenheimer, 2013). All of these mechanisms can create emergent risks (*high confidence*).

19.4.1. Crop Production, Prices, and Risk of Increased Food Insecurity

Recent literature indicates that climate trends have already influenced the yield trends of important crops (e.g. Kucharik and Serbin, 2008; Tao *et al.*, 2008; Brisson *et al.*, 2010 and Lobell *et al.*, 2011). Chapters 7 and 18 provide a detailed overview of these impacts, and have assessed with *medium confidence* that the effects of climate trends on maize and wheat yield trends have been negative in many regions over the past several decades, and have been small for major rice and soybean production areas (see Sections 7.2.1.1. and 18.4.1.1.). For projected impacts, “Without adaptation, local temperature increases in excess of about 1^{o}C above pre-industrial is projected to have negative effects on yields for the major crops (wheat, rice and maize) in both tropical and temperate regions, although individual locations may benefit (*medium confidence*) (7.4, Figures 7-4,7-5,7-7)” (Chapter 7 ES). Across all studies projecting crop yield impacts (some of which include both CO_2 fertilization and adaptation, and some which account for only one or neither of these), negative impacts on average yields become *likely* from the 2030s (Figure 7-5). Median yield impacts of 0 to -2% per decade are projected for the rest of the century (compared to yields without climate change) (Figure 7-7), and after 2050 the risk of more severe impacts increases (*medium confidence*) (Chapter 7 ES, Figure 7-5). Among the smaller number of studies that have projected global yield and price impacts, negative net effects of climate change, CO_2 increases, and agronomic adaptation on global yields are *about as likely as not* by 2050 and *likely* later in the 21st century.

Climate impacts on crop production influence food prices directly and through complex interactions with a variety of factors, including biofuel crop production and mandates, as well as other domestic policies like crop export bans (Sections 7.1.2, 7.2.2, 7.4.4). If climate changes reduce crop yields, international food prices and the number of food insecure people are expected to increase globally (*limited evidence*, *high agreement*, Section 7.4.4). For example, global rice prices exhibit sensitivity both to yield impacts from climate changes as well as the loss of arable land to sea level rise (Chen *et al*., 2012). While the evidence base of how climate change will affect future food consumption patterns is limited (Section 7.3.3.2.), there are large numbers of households that would be especially vulnerable to a loss of food access if food prices were to increase, for example, agricultural producers in low-income countries who are net food buyers (Section 7.3.3.2, Table 7-1).

In addition to the direct impacts of climate change, biofuel production in service of climate change mitigation may also affect food prices. Accurately tracking and quantifying the direct and indirect impacts of biofuel production on the food-system has become an intense area of study since AR4. As witnessed in the United States, US maize-ethanol production increased 800% since 2000, with maize commodity prices more than tripling and harvested land growing by more than 10%, mainly at the expense of soy (EIA, 2013). Ethanol recently consumed one quarter of US maize production, even after accounting for feed by-products returned to the market (USDA, 2013). However, isolating biofuels’ exact contribution to food-system changes from other factors such as extreme weather events, climate change, changing diets, and increasing population have proven difficult (Zilberman et al., 2011). Still, estimates of the supply and demand elasticity of basic grain commodities lead to a prediction that the 2009 US Renewable Fuel standard could increase commodity prices of maize, wheat, rice, and soybeans by roughly 20%, *ceteris paribus*, assuming one third of the calories used in ethanol production can be recycled as animal feed

(Roberts and Schlenker, 2013). More generally, there is *high confidence* that pressure on land use for biofuels will further increase food prices (see Table 19-2.iii).

In summary, through the global food trade system, climate change impacts on agriculture can have consequences beyond the regions in which those impacts are directly felt. Food access can be inhibited by rising food price levels and volatility (Sections 7.3.1. and 7.3.3.2), as demonstrated during the recent 2007-2008 price rise episode that resulted from the combination of poor weather in certain world regions combined with a demand for biofuel feedstocks, increased demand for grain-fed meat, and historically low levels of food stocks (Abbot and Borot de Battisti, 2011; Adam and Ajakaiye, 2011; Figure 7-3). These episodes provide an analog elucidating how reduced crop yields due to impacts of climate variability and biofuel cropping work synergistically to create a risk of increased food insecurity: hence this interaction of climate change and mitigation actions with the food system via markets comprises an *emergent risk* of the impacts of climate change acting at a distance, affecting the food security of vulnerable households (Section 7.3.3.2.).

19.4.2. Indirect, Trans-boundary, and Long-Distance Impacts of Adaptation

Risk can also arise from unintended consequences of adaptation (see Section 14.7), and this can act across distance, if for example, there is migration of people or species from one region to another. Adaptation responses in human systems can include land use change, which can have both trans-boundary and long distance effects; and changes in water management, which often has downstream consequences.

19.4.2.1. Risks Associated with Human Migration and Displacement

Human migration is one of many possible adaptive strategies or responses to climate change (Reuveny, 2007; Piguet 2010; Tacoli, 2009; McLeman, 2011), assessed in detail in Chapter 12 in the context of the many other causes of migration. Displacement refers to situations where choices are limited and movement is more or less compelled by land loss due to sea level rise or extreme drought, for example (see Section 12.4). A number of studies have linked past climate variability to both local and long distance migration (see review by Lilleør and Van den Broeck, 2011). In addition to yielding positive and negative outcomes for the migrants, migration indirectly transmits consquences of climate variability and change at one location to people and states in the regions receiving migrants, sometimes at long distances. Consequences for receiving regions, which can be assessed by a variety of metrics, could be both positive and negative, as may also be the case for sending regions (McLeman, 2011; Foresight, 2011; Chapter 12). A rapidly growing literature examines potential changes in migration patterns due to future climate changes, but projections of specific positive or negative outcomes are not available. Furthermore, recent literature underscores risks previously ignored: risks arising from the lack of mobility in face of a changing climate, and risks entailed by those migrating into areas of direct climate-related risk, like low-lying coastal deltas (Foresight, 2011; see Section 12.4.1.2).

Climate change induced sea level rise, in conjunction with storm surges and flooding, creates a threat of temporary and eventually permanent displacement from low-lying coastal areas, the latter particularly the case for small island states (Pelling and Uitto 2001; Chapter 12). The distance and permanence of the displacement will depend on whether governments develop strategies such as relocating people from highly vulnerable to less vulnerable areas nearby, and conserving ecosystem services which provide storm surge protection (Perch-Nielsen, 2004) in addition to so-called "hardening" including building sea walls and surge barriers [CC-EA]. Numbers of people at risk from coastal land loss have been estimated on a regional basis (Nicholls and Tol, 2006; Ericson *et al.*, 2006; Nicholls *et al.*, 2011) yet projections of resulting anticipatory migration or permanent versus temporary displacement are not available.

Taken together, these studies indicate that climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). Urbanization is a pervasive aspect of recent migration which brings benefits but, in the climate change context, also significant risks (see 19.2.3, 19.6.1, 19.6.2; 19.6.3.3; 8.2.2.4). While the literature projecting climate-driven migration has grown recently (Chapter 12.4), there is as of yet insufficient literature to permit assessment of projected region-specific consequences of such migration. Nevertheless, the potential for negative outcomes from migration in such complex, interactive situations is an emergent risk of climate change, with the potential to become a key risk (CC-KR).

19.4.2.2. Risk of Conflict and Insecurity

Violent conflict between individuals or groups arises for a variety of reasons (Section 12.5). Factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change and variability (*high confidence*; Sections 12.5.1, 12.5.2; 13.2). In this section, we focus on evidence for the magnitude of a climate effect on violent conflict in order to assess its potential to become a key risk.

The only meta-analysis of the literature (Hsiang *et al.*, 2013), examining 60 quantitative empirical studies generally published since AR4, implicates climatic events as a contributing factor to the onset or intensification of several types of personal violence, group conflict and social instability in contexts around the world, at temporal scales ranging from a climatologically anomalous hour to an anomalous millennium and at spatial scales ranging from the individual level (Vrij *et al*., 1994; Ranson, 2012) to the communal level (Hidalgo *et al.*, 2010; O'Loughlin *et al*., 2012) to the national level (Burke *et al*., 2009; Dell *et al*., 2012) to the global level (Hsiang *et al.*, 2011). Nevertheless, some individual studies have been unable to obtain evidence that violence has a statistically significant association with climate (Buhaug, 2010; Theisen *et al.* 2011). In detection and attribution of their impact on human conflict, there is *low confidence* that climate change has an effect (Section 18.4.6) and *medium confidence* that climate variability has an effect.

Evidence suggests that climatic events over a large range of time and spatial scales contribute to the likelihood of violence through multiple pathways discussed in section 12.5 (Scheffran *et al*., 2012; Bernauer *et al.*, 2012; Hsiang and Burke, 2013). Results from modern contexts (1950-2010) indicate that the frequency of violence between individuals rises 2.3% and the frequency of intergroup conflict rises 13.2% for each standard deviation change towards warmer temperatures (Hsiang *et al.*, 2013). Because annual temperatures around the world are expected to rise 2-4 standard deviations (as measured over 1950-2008) above temperatures in 2000 by 2050 (A1B scenario) (Hsiang *et al.*, 2013), there is potential *ceteris paribus* for large relative changes to global patterns of personal violence, group conflict and social instability in the future.

Social, economic, technological, and political changes that might exacerbate or mitigate this potential impact are discussed in Chapter 12. These changes may cause future populations to respond to their climate differently than modern populations; however the influence of climate variability on rates of conflict is sufficiently large in magnitude that such advances may need to be dramatic to offset the potential influence of future climate changes.

The effect of climate change on conflict and insecurity has the potential to become a key risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change (*medium confidence*; Sections 12.5.1, 12.5.2, 13.2) and in numerous statistical studies the influence of climate variability on human conflict is large in magnitude (*medium confidence*).

19.4.2.3. Risks Associated with Species Range Shifts

One of the primary ways species adapt to climate change is by moving to more climatically suitable areas (range shifts). These shifts will affect ecosystem functioning, potentially posing risks to ecosystem services (Dossena *et al.*, 2012; Millennium Ecosystem Assessment, 2005; *medium confidence*), including those related to climate regulation and carbon storage (Wardle *et al.*, 2011). One example of a key impact is the warming-driven expansion and intensification of Mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in North American pine forests and its current and projected impacts on carbon regulation and economies (Section 26.4.2.1). Risks also arise from projected range shifts of important resource species (e.g. marine fishes; Sections 6.3.6, 6.4.6.1), as well as from potential introductions of diseases to people, livestock, crops and native species (see Sections 7.3.2.3, 28.2.3, 23.4.2, 26.6.1.6, 5.4.2.3, 22.3.5). Many newly arrived species prey on, outcompete or hybridize with existing biota (e.g., by becoming weeds or pests in agricultural systems, Section 4.2.4.6) . The ecological implications of species reshuffling into novel, no-analogue communities largely remain unknown and pose additional risks that cannot yet be assessed (Root and Schneider 2006; Sections 6.5.3, 19.5.1, 21.4.3).

Current legal frameworks and conservation strategies face the challenge of untangling desirable species range shifts from undesirable invasions (Webber and Scott, 2012), and identifying circumstances when movement should be facilitated versus inhibited. New agreements may be needed recognizing climate change impacts on existing, new, or altered trans-boundary migration, (e.g., under the Convention on Migratory Species). As target species and ecosystems move, protected area networks may become less effective, necessitating re-evaluation and adaptation, including possible addition of sites, particularly those important as either 'refugia' or migration corridors (Warren *et al*., 2013a; Sections 9.4.3.3, 24.4.2.5, 24.5.1). Assisted colonisation – moving individuals or populations from currently occupied areas to locations with higher probability of future persistence – is arising as a potential conservation tool for species unable to track changing climates (Sections 4.4.2.4, 21.4.3). The value of these approaches, however, is contested and implementation is very limited giving *low confidence* that this would be an effective technique (Loss *et al.*, 2011). *Ex situ* collections (Section 4.4.2.5) have often been put forward as fall-back resources for conserving threatened species, yet the expense and the relatively low representation of global species and genetic diversity (Balmford *et al*., 2011; Conde *et al.*, 2011) minimizes the effectiveness of this technique.

19.4.3. Indirect, Trans-Boundary, and Long-Distance Impacts of Mitigation Measures

Mitigation, too, can have unintended consequences beyond its boundaries, which may affect natural systems and/or human systems. If mitigation involves a form of land use change, then regional implications can ensue in the same way as they can for adaptation (see Section 14.7).

Mitigation can potentially reduce direct climate change impacts on biodiversity (Warren *et al.*, 2013a). However, impacts on biodiversity as a result of land use change induced by biofuel production can offset benefits associated with biofuels (see Box 4.1, Sections 4.2.4.1, 9.3.3.4, 19.3.2.2, 22.6.3, 24.6, Box 25-10, 27.2.2.1). Climate change mitigation through 'clean energy' substitution can also have negative impacts on biodiversity. However, attention to siting and monitoring can decrease some negative ecological and socioeconomic impacts (*medium confidence*) while maximizing positive ones (Section 4.4.4). For example, the U.S. Government performed an intensive study of suitable sites for solar power on public lands in the western U.S. The end result opened 285,000 acres of public land for large-scale solar deployment while blocking development on 78 million acres to protect "natural and cultural" resources (US BLM, 2012). The construction of large hydroelectric dams can affect both terrestrial and aquatic ecosystems along river systems (World Commission on Dams, 2000; Sections 3.7.2.1, 4.4.4, 24.4.2.3, 24.9.1).

Mitigation strategies will have a range of effects on human systems. Reforestation that properly mimics existing forest ecosystems in structure and composition would potentially benefit human systems by stabilizing micro-climatic variation (Canadell and Raupach, 2008) and allowing benefits from the sustainable harvest of non-timber forest products for food, medicine and other marketable commodities (Guariguata *et al.*, 2010). However, there is a generally longer time frame and greater expense involved in recreating a diverse forest system. Afforestation creates a similar set of costs and benefits (Sections 3.7.2.1, 17.4.1, 22.3.2.1, 22.6.3). Mitigation strategies designed to reduce dependence on carbon-intensive fuels present a very different set of circumstances in relation to human systems. The development of alternative and renewable energy sources will have significant economic and market effects potentially influencing food prices (see also Section 19.4.1). This would especially affect populations that already devote a considerable portion of their household income to food (Hymans and Shapiro, 1976).

19.5. Newly Assessed Risks

Newly assessed risks are those for which the evidence base in the scientific literature has only recently become sufficient to allow for assessment. Furthermore, these risks have at least the potential to become key based on the criteria in 19.2.2. Several of the emergent risks discussed in sections 19.3 and 19.4., including those associated with human migration [19.4.2.1] and mitigation measures [19.4. 3], can be considered newly assessed. Others are related to diverse aspects of climate change, including the impacts of a large temperature rise, ocean acidification and other direct consequences of CO_2 increases, and the potential impacts of geoengineering implemented as a climate change response strategy.

19.5.1. Risks from Large Global Temperature Rise >4°C Above Pre-Industrial Levels

Most climate change impact studies focus on climate change scenarios corresponding to global mean temperature rises of up to 3.5°C relative to 1990 (slightly more than 4°C above pre-industrial levels) with only a few examples of assessments of temperature rise significantly above that level (Parry *et al.*, 2004; Hare, 2006; Warren *et al.*, 2006; Fischlin *et al.*, 2007; Easterling *et al.*, 2007). Recently the potential for larger amounts of warming has received increasing attention and preliminary assessment of impacts above that level of warming is possible for agriculture, ecosystems, water, health and large-scale singular events. In this section all temperature changes are global and relative to pre-industrial levels. Relevant climate scenarios include those based on RCP8.5, which in 2081-2100 is projected to result in a temperature rise of 4.3+/- 0.7 °C with temperature above 4°C *as likely as not* (WGI section 12.4.1, Table 12.3), and some simulations using SRES A2 and A1FI, which can reach 5.9 and 6.9°C warming, respectively, by 2100 (AR4 WG1 SPM). Literature that uses these scenarios but assumes low climate sensitivity and hence less than 4°C of warming is excluded.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more (Section 7.4.1). Among these, one indicates substantial reductions in yields in sub-Saharan Africa (Thornton *et al.*, 2011) and another indicates reversal of gains in yields and substantial reductions for Finland (Rötter *et al.*, 2011). Other studies at or below 4 °C anticipate yield losses, particularly in tropical regions, even when taking agronomic adaptations into account (Section 7.5.1.1.1). The possibility of compensation for these losses due to other responses of the food system to impacts on production, such as land use change and adjustment of trade patterns, cannot yet be adequately assessed for a world with GMT>4°C (Sections 19.6.3.4 and 19.4.1).

Assessments of ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*, 19.3.2.1, 4.3.2.5). AR4 estimated that 20-30% of species were likely at increasingly high risk of extinction as global mean temperatures exceed a warming of 2-3°C above pre-industrial levels (*medium confidence*; Fischlin *et al*., 2007); hence 4°C warming implies further increases to extinction risks for an even larger fraction of species. However, there is *low agreement* on the numerical assessment since as more realistic details have been considered in models, it has been shown that extinction risks may be either under- or overestimated when using the simpler models (Section 4.3.2.5), among other reasons due to the existence of microrefugias or to delay in population decline leading to extinction debts (e.g. Dullinger *et al.*, 2012). Additional risks include biome shifts of 400km (Gonzalez *et al*., 2010), the disappearance of analogs of current climates in regions of exceptional biodiversity in the Himalayas, Mesoamerica, E and S Africa, the Philippines and Indonesia (Beaumont *et al.*, 2011), and loss of more than half of the climatically determined geographic ranges of 57+/-6% of plants and 34+/-7% of animals studied (Warren *et al*., 2013a). Widespread coral reef mortality is expected at 4°C due to the concomitant effects of warming and a projected decline of ocean pH of 0.43 since preindustrial times (AR5 WG1 TS, AR5 WGII 5.4.2.4, Box CC-CR, Box CC-OA, *high confidence*). The corresponding CO_2 concentration in such a scenario is more than 900 ppm (AR5 WG1 Figure 12.36) whereas the onset of large scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.1.6, 5.4.2.4, 26.4.2.1).

A number of studies project increases in water stress, flood and drought in a number of regions with > 4°C warming, and decreases in others (Li *et al.*, 2009; Arnell, 2011; Fung *et al.*, 2011; Dankers *et al.*, 2013; Gerten *et al*., 2013; Gosling and Arnell 2013). For example, projections of the proportion of global population exposed to water stress due to climate change range from 5-50% (Gosling and Arnell, 2013) by 2100. The proportion of cropland exposed to drought disaster (one or more months with PDSI drought indicator below -3) is projected to increase from 15% today to 44+/-6% by 2100, based on a range of projections including some that reach or exceed 4°C global warming (Li *et al*., 2009). Concurrently irrigation water demand in currently cultivated areas in the N. hemisphere is projected to rise by 20% in the summer by 2100 under RCP8.5 due to climate change alone (Wada *et al.* 2013), although this could be partly buffered by decreasing evapotranspiration due to plant physiological responses to increased atmospheric CO_2 (Konzmann *et al*., 2013; Box CC-VW). One study (Portmann *et al*., 2013) projects 27-50% of global population affected by a >10% decrease in groundwater recharge, mostly in water stressed arid areas, and although 20-45% also receive a >10% increase, this occurs mainly in areas of low population density where water stress is not an issue. Annual runoff is projected to fall by up to 75% across the Danube, Mississippi, Amazon and Murray Darling river basins, and to increase by up to 100% in the Nile and Ganges basins (Fung *et al.*, 2011) with 4°C warming. Under RCP8.5 in 2100, nine global hydrological models driven by five global circulation models project increases in flood frequency in over half of the land surface, and decreases in roughly a third of the land surface (Dankers *et al*., 2013). According to one study, even if human population remained constant in Europe, without adaptation, 3.5°C –4.8°C global warming by the 2080s would expose an additional 250,000 – 400,00 people to river flooding, doubling economic damages since the 1970s, and expose an additional 851,000 – 5,552,000 to coastal flooding (Ciscar *et al.*, 2011), compared to 36,000 in 1995.

Under 4°C warming most of the world land area will be experiencing 4-7°C higher temperatures than the recent past which means that important tipping points for health impacts may be exceeded in many areas of the world during this century, including coping mechanisms for daily temperature/humidity making potentially large areas seasonally uninhabitable for normal human activities, including growing food or working outdoors [11.8] (*high confidence*). Exceedance of human physiological limits is projected in some areas for a global warming of 7°C, and in most areas for global warming of 11-12°C (*low confidence,* Sherwood and Huber, 2010), a temperature increase that is possible by 2300 (AR5 WGI Figure 12.5).

The risk of large-scale singular events such as ice sheet disintegration, methane release from clathrates, and regime shifts in ecosystems (including Amazon dieback), is higher with increased warming (and therefore higher above 4°C than below it) although there is *low confidence* in the temperature changes at which thresholds might exist for these processes (Section 19.6.3.6; AR5 WGI Sections 12.4.5, 12.5.5, and 13.4). There are also more gradual changes that become large with global temperature rise of 4^0C or more, such as decline in the Atlantic Meridional Overturning Circulation (AMOC) and release of carbon from thawed permafrost (CTP). The AMOC is considered *very likely* to weaken for such warming, with best estimates of loss over the 21^{st} century under RCP8.5 ranging from 36-44% (AR5 WGI Sections 12.4.7.2 and 12.5.5.2). The best estimated range for CTP by 2100 is from 50 to more than 250 PgC for RCP8.5 (AR5 WGI Section 6.4.3.4) although there are large uncertainties. Larger decreases in AMOC and increases in CTP are thus implied for a global warming of above 4°C. Similarly, since a nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5, by which time projected GMT rise amounts to 2.0 ± 0.4°C above the 1986-2005 baseline (*medium confidence,* AR5 WGI Section 12.4.61), the likelihood is even higher for global warming of above 4°C. Regions of the boreal forest could witness widespread forest dieback (*low confidence*) putting at risk the boreal carbon sink, estimated at 0.5 Pg $year^{-1}$ in 2000-2007 (AR5 WGI Section 12.5.5; AR5 WGII Section 4.3.3.1.1). Forest susceptibility to fire is projected to increase substantially in many areas for the high emissions scenario (RCP 8.5, Box 4-3) and hence larger changes are implied for global warming above 4°C.

Based on the assessment in this section, we conclude that climate change impacts at 4°C and above would be of greater magnitude and more widespread than at lower levels of global temperature rise (*medium evidence, high agreement, high confidence*), extending to higher temperature levels previous findings that risks increase with increasing global average temperature (AR4 WGII SPM.2; NRC, 2011). Few studies yet consider the interactions between these effects, which could create significant additional risks (Warren *et al.*, 2011; Section 19.7.5).

19.5.2. Risks from Ocean Acidification

Ocean acidification is defined as "a reduction in pH of the ocean over an extended period, typically decades or longer, caused primarily by the uptake of carbon dioxide from the atmosphere" (AR5 WGI 3.3.2, Box 3.2; Box CC-OA; see also WGII Glossary). Acidification is a physical and biogeochemical impact resulting from CO_2 emissions that poses risks to marine ecosystems and the societies that depend on them. Research on impacts on organisms, ecological responses, and consequences for ecosystem services is relatively new; the potential for associated risks to become key is magnified by the fact that acidification is a global phenomenon and, without a decrease in atmospheric CO_2 concentration, it is irreversible on century timescales.

It is *virtually certain* that ocean acidification is occurring now (AR5 WGI Section 3.9) and will continue to increase in magnitude as long as the atmospheric CO_2 concentration increases (NRC, 2010). Risks to society and ecosystems result from a chain of consequences beginning with direct effects on biogeochemical processes and organisms and extending to indirect effects on ecosystems, ecosystem services, and society (Figure 19-3). The degree of confidence in assessing risks decreases along this chain due to the complexity of interactions across these scales and the relatively small number of studies available for quantitative risk assessment.

[INSERT FIGURE 19-3 HERE
Figure 19-3: The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. The confidence in quantifying the impacts decreases along the pathway.]

Most studies have focused on the direct effects of ocean acidification on marine organisms and biogeochemical processes. The overall effects on organisms can be assessed with *medium confidence* (Section 6.3.2; Box CC-OA), but the effects vary widely across processes (e.g., photosynthesis, growth, calcification; Section 6.3.2) and across organisms and their life stages (Section 6.3.2; Box CC-OA).

Far fewer studies have assessed the impacts on ecosystems (Section 6.3.2.5) and ecosystem services (Section 6.4.1), and most of these studies have focused on the economic impacts on fisheries (Section 6.4.1.1). For example, changes in overall availability and nutritional value of desired mollusk species could affect economies (Narita *et al.*, 2012) and food availability (Section 6.4.1.1). In Table 19-3, we assess the risks to ecosystem services through the impact of acidification on two key marine processes, marine calcification and nitrogen fixation, using the criteria for key risks (19.2.2.2).

[INSERT TABLE 19-3 HERE
Table 19-3: An assessment of the risks to ecosystem services posed by the impacts of ocean acidification on coral calcification and nitrogen fixation, based on the four criteria for key risks (19.2.2.2).]

Based on Table 19-3, the response of coral calcification to ocean acidification and the resulting consequences for coral reefs constitute a key risk to important ecosystem services (*high confidence*). The effect of ocean acidification on marine N_2-fixation could potentially become a key risk, given that it could have potentially large consequences for marine ecosystems, but currently there is *limited evidence* on the likelihood of this risk materializing.

19.5.3. Risks from CO_2 Health Effects

There is increasing evidence that the impacts of elevated atmospheric CO_2 on plant species will affect health via two distinct pathways: the increased production and allergenicity of pollen and allergenic compounds, and the nutritional quality of key food crops. The evidence for these impacts on plant species is increasingly *robust* and recent evidence in the public health literature points to a *medium to high confidence* in the potential for these risks to be sufficiently widespread in geographical scope and large in *magnitude* of their impact on human health to be considered key risks.

Climate change is expected to alter the spatial and temporal distribution of several key allergen-producing plant species (Shea, 2008), and increased atmospheric CO_2 concentration, independent of climate effects, has been shown to stimulate pollen production (Rasmussen, 2002; Clot, 2003; Galán *et al.*, 2005; Garcia-Mozo *et al.*, 2006; Ladeau and Clark, 2006; Damialis *et al.*, 2007; Frei and Gassner, 2008). A series of studies (Ziska *et al.* 2000; Ziska *et al.*, 2003; Ziska and Beggs, 2012) found an association of elevated CO_2 concentrations and temperature with faster growing and earlier flowering ragweed species *(Ambrosia artemisiifolia*) along with greater production of ragweed pollen (Wayne *et al.*, 2002; Singer *et al.*, 2005; Rogers *et al.*, 2006) leading, in some areas, to a measurable increase in hospital visits for allergic rhinitis (Breton *et al.*, 2006). Experimental studies have shown that poison ivy, another common allergenic species, responds to atmospheric CO_2 enrichment through increased photosynthesis, water use efficiency, growth, and biomass. This stimulation, exceeding that of most other woody species, also produces a more potent form of the primary allergenic compound, urushiol (Mohan *et al.*, 2006).

While climate change and variability is expected to affect crop production (see Chapter 7), emerging evidence suggests an additional stressor on the food system: the impact of elevated levels of CO_2 on the nutritional quality of important foods. A prominent example of the effect of elevated atmospheric CO_2 is the decrease in the nitrogen (N) concentration in vegetative plant parts as well as in seeds and grains and, related to this, the decrease in the protein concentrations (Cotrufo *et al.*, 1998; Taub *et al.*, 2008; Wieser *et al.*, 2008). Experimental studies of increasing CO_2 to 550 ppm demonstrated effects on crude protein, starch, total and soluble B-amylase, and single kernel hardiness, leading to a reduction in crude protein by 4 to 13% in wheat and 11 to 13% in barley (Erbs *et al*., 2010). Other CO_2 enrichment studies have shown changes in the composition of other macro- and micronutrients (Ca, K, Mg, Fe, Zn) and in concentrations of other nutritionally important components such as vitamins and sugars (Idso and Idso, 2001). Declining nutritional quality of important global crops is a potential risk that would broadly affect rates of protein-energy and micronutrient malnutrition in vulnerable populations. While there is *medium confidence* that this risk has the potential to become key when judged by its *magnitude* and other criteria (Sections 19.2.2.1, 19.2.2.2) there is currently insufficient information to assess under what ambient CO_2 concentrations this would occur.

19.5.4. Risks from Geoengineering (Solar Radiation Management)

Geoengineering refers to a set of proposed methods and technologies that aim to alter the climate system at a large scale to alleviate the impacts of climate change (WGII Glossary; IPCC, 2012b; AR5 WGI Sections 6.5 and 7.7; WGIII Chapter 6). The main intended benefit of geoengineering would be the reduction of climate change that would otherwise occur, and the associated reduction in impacts (Shepherd *et al.*, 2009). Here we focus on risks, consistent with the goal of this chapter. Although geoengineering is not a new idea (e.g., Rusin and Flit, 1960; Budyko and Miller, 1974; Enarson and Morrow, 1998, and a long history of geoengineering proposals as detailed by Fleming, 2010), it has received increasing attention in the recent scientific literature.

Geoengineering has come to refer to both carbon dioxide removal (CDR, discussed in detail in AR5 WGI Section 6.5, FAQ 7.3) and solar radiation management (SRM; Shepherd *et al.*, 2009; Lenton and Vaughan, 2009; Izrael, 2009; discussed in detail in AR5 WGI, Section 7.7, FAQ 7.3). These distinct approaches to climate control raise very different scientific (e.g., Shepherd *et al.*, 2009), ethical (Morrow *et al.*, 2009; Preston, 2013) and governance (Lloyd and Oppenheimer, 2013) issues. Many approaches to CDR are considered to more closely resemble mitigation rather than other geoengineering methods (AR5 WGI, Chapter 6.5; IPCC, 2012b). In addition, CDR is thought to produce fewer risks than SRM if the CO_2 can be stored safely (AR5 WGI Section 6.5; Shepherd *et al.*, 2009) and unintended consequences for land use, the food system and biodiversity can be avoided (19.4.3). For these reasons, in addition to the more substantial recent literature on SRM's potential impacts, we only address SRM in this section. SRM is a potential key risk because it is associated with impacts to society and ecosystems that could be large in magnitude and widespread. Current knowledge on SRM is limited and our confidence in the conclusions in this section is *low*.

Studies of impacts on society and ecosystems have been based on two of the various SRM schemes that have been suggested: stratospheric aerosols and marine cloud brightening. These approaches in theory could produce large-scale cooling (Salter *et al.*, 2008; Lenton and Vaughan, 2009), although it is not clear that it is even possible to produce a stratospheric sulfate aerosol layer sufficiently optically thick to be effective (Heckendorn et al., 2009; English *et al.*, 2012). Observations of volcanic eruptions, frequently used as an analogue for SRM (Robock *et al.*, 2013), indicate that while stratospheric aerosols can reduce the global average surface air temperature, they can also produce regional drought (e.g., Oman *et al.*, 2005; Oman *et al.*, 2006; Trenberth and Dai, 2007), cause ozone depletion (Solomon, 1999), and reduce electricity generation from solar generators that use focused direct sunlight (Murphy, 2009). Climate modeling studies show that the risk of ozone depletion depends in detail on how much and when stratospheric aerosols would be released in the stratosphere (Tilmes *et al.*, 2008) and find that global stratospheric SRM would produce uneven surface temperature responses and reduced precipitation (Schmidt *et al.*, 2012; Kravitz *et al.*, 2013), weaken the global hydrological cycle (Bala *et al.*, 2008), and reduce summer monsoon rainfall relative to current climate in Asia and Africa (Robock *et al.*, 2008). Hemispheric geoengineering would have even larger effects (Haywood *et al.*, 2013).

The net effect on crop productivity would depend on the specific scenario and region (Pongratz *et al.*, 2012). Use of SRM also poses a risk of rapid climate change if it fails or is halted suddenly (AR5 WGI Section 7.7; Jones *et al.*, 2013), which would have large negative impacts on ecosystems (Russell et al., 2012; *high confidence*) and could offset the benefits of SRM (Goes *et al.*, 2011). There is also a risk of "moral hazard;" if society thinks geoengineering will solve the global warming problem, there may be less attention given to mitigation (e.g., Lin, 2013). In addition, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict (Brzoska *et al.*, 2012). Since the direct costs of stratospheric SRM have been estimated to be in the tens of billions of US dollars per year (Robock *et al.*, 2009; McClellan *et al.*, 2012), it could be undertaken by non-state actors or by small states acting on their own (Lloyd and Oppenheimer, 2012), potentially contributing to global or regional conflict (Robock, 2008a; Robock, 2008b). Based on magnitude of consequences and exposure of societies with limited ability to cope, geoengineering poses a potential key risk.

19.6. Key Vulnerabilities, Key Risks, and Reasons for Concern

In this section, we present key vulnerabilities, key risks, and emergent risks that have been identified by many of the chapters of this report based on the material assessed by each in light of criteria discussed in 19.2.2 and 19.2.3. We then discuss dynamic characteristics of exposure, vulnerability and risk, features which are influenced by development pathways in the past, present and future. Illustrative examples of climate-related hazards, key vulnerabilities, key risks and emergent risks in Table 19-4 are representative, having been selected from a larger number provided by the chapters of this report. The table demonstrates how these four categories are related, as well as how they differ, and how they interact with non-climate stressors. The table also provides information on how key risks actually develop due to changing climatic hazards and vulnerabilities. This knowledge is an important prerequisite for effective adaptation and risk reduction strategies that must address climate related hazards, non-climatic stressors and various vulnerabilities that often interact in complex ways and change over time.

19.6.1. Key Vulnerabilities

Several of the risks discussed in this and other chapters and noted in Table 19-4 arise because vulnerable people must cope and adapt not only to changing climate conditions, but to multiple, interacting stressors simultaneously (see Sections 19.3 and 19.4), which means that effective adaptation strategies would address these complexities and relationships.

19.6.1.1. Dynamics of Exposure and Vulnerability

This sub-section deals with the meaning and the importance of dynamics of exposure and vulnerability, while section 19.6.1.3 assesses recent literature regarding observed trends of vulnerability mostly at a global or regional scale. The literature provides increasing evidence that structures and processes that determine vulnerability are dynamic and spatially variable (IPCC, 2012a; and Section 19.6.1.3). SREX states with *high confidence* that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic, thus varying across temporal and spatial scales due to influences of and changes in social, economic, demographic, cultural, environmental, and governance factors (IPCC, 2012c, SPM.B).

Examples of such dynamics in exposure and vulnerability encompass, e.g. population dynamics, such as population growth or changes in poverty (Table 19-4; Birkmann *et al.*, 2013b) and increasing exposure of people and settlements in low lying coastal areas or flood plains in Asia (see Nicholls and Small, 2002; Fuchs *et al.*, 2011; IPCC, 2012a; Peduzzi *et al*., 2012). Also, demographic changes, such as aging of societies, have a significant influence on people's vulnerability to heat stress (see Stafoggia *et al*., 2006; Gosling *et al*., 2009). Changes in poverty or socio-economic status, ethnic compositions as well as age structures had a significant influence on the outcome of past crises and in addition were modified and reinforced through disasters triggered by climate and weather related hazards. For the United States for example, Cutter and Finch (2008) found that social vulnerability to natural hazards increased over time in some areas due to changes in socio-economic status, ethnic composition, age, and density of population. Changes in the strength of social-networks (e.g., resulting in social isolation of elderly) and physical abilities to cope with such extreme events modify vulnerability (see e.g. Khunwishit and Arlikatti, 2012).

In some cases human vulnerability might also change in different phases of crises and disasters. Hence, the factors that might determine vulnerability before a crisis or disaster (drought crises, flood disaster) might differ from those that determine vulnerability thereafter (post-disaster and recovery phases). Disaster response and reconstruction processes and policies can modify exposure and vulnerability e.g. of coastal communities (Birkmann and Fernando, 2008; Birkmann, 2011). A comprehensive assessment of vulnerability would account for these dynamics by evaluating long-distance impacts (e.g., resulting from migration or global influence of regional crop production failures following floods) and multiple-stressors (e.g. recovery policies after disasters) that often influence dynamics and generate complex crises and even emergent risks. Furthermore, the SREX also underscores that the increased intensity, frequency and duration of some extreme events as climate continues to change, might make adaptation based only on recent experience or the extrapolation of historical trends largely ineffective (Lavell *et al*., 2012, p. 44-47); hence understanding the dynamics of vulnerability and its different facets is crucial.

19.6.1.2. Differential Vulnerability and Exposure

Wealth, education, ethnicity, religion, gender, age, class/caste, disability, and health status exemplify and contribute to the differential exposure and vulnerability of individuals or societies to climate and non-climate related hazards (see IPCC, 2012a). Differential vulnerability is, for example, revealed by the fact that people and communities that are similarly exposed encounter different levels of harm, damage and loss as well as success of recovery (see Birkmann, 2006). The uneven effects and uneven suffering of different population groups and particularly marginalized groups is well documented in various studies (Bohle *et al.*, 1994; Kasperson and Kasperson, 2001; Thomalla *et al.*, 2006; Birkmann, 2006a; Sietz *et al.*, 2011; Sietz *et al.*, 2012). Factors that determine and influence these differential vulnerabilities to climate-related hazards include, e.g. ethnicity (Fothergill *et al.*, 1999; Elliott and Pais, 2006; Cutter and Finch, 2008), socioeconomic class (O'Keefe *et al.*, 1976; Peacock, 1997; Ray-Bennett, 2009), gender (Sen, 1981), age (Jabry, 2003; Wisner, 2006; Bartlett, 2008) as well as migration experience (Cutter and Finch, 2008) and homelessness (Wisner, 1998; IPCC, 2012a). Differential vulnerabilities of specific populations can often be discerned at a particular scale using quantitative or qualitative assessment methodologies (Cardona, 2006; Cardona, 2008; Birkmann *et al.*, 2013b). Various population groups are differentially exposed to and affected by hazards linked to climate change in terms of both gradual changes in mean properties and extreme events. For example, in urban areas, marginalized groups (particularly due to gender or wealth status or ethnicity) often settle along rivers or canals where they are highly exposed to flood hazards or potential sea-level rise (see Table 19-4) (e.g., Neal and Phillips, 1990; Enarson and Morrow, 1998; Neumayer and Plümper, 2007; Sietz *et al*., 2012). Studies emphasize that vulnerability in terms of gender is not determined through biology, but in most cases by social structures, institutions and rule systems; hence women and girls are often (not always) more vulnerable due to the fact that they are marginalized from decision making or experience discrimination in development and reconstruction efforts (Fordham, 1998; Houghton, 2009; Sultana, 2010; IPCC, 2012a).

19.6.1.3. Trends in Exposure and Vulnerability

Vulnerability and exposure of societies and social-ecological systems to hazards linked to climate change are dynamic and depend on economic, social, demographic, cultural, institutional, and governance factors (see IPCC, 2012c, p.7). The literature shows that there is a *high confidence* that rapid and unsustainable urban development, international financial pressures, increases in socioeconomic inequalities, failures in governance (e.g. corruption), and environmental degradation are key trends that modify vulnerability of societies, communities and social-ecological systems (Maskrey, 1993a; Maskrey, 1993b; Maskrey, 1994; Mansilla, 1996; Maskrey, 1998; Cannon, 2006; Birkmann, 2013; de Sherbinin, 2013) at different scales. Consequently, many of the factors that reveal and determine differential vulnerability change over time in terms of their spatial distribution. These dynamics unfold in different places differently and therefore local or regional specific strategies are needed that strengthen resilience (Garschagen and Kraas, 2011; Holdschlag and Ratter, 2013) and reduce exposure and vulnerability. For example, countries characterized by rapid urbanization coupled with low economic performance and high social development barriers face amongst the highest levels of climate change vulnerability. However, urbanization in some areas can yield conditions conducive to building up coping and adaptation capacities particularly when urban socio-economic development and risk management is properly implemented (see Garschagen and Romero-Lankao, 2013). The following section outlines observed trends in vulnerability according to different thematic dimensions (e.g., socio-economic, environmental, institutional), within the constraint that relevant socioeconomic data is limited.

19.6.1.3.1. Trends in socioeconomic vulnerability

Poverty is a critical factor determining vulnerability of societies to climate change and extreme events (Section 13.1.3). For example, risk due to droughts – particularly in sub-Sahara Africa - is intimately linked to poverty and rural vulnerability (see UNISDR, 2011, p. 62; Birkmann *et al.*, 2011b; Welle *et al.*, 2012; World Bank, 2010; *high confidence*). In interpreting the following estimates, it should be borne in mind that diverse concepts of poverty lead to different estimates but that for some regions, e.g., sub-Saharan Africa, the trends are *robust*. Recent evaluation of conditions in 119 countries found that at the international level there had been a clear decrease in global poverty over the previous six years (Chandy and Gertz, 2011). The number of poor people globally fell, from over 1.3 billion in 2005 to under 900 million in 2010. This trend is expected to continue (e.g. Chandy and Gertz 2011; Hughes *et al.*, 2009). However, regional trends vary, as do differences between emerging and least developed economies. As a result, there is a growing climate-related risk in some regions associated with chronic poverty. For example, approximately 47% of the population of the highly drought exposed region sub-Sahara Africa still lives in poverty (poverty headcount ration at $1.25 per day; see World Bank 2012) and this area already has been defined as a global risk hotspot (see Birkmann *et al.*, 2011b; Welle *et al.*, 2012). However, various national-level poverty statistics provide little information about the actual distribution of poverty, for example between rural-versus-urban areas. Income distribution trends show significant increases in inequality in some countries in Africa, and particularly in Asia, such as in China, India, Indonesia and Bangladesh (World Bank, 2012). In Asia and South East Asia this trend overlaps with areas of compound climate risk (19.3.2.4) in terms of people currently exposed to floods and tropical cyclones as well as sea-level rise (Förster *et al.*, 2011; Peduzzi *et al.*, 2012; IPCC, 2012a). Assessing vulnerability (and risk) in these countries requires in-depth analysis of trends and distribution patterns of poverty, income disparities and exposure of people to changing climatic hazards.

New socio-economic vulnerabilities are emerging in some countries, for example in developed countries, where the impoverishment of some population groups is observed. For example, research underscores that old age increases the risk of poverty in Greece, since the majority of people working as farmers or in the private sector receive small pensions which are below the poverty line (Karamessini, 2010, p. 279). These factors might interact with limited physical means of elderly to cope with climatic hazards, such as heat waves, and hence increase vulnerability.

Health status of individuals and population groups affects vulnerability to climate change by limiting capacities to cope and adapt to climate hazards (see Chapter 11). Although at a global scale the percentage of people undernourished is decreasing (FAO, 2012) and this trend is expected to continue (Hughes *et al.*, 2009), the regional and national differences are significant: during 2010-12, 870 million people remained chronically undernourished (FAO, 2012). Particularly in certain regions highly exposed to current and projected climate-related hazards, the number of people undernourished has increased. In Sub-Sahara Africa where exposure to drought is episodically high, the number of undernourished increased by 64 million or about 38% during 2010-12 compared to 1990-92 (FAO, 2012, p. 10; Hughes *et al.*, 2009). Moreover, at many locations, climate change is expected to reduce the access to and the quality of natural resources that are important to sustain rural and urban livelihoods as well as the capacities of states to provide help to sustain livelihoods (Barnett and Adger 2007; Section 19.3.2.1). These multi-risk contexts require new approaches for climate change adaptation.

While these trends mainly point to particularly large exposure and vulnerability in developing countries, studies regarding extreme heat vulnerability, for example, underscore that developed countries face increasing challenges to adaptation as well. Heat waves are projected to increase in duration, intensity, and extent (AR5 WGI 11.3.2). Advanced age represents one of the most significant risk factors for heat-related death (Bouchama and Knochel, 2002), since in addition to limited thermoregulatory and physiologic heat-adaptation capacities, elderly have often reduced social contacts, and higher prevalence of chronic illness and poor health (Section 11.3.3; Khosla and Guntupalli, 1999; Klinenberg, 2002; O'Neill, 2003). The trend towards an aging society, for example in Japan or Germany, therefore increases the vulnerability of these societies to extreme heat stress.

19.6.1.3.2. Trends in environmental vulnerability

Societies depend on ecosystem services for their survival; however, these ecosystem services and functions (see e.g. Millenium Ecosystem Assessment, 2005) are vulnerable to climate change (see Cardona *et al*., 2012, p. 76-77; Table 19-4; Section 19.3.2.1). Various societies and communities that rely heavily on the quality of ecosystem services, such as rural populations dependent on rain fed agriculture where drying is projected (see also Table 19-4), will experience increased risk from climate change due to its negative influence on ecosystem services (see Sections 4.3.4 and 6.4.1, *high confidence*). Although no global overview is available, recent reports (UNDP, 2007; IPCC, 2012a) underscore that a number of current environmental trends threaten human wellbeing and thus increase human vulnerability (UNEP, 2007). Many communities that have suffered large losses due to extreme weather events - for example coastal flooding - also experienced earlier degradation of ecosystems providing protective services. Recent global studies and local studies, such as for the US East Coast, underscore that intact ecosystems, such as marshes, can have an important protective role against coastal hazards e.g. by wave attenuation (Beck *et al.*, 2013; Shepard *et al.*, 2011). Hence, coastal degradation, such as destruction of coral reefs in Asia, is increasing the exposure of communities to such hazards (Welle *et al.*, 2012). Moreover, the extinctions of species and the loss of biodiversity pose a threat of diminution of genetic pools that otherwise buffer the adaptive capacities of social-ecological systems dependent on these services in the medium and long-run (e.g. in terms of medicine and agricultural production).

19.6.1.3.3. Trends in institutional vulnerability

Institutional vulnerability refers, among other issues, to the role of governance. Governance is increasingly recognized as a key factor that influences vulnerability and adaptive capacity of societies and communities exposed to extreme events and gradual climate change (Kahn, 2005; Nordås and Gleditsch, 2007; Welle *et al.*, 2011). People in countries or places that are facing severe failure of governance, such as violent conflicts (e.g. Somalia, Afghanistan) are particularly vulnerable to extreme events and climate change, since they are already exposed to complex emergency situations and hence have limited capacities to cope or undertake effective risk management (see Ahrens and Rudolph, 2006; Menkhaus 2010). Countries classified as failed states are often not able to guarantee their citizens basic standards of human security and consequently do not provide adequate or any support in crises or disaster situations for vulnerable people. The Failed State Index (Fund for Peace, 2012; Foreign Policy, 2012) as well as the Corruption Perception Index (Transparency International, 2012) are used to characterize institutional vulnerability and governance failure. Trends in the Failed State Index from 2006 to 2011 show that countries with severe problems in the functioning of the state cannot easily shift or change their situation (*persistence* of institutional vulnerability). Studies at the global level also confirm that countries classified as failed states and affected e.g. by violence are not able to effectively reduce poverty compared to countries without violence (see World Bank, 2011). Countries characterized in the literature as substantially failing in governance or in some particular aspects of governance during some period, such as Somalia and Ethiopia, Afghanistan, or Haiti have shown in the past severe difficulties in dealing with extreme events or supporting people that have to cope and adapt to severe droughts, storms or floods (see e.g. Lautze *et al.*, 2004; Ahrens and Rudolph, 2006; Menkhaus, 2010, p. 320-341; Heine and Thompson, 2011; Khazai *et al.*, 2011, p. 30-31). In addition, climate change is also likely to undermine the capacity of some states to provide the services and support that help people to sustain their livelihoods in a changing climate (Barnett and Adger, 2007). Governance failure and violence as characteristics of institutional vulnerability have significant influence on socio-economic, and therefore climatic vulnerability. Furthermore, corruption has been identified as an important factor that hinders effective adaptation policies and crisis response strategies (Birkmann *et al.*, 2011b; Welle *et al.*, 2012). At the local level, various aspects of governance in developing and developed countries, particularly institutional capacities and self-organization as well as political and cultural factors, are critical for social-learning, innovations and actions that can improve risk management and adaptation to climate related risks and for empowering highly vulnerable groups (IPCC, 2012a).

Overall, unless governance improves in countries with severe governance failure, risk will increase and human security will be further undermined there as a result of climate change and increased human vulnerability (Lautze *et al.*, 2004; Ahrens and Rudolph 2006, Barnett and Adger, 2007; Menkhaus 2010; *high confidence*).

19.6.1.4. Risk Perception

Risk perceptions influence the behavior of people in terms of risk preparedness and adaptation to climate change (Burton *et al.*, 1993; van Sluis and van Aalst, 2006; IPCC, 2012a). Factors that shape risk perceptions and therewith also influence actual and potential responses (and thus exposure, vulnerability and risk) include a) interpretations of the threat, including the understanding and knowledge of the root cause of the problem, b) exposure and personal experience with the events and respective negative consequences, particularly recently (i.e., availability) c) priorities of individuals, d) environmental values and value systems in general (see e.g. O'Connor *et al.*, 1999; Grothmann and Patt, 2005; Weber, 2006; Kuruppu and Liverman, 2011). Furthermore, the perceptions of risk and reactions to such risk and actual events are also shaped by motivational processes (Weber, 2010). In this context people will often ignore predictions of climate-related hazards if those predictions fail to elicit emotional reactions. In contrast, if the event or forecast of such an event elicits strong emotional feelings of fear, people may overreact and panic (see Slovic *et al.*, 1982; Slovic, 1993; Slovic, 2010; Weber, 2006). Public perceptions of risks are not solely determined by the "objective" information, but rather are the product of the interaction of such information with psychological, social, institutional, and cultural processes and norms which are partly subjective, as demonstrated in various crises in the context of extreme events (Kasperson *et al.*, 1988; Sagiya, 2011; Funabashi and Kitazawa, 2012). Risk perceptions particularly influence and increase vulnerability in terms of false perceptions of security (Cardona *et al*, 2012, p. 70). Finally, it is important to acknowledge that everyday concerns and satisfaction of basic needs may prove more pressing than attention and effort toward actions to address longer-term risk factors e.g., climate change (Maskrey, 1989; Wisner *et al.*, 2004; Maskrey, 2011). Rather, peoples' worldviews and political ideologies guide attention toward events that threaten their preferred social order (Douglas and Wildavsky, 1982; Kahan, 2010).

19.6.2. Key Risks

19.6.2.1. Assessing Key Risks

Key risks arise from the interaction of climate-related hazards and key vulnerabilities of societies, communities, or systems exposed (see Figure 19-1). Various chapters in this report have assessed key risks from their particular perspectives. We asked each chapter author team to provide Chapter 19 authors with the key risks of highest concern to their chapter based on the criteria for defining key risks and key vulnerabilities as outlined in 19.2.2. A complete presentation of the key risks provided by chapters is found in CC-KR (allowing for some condensation by authors of Chapter 19 to avoid repetition). The key risks provided by the chapters represent the issues most pressing to each set of experts. The list is neither unique nor exhaustive: other authors might express other preferences; however, this compilation provides important insights about key risks and their determinants: hazard, exposure, and vulnerability. Chapter 19 authors further consolidated these key risks in Table 19-4 in order to produce the following list which, in their judgment (*high confidence*), is representative of the range of key risks forwarded to this chapter. Roman numerals preceding each key risk correspond with entries in Table 19-4. Each key risk is followed with a notation in brackets indicating the Reason(s) for Concern (RFCs, see 19.6.3.) with which it is aligned. Additionally, a representative set of lines of sight is provided from across the chapters. Examples of these risks are also displayed geographically in Figure 19-2:

- **(i) Risk of death, injury, and disruption to livelihoods, food supplies, and drinking water, in addition to loss of common-pool resources, sense of place, and identity due to sea level rise, coastal flooding and storm surges affecting high concentrations of people, economic activity, biodiversity, and critical infrastructure in low-lying coastal zones and small island developing states.** These risks further increase in regions where the capacity to adapt long-lived coastal infrastructure (e.g. electricity, water and sanitation infrastructure) to local sea level rise beyond one meter is limited. Urban populations with substandard housing and inadequate insurance, as well as marginalized rural populations with multidimensional poverty and limited alternative livelihoods are particularly vulnerable to these hazards. Inadequate local governmental attention to disaster risk reduction and adaptation can further increase the vulnerability of people and also the risk of adverse consequences (AR5 WGI Sections 3.7.1, 13.5.1, Table 13.5; AR5 WGII Sections 5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, Box 25-1, Box 25-7, 26.7, 26.8, 29.3.1, 30.3.1). [*RFC 1, 2, 3, 4, and 5*]

- **(ii) Risk of food insecurity and the breakdown of food systems linked to warming, drought and precipitation variability particularly in regions that are characterized by poorer populations in urban and rural settings. This risk is a particular concern for** farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers). Climatic hazards and the vulnerability of people (see above) may exacerbate malnutrition, giving rise to a larger burden of disease in these groups, especially among elderly and female-headed households having limited ability to cope. The reversal of progress in reducing malnutrition is a potential outcome (AR5 WGI Section 11.3.2; AR5 WGII Sections 7.4, 7.5, 11.3, 11.6.1, 13.2.1, 13.2.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4). [*RFC 2, 3 and 4*]
- **(iii) Risk of severe harm due to inland flooding and the limited coping and adaptive capacities of large urban populations.** Particularly vulnerable are marginalized and poverty-stricken residents in low-income informal settlements as well as children, the elderly, and the disabled that have limited means to cope and adapt. Risks are increasing due to rapid and unsustainable urbanization especially in areas where risk governance capacities are constrained or limited attention is given to risk reduction and adaptation measures. Also, overwhelmed, aging, poorly maintained and inadequate infrastructure (e.g. drainage infrastructure, electricity, water supply, etc.) can further increase the risk of severe harm and threats to human security in the case of inland flooding (AR5 WGI Section 11.3.2.5; AR5 WGII Sections 3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, Box 25-8, 26.3, 26.7, 26.8, 27.3.5). [*RFC 2 and 3*]
- **(iv) Risk of loss of rural livelihoods and income of rural residents due to insufficient access to drinking and irrigation water, and reduced agricultural productivity, as well as risk of food insecurity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. Interaction of warming and drought with lack of alternative sources of income, and the presence of regional and national conditions that lead to a breakdown of food distribution and storage systems increases risk.** Especially vulnerable are those with limited ability to compensate for losses in water-dependent farming and pastoral systems, as well as those subject to conflict over natural resources. Additionally, insufficient supply of water due to droughts and institutional vulnerabilities (e.g., lack of state capacities, conflicts) for both industry and urban populations lacking running water, yielding severe economic impacts and other harms (AR5 WGI Section 12.4.1, 12.4.5; AR5 WGII Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, 24.4). [*RFC 2 and 3*]
- **(v) Systemic risks due to multiple interacting hazards affecting infrastructure in combination with a high dependency of people on critical services (electricity, water supply, health and emergency services) which may break down during extreme events.** Interdependency of critical infrastructure increases the risk of systemic breakdowns of vital services, for example, the risk of failure in systems dependent on electric power (such as drainage systems reliant on electric pumps) during extreme events. Health and emergency services rely on critical infrastructure (e.g. telecommunication) that can be disrupted during such power failures. For example, Hurricane Katrina left 1,220 electricity-dependent drinking water systems in Louisiana, Mississippi, and Alabama inoperable for several weeks (Copeland, 2005). Overly hazard-specific management planning and infrastructure design and/or low forecasting capabilities exacerbate such risks (AR5 WGI 11.3.2; AR5 WGII Sections 8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, 26.8). [*RFC 2, 3, and 4*]
- **(vi) Risk of loss of marine ecosystems and the services they provide for coastal livelihoods. Biodiversity and coastal ecosystem services important for fishing communities in the tropics and the Arctic are especially at risk due to rising water temperature and the increase of stratification and ocean acidification.** Loss of Arctic sea ice and degradation of coral reefs, as well as other natural barriers, presents a high risk to ecosystem services where many people are exposed to coastal hazards and also depend on coastal resources for livelihoods, such as Alaska, the Philippines and Indonesia (AR5 WGI Section 11.3.3; AR5 WGII Sections 5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2.3, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, 30. 6, CC-OA, CC-CR). [*RFC 1, 2, 3, 4, and 5*]

- **(vii) Risk of loss of terrestrial ecosystems and the services they provide for terrestrial livelihoods. Biodiversity and terrestrial ecosystem services are important for rural and urban communities globally. These services are at risk due to rising temperatures, changes in precipitation patterns, and extreme weather events. Risks are high for communities whose livelihoods depend on provisioning services.** Human and natural systems are susceptible to loss of provisioning services such as food and fibre, regulating services such as water quality, fire and erosion, and cultural services such as aesthetic values and tourism (AR5 WGI Section 11.3.2.5; AR5 WGII Sections 4.3.4, FAQ 4.4, 19.3.2.1, 22.4.5.6, Table 23-2, 27.3.2.1, Box CC-WE). [*RFC 1, 3 and 4*]
- **(viii) Risk of mortality, morbidity, and other harms during periods of extreme heat, particularly for urban populations of the elderly, infants, people with chronic diseases or compromised immune systems, and expectant mothers. Increasing frequency and intensity of extreme heat (including exposure to the urban heat island effect and air pollution) interacts with an inability of some local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups.** In addition, the impact of heat stress on aging populations, such as during the heat wave disaster in 2003 in Europe, shows how changing climatic conditions interact with trends in population structure, health conditions and social isolation (characteristics of vulnerability) to create key risks [AR5 WGI Section 11.3.2; AR5 WGII Sections 8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8, CC-HS). [*RFC 2 and 3*]

An important common characteristic of all key risks associated with anthropogenic climate change is that they are determined by hazards due to changing climatic conditions on the one hand and the vulnerability of exposed societies, communities and social-ecological systems, e.g. in terms of livelihoods, infrastructure, ecosystem services and management/governance systems on the other (see Table 19-4). The compilation of key risks underscores that effective adaptation and risk reduction measures would address all three components of risk (*high confidence*).

[INSERT TABLE 19-4 HERE
Table 19-4: A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems which often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g. urbanization and other demographic changes) in combination and in specific development context (e.g. in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. Roman numerals correspond with key risks listed in 19.6.2.1. A representative set of lines of sight is provided from across AR5 WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries.]

19.6.2.2. The Role of Adaptation and Alternative Development Pathways

As discussed in section 19.2.4, the identification of key risks depends in part on the underlying socio-economic conditions assumed to occur in the future, which can differ widely across alternative development pathways. This section assesses literature that compares impacts across development pathways, compares the contributions of anthropogenic climate change and socio-economic development (through changes in vulnerability and exposure) to climate-related impacts, and examines the potential for adaptation to reduce those impacts. Based on this assessment, risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region and time period, but in general both are important to understanding possible outcomes (*high confidence)*. In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a critical role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services (Rothman *et al.*, 2013).

Direct comparison of impacts across alternative development pathways shows, for example, that socio-economic conditions are an important determinant of the impacts of climate change on food security, water stress and the consequences of extreme events and sea level rise. The additional effect of climate change and CO_2 fertilization on the number of people at risk from hunger by 2080 generally spans a range of +/- 10-30 million across the four marker SRES scenarios, each of which assumes different socio-economic futures. However, in a scenario (A2) with high population growth and slow economic growth, this effect becomes as high as 120-170 million in some analyses (Schmidhuber and Tubiello, 2007). Similarly, the number of people exposed to water stress in a global study is sensitive to population growth assumptions (Arnell and Lloyd-Hughes, 2013), as are projected water resources in the Middle East under an A1B climate change scenario (Chenoweth et al., 2011). Assessments of the risks from river flooding depend on alternative future population and land use assumptions (Bouwer *et al.*, 2010; te Linde *et al.*, 2011), and sea level rise impacts depend on development pathways through their effect on the exposure of both the population and economic assets to coastal impacts, as well as on the capacity to invest in protection (Anthoff *et al.*, 2010).

The view that development pathways are an important determinant of risk related to climate change impacts is further supported by two other types of studies: those that examine the vulnerability of subgroups of the current population, and those that compare the relative importance of climate and socio-economic changes to future impacts. The first type finds that variation in current socio-economic conditions explains some of the variation in risks associated with climate and climate change, supporting the idea that alternative development pathways, which describe different patterns of change in these conditions over time, should influence the future risks of climate change. For example, socio-economic conditions have been found to be a key determinant of risks to low-income households due to climate change effects on agriculture (Ahmed *et al*., 2009; Hertel *et al.*, 2010), to sub-populations due to exposure to heterogeneous regional climate change (Diffenbaugh *et al.*, 2007), and to low-income coastal populations due to storm surges (Dasgupta *et al.*, 2009). Assessments of environmentally induced migration have concluded that migration responses are mediated by a number of social and governance characteristics that can vary widely across societies (Warner, 2010; see Sections 19.4.2.1, 12.4).

The second type of study finds that within a given projection of future climate change and change in socio-economic conditions, typically both are important to determining risks. In fact, the effect of the physical impacts of climate change on globally-aggregated changes in food consumption or risk of hunger have been found to be small relative to changes in these metrics driven by socio-economic development alone (Schmidhuber and Tubiello, 2007; Nelson *et al.*, 2010; Wiltshire *et al.*, 2013). Similarly, future population growth is found to be an equally (Murray *et al.*, 2012) or more (Fung *et al.*, 2011; Shewe *et al.*, in press) important determinant of globally-aggregated water stress as the level of climate change, and population growth, economic growth, and urbanization are expected to largely drive potential future damages to coastal cities due to flooding (*high confidence*, Section 5.4.3.1; Hallegatte *et al.*, 2013) and to be important determinants of damages from tropical cyclones (Bouwer *et al.*, 2007; Pielke Jr., 2007; Mendelsohn et al., 2012). At the regional level, socio-economic development has also been found to be equally or more important than climate change to impacts in Europe due to sea level rise, through coastal development (Hinkel *et al.*, 2010); heat stress, especially when acclimatization (Watkiss and Hunt, 2012) or aging (Lung *et al.*, 2013) is taken into account; and flood risks, through exposure due to land use and distributions of buildings and infrastructure (Feyen *et al.*, 2009; Bouwer *et al.*, 2010). Climate change was the dominant driver of flood risks in Europe when future changes in the value of buildings and infrastructure at risk were excluded from the analysis (te Linde *et al.*, 2011; Lung *et al.*, 2013) or when biophysical impacts such as stream discharge, rather than its consequences, were assessed (Ward *et al.*, 2011).

Land use is another socio-economic factor that can affect risks in addition to climate change, but until recently few studies have addressed the combined impacts of climate change and land use on ecosystems (Warren *et al.*, 2011). Studies of land use change scenarios alone project a large increase in extinction rates in the coming decades (Sala *et al.*, 2000; Millenium Ecosystem Assessment, 2005). A study of land bird extinction risk found some sensitivity to four alternative land use scenarios, but by 2100 risk was dominated by the climate change scenario (Şekercioğlu, 2008). A study of European land use found that while land use outcomes were more sensitive to the assumed socio-economic scenario, consequences for species depended more on the climate scenario (Berry *et al*., 2006).

Explicit assessments of the potential for adaptation to reduce risks have indicated that there is substantial scope for reducing impacts of several types, but the capacity to undertake this adaptation is dependent on underlying development pathways. Assessments of the impacts of sea level rise, for example, show that if development pathways allow for substantial investment of resources in adaptation through coastal protection, as opposed to accommodation or abandonment strategies, reducing impacts by investing in coastal protection can be an economically rational response for large areas of coastline globally (Nicholls *et al.*, 2008a; Nicholls *et al.*, 2008b; Anthoff *et al.*, 2010; Nicholls and Cazenave, 2010; Hallegatte *et al.*, 2013) and in Europe (Bosello *et al.*, 2012b). For the specific case of sea level rise impacts in Europe, adaptation in the form of increasing dike heights and nourishing beaches, at a cost reaching about €2 billion per year by 2100, was found to reduce the number of people affected by coastal flooding in 2100 from hundreds of thousands to a few thousand per year depending on the socio-economic and sea level rise scenario (A2 vs B1), and total economic damages from about €17 billion to about €2 billion per year (Hinkel *et al.*, 2010). In contrast, in some areas with higher current and anticipated future vulnerability such as low-lying island states and parts of Africa and Asia, impacts are expected to be greater and adaptation more difficult (Nicholls *et al.*, 2011).

Similarly, the risk to food security in many regions could be reduced if development pathways increase the capacity for policy and institutional reform, although most impact studies have focused on agricultural production and accounted for adaptation to a limited and varying degree (Lobell *et al.*, 2008; Nelson *et al.*, 2009; Ziervogel and Ericksen, 2010). A study of response options in Sub-Saharan Africa identified some scope for adapting to climate change associated with a global warming of 2°C above pre-industrial levels (Thornton *et al.*, 2011), given substantial investment in institutions, infrastructure, and technology, but was pessimistic about the prospects of adapting to a world with 4°C of warming (Thornton *et al.*, 2011; see also section 19.7.1). Improved water use efficiency and extension services have been identified as the highest priority agricultural adaptation options available in Europe (Iglesias *et al.*, 2012) and a potentially large role for expanded desalination has been identified for the Middle East (Chenoweth *et al.*, 2011).

19.6.3. Updating Reasons for Concern

The Reasons for Concern (RFCs) are the relationship between global mean temperature increase and five categories of impacts that were introduced in the IPCC TAR (Smith *et al.*, 2001) in order to facilitate interpretation of Article 2 (1.2.3, Box 19-2). In AR4, new literature related to the five RFCs was assessed, leading in most cases to confirmation or strengthening of the judgments about their relevance to defining dangerous anthropogenic interference based on evidence that some impacts were already apparent, higher likelihoods of some climate-related hazards, and improved identification of currently vulnerable populations (Schneider *et al.*, 2007; Smith *et al.*, 2009).

RFCs are related to the framework of key risks, climate-related hazards, and vulnerabilities used in this chapter because each RFC is understood to represent a broad category of key risks to society or ecosystems associated with a specific type of hazard (extreme events, large-scale singular events), system at risk (unique and threatened systems), or characteristic of risk to social-ecological systems (aggregate impacts on those systems, distribution of impacts to those systems). For example, the RFC for extreme events implies a concern for risks to society and ecosystems posed by extreme events, rather than a concern for extreme events *per se*. Accordingly, in this chapter we have reworded the definition of RFCs to emphasize risk.

In this section we assess new literature related to each of the RFCs, concluding that, compared to judgments presented in AR4 and in Smith *et al.* (2009), levels of risk associated with extreme events and distribution of impacts are similar but can be assessed with higher confidence; risks associated with aggregate impacts are similar and confidence in the assessment unchanged; and risks to unique and threatened systems and those associated with large-scale singular events are higher above 2°C (compared to a 1986-2005 baseline), than assessed previously. These judgments are illustrated in Figure 19-4, an updated version of the “burning embers” diagram that describes how the additional risk due to climate change for each RFC changes with increasing GMT. We retain the color scheme employed in previous versions of this figure (Smith *et al.* 2001; Smith *et al.*, 2009) with some refinement. White, yellow, and red indicate neutral, moderate, and high additional risk, respectively. Risk is low in the transition between white and yellow, and substantial in the transition between yellow and red. We add a new color (purple) indicating very high risk as elaborated below.

Sub-sections below assess risks for each RFC and locate transitions between colors using the criteria for key risks as a guide (19.2.2.2). The transition from white to yellow is partly defined by the GMT at which there is at least medium confidence that impacts associated with a given risk are both detectable and attributable to climate change, while also accounting for the magnitude of the risk. We draw on Section 18.6.4 to inform the placement of this transition relative to recent GMT. The transition from yellow to red is defined by increasing magnitude (including pervasiveness) or likelihood of impacts, with high risk (red color) defined as risk of severe and widespread impacts that is judged to be "high" on one or more criteria for assessing key risks (19.2.2.2). The transition from red to purple is defined by very high risk of severe impacts and the presence of significant irreversibilities or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. As was true in the TAR and Smith et al. (2009), transitions are fuzzy due to uncertainties in a variety of factors determining the relation between GMT and risk, including the rate of climate change, the time at which the temperature is reached, and the extent and agreement of the evidence base in the literature.

We also clarify the concept of RFCs: because risks depend not only on physical impacts of climate change but also on exposure and vulnerability of societies and ecosystems to those impacts, RFCs as a reflection of those risks depend on both factors as well (see also Section 19.1).

19.6.3.1. Variations in RFCs across Socio-Economic Pathways

The determination of key risks as reflected in the Reasons for Concern (RFCs) has not previously been distinguished across alternative development pathways. In the TAR and AR4, RFCs took only autonomous adaptation into account (Smith *et al.*, 2001; Schneider *et al*., 2007, AR4 WGII Chapter 19). However, the RFCs represent risks that are determined by both climate-related hazards and the vulnerability and exposure of social and ecological systems to climate change stressors. Figure 19-5 illustrates this dependence on vulnerability and exposure in a modified version of the burning embers diagram. Current literature is not sufficient to support confident assessment of specific RFCs using this approach.

As literature accumulates, it could inform new versions of this figure applied to specific RFCs. For example, studies that employ particular scenarios of socio-economic conditions could be categorized according to the levels of vulnerability represented by those scenarios (van Vuuren *et al.*, 2012) to locate results along the horizontal axes, while climate conditions assumed in those studies would locate results along the vertical axis. As with previous versions of the burning embers, however, this new figure does not explicitly address issues related to rates of climate change or to when impacts might be realized. The updates of RFCs in 19.6.3.2-19.6.3.6 which follow (and are illustrated in Figure 19-4) do not account for differences in vulnerability across development paths; rather, they are based on the same assessment framework as used in AR4 and Smith *et al.* (2009), but with additional elaboration.

[INSERT FIGURE 19-4 HERE
Figure 19-4: The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated from TAR and Smith *et al.* (2009). The color scheme indicates the additional risk due to climate change as described in the text. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual "reason." The transition from red to purple, introduced here, is defined by very high risk of severe impacts and the presence of significant irreversibilities or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. In general, assessment of RFCs takes autonomous adaptation into account, as was done previously (Smith *et al.*, 2001; Schneider *et al.*, 2007, AR4 WGII Chapter 19). In addition, this assessment took into account limits to adaptation in the case of RFC1, RFC3, and RFC5, independent of the development pathway. The rate and timing of climate change and physical impacts, not illustrated explicitly in this diagram, was taken into account in assessing RFC1 and RFC5. Comments superimposed on RFCs provide additional details which were factored into the assessment. The levels of risk illustrated reflect the judgments of Chapter 19 authors.]

[INSERT FIGURE 19-5 HERE
Figure 19-5: Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and exposure and vulnerability (E&V) of society. This figure is schematic; the degree of risk associated with particular levels of climate change or E&V has not been based on a literature assessment, nor associated with a particular RFC (the “burning ember” in the figure refers generically to any of the embers in Figure 19-4). The E&V axis is relative rather than absolute: “Medium” E&V indicates a future development path in which E&V changes over time are driven by moderate trends in socio-economic conditions. “Low” and “High” E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding exposure and vulnerability. Judgments made in other burning ember diagrams of the RFCs (Smith *et al.*, 2001, 2009) including Figure 19-4, which do not explicitly take changes in E&V into account, are consistent with Medium future E&V. Arrows and dots illustrate the use of SRES scenario-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socio-economic conditions over time. This figure does not explicitly address issues related to the rates of climate change or when impacts might be realized.]

19.6.3.2. Unique and Threatened Systems

Unique and threatened systems include a wide range of physical, biological and human systems that are restricted to relatively narrow geographical ranges and are threatened by future changes in climate (Smith *et al.*, 2001). Where consequences are *irreversible* and *importance* to society and other systems is high, the potential for loss of or damage to such systems constitutes a key risk. AR4 stated with *high confidence* that a warming of up to 2°C above preindustrial levels would result in significant impacts on many unique and vulnerable systems and would increase the endangered status of many threatened species, with increasing adverse impacts (and increasing confidence in this conclusion) at higher temperatures (Schneider *et al.*, 2007). Since AR4, there is a growing body of literature suggesting that the number of threatened systems and species is greater than previously thought.

Chapters 4, 22, 23, 24, 25, 26, and 27 highlight areas where unique and threatened systems are particularly vulnerable to climate change. Evidence for severe and widespread impacts to humans and social systems, ecosystems and species in polar regions as warming progresses has continued to accrue (Sections 4.3.3.4, 28.2). Projections of Arctic sea ice melt rates have increased since AR4 (WGI Section 12.4.6), increasing risks to the Inuit and the sea ice-dependent ecosystems upon which they subsist . CMIP5 model runs for September with all RCPs show substantial additional losses of Arctic Ocean ice for a global warming of 1^0C relative to 1986-2005 and a nearly ice-free Arctic Ocean for global warming greater than 2^0C (AR5 WGI Figures 12-30). Futhermore, a nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*, AR5 WGI Section 12.4.6).

Coral reef ecosystems are still considered amongst the most vulnerable of unique marine systems (Sections 5.4.2.4, 19.3.2.4), with corals’ evolutionary responses being outpaced by climate change (Hoegh-Guldberg, 2012) resulting in projections of extensive reef decline throughout the 21st century. Globally, large-scale reef dissolution may occur if CO_2 concentrations reach 560 ppm (Sections 5.4.2.4) due to the combined effects of warming and ocean acidification. Even if global temperature rise in the 2090s is constrained to 1.2-2.0°C above pre-industrial levels (AR5 WGI Table 12.3, RCP2.6), 9-60% of reefs are projected to be subject to long-term degradation; whilst 30-88% of reefs are projected to eventually degrade if global temperature rises in the 2090s by 1.9-2.9°C above pre-industrial levels (RCP4.5; Box CC-CR, Coral Reefs; temperatures from AR5 WGI Table 12.3). Loss of corals and mangrove ecosystems would endanger the livelihoods of unique human communities and cause economic damage (Section 4.3.3 for global discussion; Sections 22.3.2.3, 24.4.3, 25.6 for Africa, Asia, and Australia; section 26.4 for N. America; section 27.3.3.1 and Figure 27.5 for S. America).

There is a large and increasing amount of evidence for escalating risks of species range loss, extirpation and extinction based on studies for global temperatures exceeding 2°C above pre-industrial levels (1.4°C above 1986-2005; Warren *et al.*, 2011; Şekercioğlu *et al.*, 2012, Foden *et al.*, 2013; Warren *et al*., 2013a). An assessment of 16,857 species (Foden *et al.*, 2013) found that with approximately 2°C of warming above preindustrial (A1B, 2050s), 24-50% of the birds, 22-44% of the amphibians and 15-32% of the corals were highly vulnerable to climate change defined as having high sensitivity, high exposure, and low adaptive capacity.

An increasing number of threatened systems has been identified, in the form of projected species range losses and extinction risks, although without yet tying risks to specific levels of warming. Evidence of climate risks to unique mountain ecosystems and their numerous endemic alpine species has continued to accrue in Europe, Asia, Australia and South America (Sections 23.6.4, 24.4.2.3, 25.6.1, 27.3.2.1). Siberian, tropical, and desert ecosystems in Asia (24.4.2.3), Africa (Warren *et al.*, 2013a), and Mediterranean areas in Europe (Klausmeyer and Shaw, 2009; Maiorano *et al.*, 2011), the Southwest Kakadu, and Queensland rainforests in Australia (Section 25.6.1), Amazonian ecosystems in South America (Foden *et al.*, 2013; Warren *et al.*, 2013a) and freshwater ecosystems in Africa (specifically Ethiopia, Malawi, Mozambique, Zambia and Zimbabwe) (Sections 4.3.3.3, 22.3.2.2) are particularly at risk, as are the Fynbos and succulent Karoo areas of South Africa (Midgley and Thuiller, 2011; Kuhlmann *et al.*, 2012; Huntley and Barnard, 2012) and dune systems in temperate climates (Section 23.6.5). Recent research has identified risks to highly biodiverse tropical wet and dry forests (Sections 4.3.3 and 24.4.2.3; Wright et al., 2009; Kearney *et al.*, 2009, Toms *et al.*, 2012) and tropical island endemics (Fordham and Brook, 2010). Globally amphibians were found to be the most vulnerable of vertebrate taxa (Stuart *et* al., 2004; Brito, 2008; Rohr and Raffel, 2010; Liu *et al*., 2013; Warren *et al.*, 2013a).

Owing to higher projections of sea level rise than in AR4 (AR5 WGI Sections 13.5, 13.6, 13.7), risk of partial inundation of small island states has increased.

Since AR4, almost all glaciers world-wide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass (*very high confidence*, AR5 WGI Chapter 4 ES). There is substantial new evidence that across most of Asia glaciers have been shrinking, except in some areas in the Karakorum and Pamir (section 18.5.3). In the Andes, glacier loss threatens to reduce the water and electricity supplies of large cities and hydropower projects, as well as the agricultural and tourism sectors (27.3.1.1, 27.3.1.2, Table 27.3, case study 27.6.1). Some climate model simulations show significant loss of glacial cover in central Asia by 2100 under "the higher climate change scenarios considered by IPCC AR4" (Section 24.9.2). Loss of glacial cover has been projected to significantly reduce water supplies in meltwater-dependent arid regions (Kaser, 2010), potentially threatening the food security of 60 million people in the Brahmaputra and Indus basins by the 2050s (Immerzeel *et al.*, 2010). A caveat is that recent work has suggested that glacier melt rates were overestimated and precipitation may increase, so that runoff would rise at least until 2050 (Immerzeel *et al*., 2013). Large uncertainties in projections of Himalayan ice cover and runoff dynamics remain (Bolch *et al.*, 2012).

In Figure 19-4, we locate the transition to moderate risk (white to yellow) below recent global temperatures because there is at least *medium confidence* in attribution of a major role for climate change for impacts on at least one each of ecosystems, physical systems, and human systems (AR5 WGII Section 18.6.4). A transition to purple is located around 2°C above 1986-2005 levels to reflect the very high risk to species and ecosystems projected to occur beyond that level as well as limited ability to adapt to impacts on coral reef systems and on Arctic sea ice-dependent systems (Chapters 4, 24) if that level of warming were exceeded (*high confidence)*. A transition to red is located at 1°C above 1986-2005 levels, midway between current temperature and the transition to purple, indicating the increasing risk to unique and threatened systems, including Arctic sea ice and coral reefs, as well as threatened species as temperature increases over this range.

19.6.3.3. Extreme Events

Extreme weather events (e.g., heat waves, intense precipitation, drought, tropical cyclones) trigger impacts that can pose key risks to societies that are exposed and vulnerable (Lavell *et al*., 2012 (SREX, Chapter 1)). With regard to the physical hazard aspect of risk, AR5 assesses a higher likelihood of attribution of heat waves and extreme hot days and nights to human activity than AR4. AR5 WGI states, "We assess that it is *very likely* that human influence has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century" (AR5 WGI 10.6.1.1) and "it is *likely* that human influence has substantially increased the probability of occurrence of heat waves in some locations" (AR5 WGI Section 10.6.2). WGI finds *medium confidence* in attribution of intensification of heavy precipitation over Northern Hemisphere land areas with sufficient data (AR5 WGI Section 10.6.1.2), and *low confidence* in detection and attribution of changes in drought over global land areas (AR5 WGI Section 10.6.1.3) and global changes in tropical cyclone activity (AR5 WGI Section 10.6.1.4) to human influence. There is *high confidence* in attribution of impacts of weather extremes (as opposed to the physical hazards alone) on coral reef systems (Section 18.6.4; Table 18-10; Section 19.6.3.2), with evidence for impact attribution limited and highly localized otherwise.

The likelihood of projected 21st century changes in extremes has not changed markedly since AR4 (AR5 WGI Chapters 10 and 12), but for the first time near-term changes (for the period 2016-2035 relative to 1986-2005) are assessed (AR5 WGI Chapter 1), a period during which the increase in the model and scenario averaged GMT is projected to remain below 1°C relative to 1986-2005 (AR5 WGI Figure 11.8; AR5 WGI Section 11.3.6.3). Among the conclusions are, "In most regions the frequency of warm days and warm nights will *likely* increase in the next decades, while that of cold days and cold nights will decrease" (AR5 WGI Chapter 11 ES). Specifically, 15% of currently observed maximum daily temperatures exceed the historical 90th percentile values (rather than the historical 10%) and by about 2035, 25-30% of daily maximums are projected to exceed the historical 90th percentile value (AR5 WGI Figures 11-17). WGI also notes that "Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells" (AR5 WGI Section 11.3.2.5.1, Table SPM.1). With regard to extreme precipitation events, WGI finds "The frequency and intensity of heavy precipitation events over land will *likely* increase on average in the near term. However, this trend will not be apparent in all regions because of natural variability and possible influences of anthropogenic aerosols and land use change" (AR5 WGI Chapter 11 ES). In addition, SREX (Figure SPM 4B) projects a reduction in return period for historical once-in-20-yr precipitation events globally (land only) to about once-in-14-yr or less by 2046-65.

With regard to the vulnerability and exposure aspects of risk, SREX reviewed literature on the relationship between changes in these factors and the risk of extreme events (SREX Sections 4.5.4, 4.5.6). Increases in local vulnerability and exposure to extreme precipitation can lead to a disproportionate increase in overall risk (SREX sections 4.3.5.1, 9.2.8; Douglas *et al.*, 2008; Douglas, 2009; Hallegate *et al.*, 2011; Ranger, 2011). For example, growth of megacities both concentrates exposure and vulnerability and can generate "synchronous failure" that spreads beyond the immediate vicinity of extreme events. Megacities increase nighttime temperature extremes via the urban heat island effect (Section 8.2.3.1; IPCC, 2012a Section 4.4.5.2) while also enhancing exposure to high air pollution levels (Fang *et al*., 2013; IPCC, 2012 Section 9.2.1.2.3) and consequent health effects (Sections 11.5.3.2, 11.5.3.4, Table 11-2), with widespread impacts by midcentury in some studies. Densely populated areas of East and South Asia and North America are projected to be especially affected by climate-related air pollution (Fang *et al.*, 2013). Projections of the global socioeconomic (Mendelsohn *et al.*, 2013) impact of tropical cyclones demonstrate increasing risk due to interactions of increasing storm intensity with exposure. Hazard projection suggests a disproportionate increase in exposure to tropical cyclone risk with increasing temperature at New York City due to combined effects of storm intensification and sea level rise (Lin *et al.*, 2012). Other studies (Jongman *et al.*, 2012; Hallegate *et al*., 2013; Preston, 2013) project increasing coastal flood risk due to increasing exposure, although the first two do not disaggregate to specific types of extreme events. Taken together, this evidence supports a conclusion of disproportionate increase in risk associated with extreme events as temperature, and in many cases, exposure and vulnerability increase as well.

Based on the above assessments of the physical hazard alone, we find increased confidence in the AR4 assessment of the risk from extreme events. Based on the attribution of heat and precipitation extremes to anthropogenic climate change, the attribution to climate change of impacts of climate extremes on one unique and threatened system, and the current vulnerability of other exposed systems, we assign a "yellow" level of risk at recent temperatures in Figure 19-4 [*high confidence*], consistent with Smith *et al.*, (2009). We assign a transition to "red" beginning below 1°C compared to 1986-2005 (also consistent with Smith *et al.*, (2009)) based primarily on the *magnitude* and *likelihood* and *timing* (see 19.2.2.2) of the projected change in hazard of extreme events, indicating that impacts will become more severe and widespread over the next few decades [*medium confidence*].

19.6.3.4. Distribution of Impacts

The distribution of impacts is a category of climate change consequences that includes key risks to particular societies and social-ecological systems that may be disproportionately affected due to unequal distribution of hazards, exposure, or vulnerability. AR4 concluded that there is *high confidence* that low-latitude, less-developed areas are generally at greatest risk and found that, because vulnerability to climate change is also highly variable within countries, some population groups in developed countries are also highly vulnerable even to a warming of less than 2°C above 1990-2000 (Schneider *et al.*, 2007). These conclusions remain valid and are now supported by a limited number of impact studies that explicitly consider differences in socio-economic conditions that affect vulnerability across regions or populations (Müller *et al.* 2011, Mougou *et al.* 2011, Schewe *et al.* 2013, Gosling and Arnell, 2013). Furthermore, we have increased confidence in the AR4 assessment of the risk arising in the near term from the distribution of impacts from extreme events because, by their very nature, these events change in a locally and temporally variable fashion with, e.g., a larger change in extreme temperatures at higher latitudes (SREX Figure SPM 4A).

Impacts of climate change on food security depend on both production and non-production aspects of the food system, including not just yield effects but also changes in the amount of land in production and adjustments in trade patterns (Section 7.1.1). Effects on prices are often taken as an indicator of impacts on food security, and the combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices by 2050, with few new studies examining prospects at longer time horizons (Section 7.4.4). Most studies have focused on geographical differences in the effects of climate change on crop yields. With regard to such distributional consequences, yields of maize and wheat begin to decline with 1-2^{o}C of local warming in the tropics, with or without adaptation taken into account. Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with local warming of 3-5^{o}C particularly without adaptation (based on studies with various baselines, see Section 7.3.2.1). These data confirm AR4 findings that even small warming will decrease yields in low-latitude regions (*medium evidence, high agreement*) (Section 7.3.2.1.1), and increase the risk assigned to yields in mid- to high-latitude regions (compared to AR4), suggesting that temperate wheat yield decreases are *about as likely as not* for moderate warming.

Risks of climate change related to freshwater systems such as extreme water shortage increase with global mean temperature rise (*high agreement, medium evidence*) (Chapter 3 ES, Table 3-2). Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*high agreement, robust evidence)* (Section 3.5). One study using multiple climate and hydrological models to simulate impacts of scenario RCP8.5 and SSP2 project that global warming of 1.7 ^{o}C above pre-industrial will reduce water resources by more than one standard deviation, or by more than 20%, for 8% of the global population, whilst for warming of 2.7 ^{o}C above pre-industrial this increases to 14% (model range 10-30%) (Schewe *et al*., 2013); and for warming of 3.7 ^{o}C above pre-industrial it reaches a mean of 17% across models (Schewe *et al.* 2013). Additionally, in another study (Gosling and Arnell, 2013), climate change amplifies water scarcity by 30-40% for 1.7-2.7 ^{o}C of warming, with around 40% of the global population under increased water stress. In one model, exposure to water scarcity increases steeply up to 2.3^{o}C above pre-industrial in N and E Africa, Arabia and S. Asia (Gosling and Arnell, 2013). In Africa water resources risks are 'medium-high' at 2°C and 'high-very high' at 4°C (Chapter 22 Table 22-6). Model projections generally agree that discharge will decrease in the Mediterranean and in large parts of N. and S. America (Schewe *et al.*, 2013). However, there are opportunities for adaptation in the water resources sector, particular for municipal water supply (Section 3.6.5).

The first global scale analysis of climate change impacts on almost 50,000 species of plants and animals has highlighted that risks are not distributed equally, with sub-Saharan Africa, Central America, Amazonia and Australia at risk for plants and animals, and North Africa, Central Asia and Southeastern Europe for many plants (Warren *et al*., 2013a). A traits-based analysis of more than 16,000 species identified Amazonia and Mesoamerica as being at risk for birds and amphibians and central Eurasia, the Congo Basin, the Himalayas and Sundaland for birds, and the Coral Triangle region for corals (Foden *et al.*, 2013).

In summary, since AR4, new evidence has emerged highlighting the *magnitude* of risk for particular regions, for example in relation to the potential for regional impacts upon ecosystems (see Section 19.6.3.2), megadeltas (see

Sections 8.2.3.4 and Chapter 5], and agricultural systems, which is exacerbated by the potential for changes in the monsoon systems (see Section 19.6.3.5; AR5 WGI 12.5.5.). Overall there is increased evidence that low-latitude and less-developed areas generally face greater risk than higher-latitude and more-developed countries (Smith *et al.*, 2009). At the same time, there has been an increase in appreciation for vulnerability (e.g., to extreme events) in developed countries, especially, localised issues of differential vulnerability in particular areas of the developed world [SREX 2.5.1.2].

Regionally differentiated impacts on crop production have been detected and attributed to climate change *with medium to high confidence* (Section 18.4.1.1), and we interpret this as an early warning sign of attributable impacts on food security. For this reason, as well as for reasons of *timing* and *likelihood* and *magnitude* of these risks, the transition from “white” to “yellow” levels of risk in Figure 19-4 is assessed to occur at recent temperatures. Based on risks to regional crop production and water resources the transition from yellow to red is assessed to occur between 1° and 2°C above the 1986-2005 global mean temperature [*medium confidence*]. Both assessments are consistent with Smith *et al.*, (2009). Furthermore, given evidence that agronomic adaptations would be more than offset for tropical wheat and maize where increases in local temperature of more than 3°C above preindustrial occur (*limited evidence, medium agreement;* Section 7.5.1.1.1; AR5 WGII Chapter 7 ES) the intensity of red increases non-linearly toward purple in recognition of the temperature sensitivity of crop productivity and limited efficacy of agronomic adaptation above 2°C compared to 1986-2005.

19.6.3.5. Aggregate Impacts

The RFC pertaining to aggregate impacts includes risks that are aggregated globally into a single metric, such as monetary damages, lives affected, lives lost, or species or ecosystems lost. Estimates of the aggregate, economy-wide risks of climate change since AR4 continue to exhibit a *low level of agreement*. Studies at the sectoral level have been refined with new data and models, and have assessed new sectors.

AR4 stated with *medium confidence* that approximately 20-30% of the plant and animal species assessed to date are likely at increasing risk of extinction as global mean temperatures exceed a warming of 2-3°C above pre-industrial levels (Fischlin *et al.*, 2007). There is *high confidence* that climate change will contribute to increased extinction risk for terrestrial and marine species over the coming century (Section 4.3.2.5). Since AR4 a substantial amount of additional work has been done, looking at many more species and using new and/or improved modelling and traits-based techniques, strengthening the evidence of increasing risk of extinction with increasing temperature (e.g. Hunter *et al.*, 2010; Amstrup *et al.*, 2010; Pearman *et al.*, 2011; Lenoir *et al.*, 2008; Balint *et al.*, 2011; Barnosky *et al.*, 2012; Norberg *et al.*, 2012; Bellard *et al*., 2012; Foden *et al*., 2013). More studies have scrutinized caveats to previous studies and assesed their role in either under- or overestimating extinction risks (e.g. Beale *et al.*, 2008; Cressey, 2008; Randin *et al.*, 2009; He and Hubbell, 2011; Harte and Kitzes, 2012), including the role of evolution (Norberg *et al.*, 2012), while others have carefully examined risk considering other species traits (looking at exposure, sensitivity and potential adaptive capacity for large numbers of species; Foden *et al*., 2013).Literature incorporating multiple new assessment techniques quantifying extinction risks supports the conclusion that the dependence between increasing extinction risk and temperature is *robust* [*medium confidence]*, albeit varying across biota. However, there is *low agreement* on assigning specific numerical values for species at risk (Sections 19.3.2.1, 19.5.1).

Since AR4 it has been found that species that are widespread geographically, not only endemics (which have tended to be the focus of many previous studies) are at risk (Warren *et al.*, 2013a) implying a significant and widespread potential loss of ecosystem services (Section 4.3.2.5, Gaston and Fuller, 2008; Allesina *et al.*, 2009, Staudinger *et al.* 2012), comprising a new emergent risk (Table 19-4). At a global temperature rise of 3.5-4°C above preindustrial, Foden *et al.* (2013) estimated that 20 - 60% of the birds, amphibians and corals studied are highly vulnerable to climate change. Taking this estimate conservatively as a maximum (i.e., assuming all species not studied are able to adapt at least as well as the groups investigated), and combining this estimate with the finding of >50% loss of potential range in 57% of plants and 34% of animals studied globally for the a global temperature rise of 3.5-4°C by the 2080s allowing for realistic dispersal rates (Warren *et al.*, 2013a), there is *high confidence* that climate change will significantly affect biodiversity, and related ecosystem services.

Much new work has focused on future projected synergistic impacts of climate-change induced increases in fire, drought, disease, and pests (Flannigan *et al.*, 2009; Krawchuk *et al.*, 2009; Hegland *et al.*, 2009; Koeller *et al.*, 2009; Garamszegi, 2011). New work has demonstrated that the expected large turnovers of up to 60% in marine species assemblages in response to unmitigated (SRES A1B and SRES B1) climate change by the 2050s, combined with shrinkage of fish body weight of 14–24% (SRES A2) (Cheung *et al.*, 2009; Cheung *et al.*, 2012) put marine ecosystem functioning at risk with negative consequences for fishing industries, coastal communities and wildlife that are dependent on marine resources (Lam *et al.*, 2012).

Consistent with AR4, global aggregate economic impacts from climate change are highly uncertain, with most estimates a small fraction of gross world product up until at least 2.5°C of warming above preindustrial (Section 10.9.1). Some studies suggest net benefits of climate change at 1°C of warming (10.9.1). Little is known about global aggregate damages above 3°C (Sections 10.9.1, 19.5.1) (Ackerman *et al.*, 2010; Weitzman, 2010; Ackerman and Stanton, 2012; Kopp *et al.*, 2012). Aggregate damages vary with alternative development pathways, but the relationship between development pathway and aggregate damages is not well explored. In many sectors, damages as a fraction of output are expected to be larger in low-income economies, although monetized damages are expected to be larger in high-income economies (e.g., Anthoff and Tol, 2010). Adaptation is treated differently across modeling studies (Hope, 2006; de Bruin *et al.*, 2009; Bosello *et al.*, 2010; Füssel, 2010; Patt *et al.*, 2010) and affects aggregate damage estimates in ambiguous ways.

Estimates of global aggregate damages omit a number of factors (Yohe and Tirpak, 2008; Kopp and Mignone, 2012). While some studies of aggregate damages include market interactions between sectors in a computable general equilibrium framework (e.g., Bosello *et al.*, 2012a; Roson and van der Mensbrugghe, 2012), none treat non-market interactions between impacts (Warren, 2011), such as the effects of the loss of biodiversity among pollinators and wild crops on agriculture or the effects of land conversions owing to shifts in agriculture on terrestrial ecosystems (see sections 19.3, 19.4). They do not include the effects of the degradation of ecosystem services by climate change (19.3.2.1) and ocean acidification (19.5.2), and in general assume that market services can substitute perfectly for degraded environmental services (Kopp *et al.*, 2012; Sterner and Persson, 2008; Weitzman, 2010). The global aggregate damages associated with large-scale singular events (19.6.3.6) are not well explored (Kopp and Mignone, 2012; Lenton and Ciscar, 2013).

The risk associated with aggregate impacts is similar to that expressed in AR4 and Smith *et al.*, (2009) as indicated in Figure 19-4, with risk based primarily on economic damages and confidence in the assessment unchanged. For aggregate economic impacts, there is *low* to *medium* confidence in attribution of climate change influence on a few sectors (AR5 WGII Table 18-11 and Section 18.6.4) so that this RFC is still shaded white at recent temperature in Figure 19-4. The “white” to “yellow” transition occurs around 1°C warming compared to 1986-2005 reflecting increasing confidence that the global aggregate economic impact of climate change will become negative and moderate in magnitude [*medium confidence*]. The “yellow” to “red” transition occurs around 3°C, reflecting an increase in the *magnitude* and *likelihood* of both aggregate economic risks (*low confidence*) and risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*, 19.3.2.1).

19.6.3.6. Large-Scale Singular Events: Physical, Ecological, and Social System Thresholds and Irreversible Change

Large-scale singular events (sometimes called “tipping points”, or critical thresholds) are abrupt and drastic changes in physical, ecological, or social systems in response to smooth variations in driving forces (Smith *et al.*, 2001; Smith *et al*., 2009; McNeall *et al*., 2011). Combined with widespread vulnerability and exposure, they pose key risks because of the potential magnitude of the consequences, the rate at which they would occur, and depending on this rate, the limited ability of society to cope with them. Research on the societal impacts associated with such events is limited; we focus in this section on physical hazards and ecological thresholds.

Regarding singular events in physical systems, AR4 expressed *medium confidence* that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic Ice Sheet (WAIS), would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4°C (relative to 1990-2000), causing a contribution to sea-level rise of 4-6 m or more (Schneider *et al.*, 2007). Studies since AR4 are consistent with these judgments but provide a more detailed view (see AR5 WGI Chapter 13). The Greenland ice sheet (*very likely*) and the Antarctic ice sheet (*medium confidence*) contributed to the 5m (*very high confidence*) to 10m (*high confidence*) sea level rise that occurred during the Last Interglacial (AR5 WGI SPM; Kopp *et al.* 2009; McKay *et al.*, 2011; Dutton and Lambeck, 2012). This period provides a partial analog for the magnitude of mid-to-late 21st century warming because GMT was not more than 2°C warmer than pre-industrial (AR5 WGI SPM, *medium confidence*). However, the resulting sea level rise may have taken millennia to complete.

With regard to projection, AR5 WGI finds that "The available evidence indicates that sustained warming greater than a certain threshold above preindustrial would lead to the near-complete loss of the Greenland Ice Sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than 1°C but less than 4°C global mean warming with respect to preindustrial, but *confidence* is *low"* (AR5 WGI SPM). A threshold for the disintegration of WAIS remains difficult to identify due to shortcomings in various aspects of ice sheet modeling, including representation of the dynamical component of ice loss and ocean processes. AR5 notes that sea level rise by 2300 larger than 1-3m "could result from sustained mass loss by ice sheets, and some part of the mass loss might be irreversible" (AR5 WGI SPM). Extreme exposure and vulnerability to the *magnitude* of sea level rise associated with loss of a significant fraction of either ice sheet is found worldwide (Nicholls and Tol, 2006) but millennial timescales for ice loss allow greater opportunities to adapt successfully than do century scales so *timing* is a critical and highly uncertain factor in assessing the risk.

There is also additional evidence regarding singular events in other physical systems. Feedback processes in the Earth system could cause accelerated emissions of methane from wetlands, permafrost and ocean hydrates. There are large uncertainties in the size of carbon stores, the timescales of release and the fate of the carbon once released. The risk of substantial carbon release in the form of methane or carbon dioxide increases with warming. (AR5 WGI Section 6.4.7.3, Figure 6.37; Archer *et al*., 2009; O'Connor *et al.*, 2010). AR5 WGI finds "*low confidence* in modelling abilities to simulate transient changes in hydrate inventories, but large CH_4 release to the atmosphere during this century is *unlikely*" (AR5 WGI Section 6.4.7.3). Due to such uncertainties, the existence of a tipping point cannot be ascertained.

AR4 stated that Arctic summer sea ice disappears almost entirely in some projections by the end of the century (AR4 WGI Section 10.3); WGI AR5 finds that a "nearly ice-free Arctic Ocean (sea ice extent less than 1×10^6 km^2) in September before mid-century is *likely* under RCP8.5 (*medium confidence)* but global climate models show no evidence of a tipping point" (AR5 WGI Chapter 12 ES). Whether or not the physical process is reversible, effects of ice loss on biodiversity may not be.

Large uncertainties remain in estimating the probability of a shutdown of the Atlantic meridional overturning circulation (AMOC). One expert elicitation finds the chance of a shutdown to be between 0 and 60% for global average warming between 2-4°C, and between 5 and 95% for 4-8°C of warming relative to 2000 (Zickfeld *et al.*, 2007; Kriegler *et al.*, 2009). AR5 judges that "It is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered. There is *low confidence* in assessing the evolution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results. A collapse beyond the 21st century for large sustained warming cannot be excluded" (AR5 WGI SPM).

Regarding regime shifts in ecosystems, there are "early warning signs" from detection and attribution analysis that both Arctic and warm-water coral reef systems are experiencing irreversible regime shifts (Section 18.6.4). Recent observational evidence confirms the susceptibility of the Amazon to drought and fire (Adams *et al.*, 2009), and recent improvements to models provide increased confidence in the existence of a tipping point in the Amazon from humid tropical forest to seasonal forest or grassland as the dominant ecosystem (Jones *et al.*, 2009; Lapola *et al.*, 2009; Malhi *et al.*, 2009; Section 4.3.3.1). In contrast, one recent study suggests that the Amazon may be less susceptible to crossing a tipping point than previously thought (Cox *et al.*, 2013), although this is contingent upon the uncertain role of CO_2 fertilisation being as strong as models project. Overall, recent multi-model estimates based on different CMIP3 climate scenarios and different dynamic global vegetation models predict a moderate risk of tropical forest reduction in South America (AR5 WGI Section 12.4.8.2).

Based on the weight of the above evidence, we judge that the overall risk from large-scale singular events is somewhat higher than assessed in AR4 and indicated by Smith *et al.* (2009). The position of the transition from "white" to "yellow" between 0°C and 1°C compared to 1986-2005 remains as before but with higher confidence due to the existence of early warning signs regarding regime shifts in Arctic and warm-water coral reef systems. The transition from "yellow" to "red" occurs over the 1-4°C range, consistent with Smith et al. (2009) and based primarily on the uncertainty in the warming level associated with eventual ice sheet loss. However, we assess a faster increase in risk as temperature increases between 1°C and 2°C compared to 1986-2005, largely determined by the risk arising from a very large sea level rise due to ice sheet loss as occurred during the Last Interglacial (AR5 WGI Section 5.6.2) when GMT was no more than 2°C warmer than preindustrial (*medium confidence*). This assessment of risk is based primarily on the *magnitude* and *irreversibility* of such sea level rise and the widespread exposure and vulnerability to it. However, as noted, the slower the rate of rise, the more feasible becomes adaptation to reduce vulnerability and exposure. Due to this uncertainty in *timing*, we refrain from imposing a transition to purple in Figure 19-4.

19.7. Assessment of Response Strategies to Manage Risks

The management of key and newly identified risks of climate change can include mitigation that reduces the likelihood of climate changes and physical impacts and adaptation that reduces the exposure and vulnerability of society and ecosystems to both. Key risks, impacts, and vulnerabilities to which societies and ecosystems may be subject will depend in large part on the mix of mitigation and adaptation measures undertaken, as will the evaluation of Reasons for Concern (Section 19.6.3). This section therefore assesses relationships between mitigation, adaptation, and the residual impacts that generate key risks. It also considers limits to both mitigation and adaptation responses, because understanding where these limits lie is critical to anticipating risks that may be unavoidable. Potential impacts involving thresholds for large changes in physical, ecological, and social systems (Section 19.6.3.6) are particularly important elements of key risks, and the section therefore assesses response strategies aimed at avoiding them or adapting to crossing them.

19.7.1. Relationship between Adaptation Efforts, Mitigation Efforts, and Residual Impacts

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). Evaluating potential mixes of mitigation, adaptation, and impacts requires joint consideration of outcomes for climate change and socio-economic development. A principal way in which these different mixes are assessed is comparing the impacts that result from scenarios with little or no mitigation (and therefore more climate change) to those with substantial mitigation (and less climate change). Climate change mitigation costs have been extensively explored (AR5 WGIII Chapter 6), but there has been less work on quantifying the impacts avoided by mitigation and, with the exception of studies of the impacts of sea level rise (Nicholls *et al.*, 2011), treatment of adaptation has been limited and uneven. In this section, unless otherwise stated global temperature rise is given relative to pre-industrial levels.

Impact studies generally indicate that mitigation can reduce a large proportion of climate change impacts that would otherwise occur *(high confidence).* In one study, mitigation that stabilizes global CO_2 concentrations at 500ppm reduces by 80-95% the number of people additionally at risk of hunger (largely in Africa) in 2080 under a SRES A2 scenario with CO_2 concentrations of 800ppm, avoiding an estimated 23-34 billion US$ of damage to agricultural output (Tubiello and Fischer, 2007). In Africa, there are much greater impacts upon crop productivity, freshwater resources, and ecosystems at 4^{o}C than 2^{o}C with adaptation failing to reduce risk below a 'high' level at 4^{o}C ('very high' for crop productivity), whereas at 2^{o}C risks are lower and adaptation could reduce these risks to a 'medium' level (Chapter 22 Table 22-6). In North America, with 4^{o}C warming, adaptation is not expected to reduce risks below 'high' for urban flooding (both riverine and coastal) or for fire damage in ecosystems, or below 'medium' for heat-related human mortality. Without adaptation risk is 'very high' for these sectors. In contrast at 2^{o}C risks are 'high' in these sectors, with adaptation expected to reduce urban flooding risk to 'medium' and heat-related human mortality risk to 'low' (Chapter 26 Table 26-1). Impacts on water resources would also be reduced (Chapter 3 Table 3-2). Fung *et al.* (2011) and Gosling and Arnell *et al.* (2013) both found that climate change-induced increases in water stress (defined as persons with <1700 or <1000 m3/capita/yr respectively in the two studies) globally would be reduced significantly were global temperature rise to be constrained to 2°C rather than 3.5 °C. Reducing climate change from an RCP8.5 scenario to and RCP2.6 scenario reduces the proportion of the global population that experiences >10% declines in available groundwater from 27-50% to 11-39% (Portmann *et al*., 2013).

Figure 19-6 highlights results from three studies that estimated the global avoided impacts for multiple sectors when global average temperature is limited to 2ºC rather than following scenarios with no mitigation, such as the SRES A1B or A1FI baseline scenarios in which global average temperature reaches 4 and 5.6°C respectively (Arnell *et al.*, 2013; Warren *et al.*, 2013a; Warren *et al.*, 2013b). The studies isolate the effects of climate change by using common socioeconomic assumptions in mitigation and baseline scenarios. Overall, sector-specific impacts were reduced by 20-80%, with aggregate global economic damages reduced by about one half (Warren *et al*., 2013b). The largest impacts avoided were for crop productivity, drought in cropland, biodiversity, exposure to coastal and pluvial flooding, energy use for cooling, while avoided impacts were smaller for water resources stress. Since some areas become wetter and others drier (AR5 WGI Section 12.4.5) there are regions where climate change results in decreases in flood, drought or water stress. There are shown as the blue bars in Figure 19-6. Avoided impacts are significantly larger when an A1FI baseline is used compared to an A1B baseline (Figure 19-6) because emissions and global temperature rise is greater in the A1FI baseline scenario. All these studies employed an ensemble of climate change projections based on emulation of 7 different GCM models. The proportion of impacts avoided at the global scale was relatively robust to uncertainties in regional climate projection, but the magnitude of avoided impacts varied considerably with climate projection uncertainty.

The timing of emissions reductions strongly affects impacts. In general fewer impacts can be avoided when mitigation is delayed (Arnell *et al*., 2013; Warren *et al*., 2013a; Warren *et al.*, 2013b; Figure 19-6 panel b) because there are limits to how fast emissions can be reduced subsequently to compensate for the delay (19.7.2). For example, if global emissions peak in 2016 and are then reduced at 5% annually, one half of global aggregate economic impacts might be avoided (Figure 19-6, panel b, orange bars), or around 42% if emissions are reduced more slowly at 2% annually (Figure 19-6, panel b, pink bars); compared to only one third if emissions peak in 2030 even if emissions are reduced at 5% thereafter (Warren *et al.,* 2013b, Figure 19-6, panel b, brown bars).

Avoided impacts vary significantly across regions as well as sectors (*high confidence*) due to (a) differing levels of regional climate change, (b) differing numbers of people and levels of resources at risk in different regions, and (c) differing sensitivities and adaptive capacities of humans, species or ecosystems (Tubiello and Fischer, 2007; Ciscar *et al.*, 2011; Arnell *et al.*, 2013; Section 25.10.1). The length of time it takes for avoided impacts to accrue is determined partly by the nature of the climate system. Benefits accrue least rapidly for impacts associated with sea level rise such as coastal flooding, loss of mangroves and coastal wetlands because sea level rise responds very slowly to mitigation efforts (Meehl *et al.*, 2012). Nevertheless, mitigation limits 21st century impacts of increased coastal flood damage, dry land loss and wetland loss substantially (*limited evidence*, *medium agreement*) albeit there is *little agreement* on the exact magnitude of this reduction (Section 5.4.3.1). Benefits accrue more rapidly for impacts associated with global temperature change (AR5 WGI Section 12.5.2) and those associated with reduced ocean acidification since surface pH responds relatively quickly to changes in emissions of CO_2 (Chapter 30 FAQ 30.1).

[INSERT FIGURE 19-6 HERE
Figure 19-6: Panel **a**: Climate change impacts avoided by an early, rapid mitigation scenario in which global emissions peak in 2016 and are reduced at 5% thereafter, compared to two no-mitigation baseline cases SRES A1B (orange bars) and SRES A1FI (red bars). Impacts avoided are larger if the A1FI baseline scenario is used than if the A1B baseline is used, because greenhouse gas emissions in A1FI exceed those in A1B (see 19.7.1). Panel **b**: The dependence of the potential to avoid climate change impacts upon the timing of emission reductions is illustrated. Climate change impacts avoided by the same early, rapid mitigation scenario compared to the no-mitigation baseline case SRES A1B (orange bars) are shown. The information displayed is identical to the orange bars in panel a, but a comparison is now made with the impacts avoided from two other less stringent mitigation scenarios. Impacts avoided if global emissions peak in 2016 but are subsequently reduced more slowly (2% annually) are lower (pink bars compared to orange bars). However, if mitigation occurs later, so that global emissions do not peak until 2030, even if emissions are subsequently reduced at 5% annually, the avoided impacts are smaller than in either of the

other two cases (brown bars compared to orange and pink bars). Both panels show the uncertainty range (error bars) due to regional climate change projected with 7 GCMs. Errors due to uncertainty within impacts models are not shown. Uncertainties associated with sea level rise related impacts are smaller because the models used encompass a narrow range of alternative sea level rise projections. Since increases and decreases in water stress, flood risks and crop suitability are not co-located and affect different regions, these effects are not combined. From Arnell *et al.*, 2013, Warren *et al*, 2013a; Warren *et al.*, 2013b]

In AR5 WGIII Chapter 6, the emission scenarios in the literature (as collected in the AR5 database) have been categorized on the basis of the 2100 radiative forcing (in total 7 categories). Most IAM models provide information on concentration, forcing and temperature. However, as the climate components of the IAMs differ, all scenarios were reanalyzed in the simple climate model MAGICC (Meinshausen et al. 2011) using its probabilistic set-up. The results of this categorization can be used to connect emission trajectories to climate outcomes (Figure 19-7, panel a) and impacts and risks (Figure 19-7, panel b, and Table 19-4).

Mitigation scenarios in category 1 with a 2100 CO_2-equivalent concentration of 430-480 ppm CO_2e constrain global temperature rise to between 1.3 and 2.3^{o}C above pre-industrial (Figure 19-7, panel a). These scenarios correspond to a 2011-2100 cumulative emission level of around 800-1250 $GtCO_2$ (AR5 WGIII Table 6.3). Under these scenarios, based on the MAGICC calculations, warming is *likely* to stay below 2^{o}C and *very likely* to stay below 2.5^o C during the 21st century. This significantly reduces the key risks listed in Table 19-4, as well as others discussed in this chapter. Constraining global temperature rise to 2^{o}C would constrain the risks associated with Aggregate Impacts to the 'white' or 'neutral' level, to the 'yellow' or 'moderate' level for Large Scale Singular Events and Distribution of Impacts and to the lower part of the 'red' 'high' level for Unique and Threatened Systems and Extreme Weather Events. The temperature levels in the RCP2.6 scenario are 1.2-2.0^o C (AR5 WG1 Table 12.2) matching closely the scenarios in this category.

Mitigation scenarios in category 2 with a 2100 concentration of 480-530 ppm CO_2e in 2100 correspond to a global temperature rise between 1.4 and 2.7^{o}C in the MAGICC calculations. These scenarios correspond to a cumulative emission level over the 2011-2100 period on the order of 1000-1500 $GtCO_{2.}$ (AR5 WGIII Table 6.3) and lead to likelihood of staying below roughly 2^{o}C of *more-likely-than-not (50-66%)*. Thus, scenarios in category 2 also reduce risks, but to a lesser extent than for category 1. If global temperature rise reaches 2.5^o C in 2100, levels of risk due to Extreme Weather Events are at the 'red' 'high' level, whilst those to Unique and Threatened Systems now reach the 'very high' or 'purple' level reflecting inability to adapt. Risks associated with Aggregate Impacts reach the 'yellow' 'moderate' level, whilst risks to the Distribution of Impacts and Large Scale Singular Events closely approach the 'red' or 'high' level.

Mitigation scenarios in category 3 with 530-580 ppm CO_2e constrain temperature rise to between 1.7 and 2.9^o C above pre-industrial levels, affording little protection to coral reefs, so that risks to Unique and Threatened Systems remain 'high' or 'very high' indicating inability to adapt. Risks associated with Extreme Weather Events remain at the 'high' level. Risks to Distribution of Impacts may be 'moderate' or 'high'. Levels of risk in Aggregate Impacts and Large Scale Singular Events are constrained to the upper 'moderate' level.

Mitigation scenarios in category 4 with 580-720 ppm CO_2e result in range of possible temperature outcomes between 1.8 and 3.6^o C above pre-industrial levels, affording very little protection to coral reefs, whilst risks to Unique and Threatened Systems remain 'high' or 'very high' indicating inability to adapt. Risks associated with Extreme Weather Events and Distribution of Impacts remain 'high'. Levels of risk associated with Aggregate Impacts and Large Scale Singular Events may be 'moderate' or 'high'. *(high confidence).* Global temperature rise in RCP4.5 in 2100 is 1.9-2.9^o C above pre-industrial levels (AR5 WG1 Table 12.2) matching the low scenarios in this category.

Onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Section 5.4.1.6, 5.4.2.4, 19.6.3.2, 26.4.2.1; Silverman *et al.* 2009), due to the combined effects of warming and ocean acidification. However already at 450 ppm, reef growth rates are projected to be reduced by more than 60% globally; and by at least 20% globally at 380ppm (Silvermann *et al.*, 2009). Coral organisms themselves are projected to be damaged by warming at concentrations below 560 ppm: specifically, RCP4.5 is projected to result in long term degradation of

2/3 of coral reefs, compared with 1/3 of them under RCP3PD (Box CC-CR) *(medium confidence)*. Hence, maintenance of moderately healthy coral reefs is consistent only with scenarios in the scenarios in the 430-480 ppm CO_2e category; while some reef protection is achieved with scenarios in the category 480-530 ppm CO_2e. A low level of protection exists for the category 530-580 ppm CO_2e while all other categories exceed the 560ppm level.

Finally, scenarios in category 6 with a concentration level above >1000 ppm CO_2e are projected to result in temperature rise of between 3.3 and 6.3^{o}C above pre-industrial with negligible chances to constrain it below 2.5^{o}C above pre-industrial (panel a) and would allow significant key risks to persist in all the areas listed in Table 19-4.Risk is at the 'red' level for all Reasons for Concern except Unique and Threatened Systems, where risk is at the purple level indicating infeasibility of adaptation. For Distribution of Impacts, risk reaches the transition to purple if temperatures rise in excess of 4^{o}C above pre-industrial levels. For the scenarios with a concentration level between 720 ppm and 1000 ppm, category 5, outcomes for risk levels are similar to the highest category, except that risk to Aggregate Impacts is at the 'yellow' 'moderate' level.

Scenarios with rapid, early mitigation (particularly those which with a 2100 CO_2-equivalent concentration of 430-480 ppm CO_2e) generally delay the onset of a given global annual mean temperature rise until several decades later in the century than is the case for scenarios with slower, delayed mitigation or no mitigation (such as those with a 2100 CO_2-equivalent concentration of 720-1000 ppm), thus allowing impacts to be further reduced by adaptation during this time.

[INSERT FIGURE 19-7 HERE
Figure 19-7: Relationship between mitigation scenarios considered in AR5 WGIII, in terms of their CO_2e concentrations and global temperature rise outcomes relative to pre-industrial times, and level of risk associated with Reasons for Concern. Panel **a** shows the projected increase in global mean temperature in 2100 compared to preindustrial, calculated using the MAGICC climate model for the scenarios defined in Chapter 6, Working Group III, indicating the uncertainty range resulting both from the range of emission scenario projections within each category and the uncertainty in the climate system as represented by MAGICC (data taken from Chapter 6 – AR5 WGIII). Panel **b** reproduces Figure 19-4 for ease of comparison. Note the different temperature baselines used in Figure 19-4. Beyond 2100, temperature, and therefore risk, decreases in most of the lowest three scenarios and increases further in most of the others.]

19.7.2. Limits to Mitigation

Mitigation possibilities, such as those implicit in scenarios discussed in 19.7.1, are not unlimited. Assessment of maximum feasible mitigation (and lowest feasible emissions pathways) must account for the fact that feasibility is a subjective concept encompassing technological, economic, political, and social dimensions (Hare *et al.*, 2010, UNEP Chapter 2). Most mitigation studies have focused on technical feasibility, for example demonstrating that it is possible to reduce emissions enough to have at least a 50% chance of limiting warming to less than 2 °C relative to pre-industrial (den Elzen and van Vuuren, 2007; Clarke *et al.*, 2009; Edenhofer *et al.*, 2010; Hare *et al.*, 2010; O'Neill *et al.*, 2010), taking into account uncertainty in climate and carbon cycle response to emissions (see AR5 WGI Section 12.5.4 for a discussion of uncertainties in the relationship between emissions and long-term climate stabilization targets). RCP2.6, based on an integrated assessment model-based mitigation scenario (van Vuuren et al., 2012), is *unlikely* to produce more than 2°C of warming relative to pre-industrial (*medium confidence*; AR5 WGI Section 12.4.1.1). Such scenarios lead to pathways in which global emissions peak within the next 1-2 decades and decline to 50-85% below 2000 levels by 2050 (or 40-70% compared to 1990 levels), and in some cases exhibit negative emissions before the end of the century (Metz *et al.*, 2007, den Elzen *et al.*, 2007, Den Elzen *et al.*, 2010, van Vuuren et al. 2012). Very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5 °C with at least 50% likelihood (Rogelj et al., 2012); most 1.5 °C scenarios have been based on stylized emissions pathways (Hare *et al.*., 2010; Ranger *et al.*, 2012). The highest emission reduction rate considered in most integrated modeling studies that attempt to minimize mitigation cost is typically between 3 and 4% but with larger values not ruled out although some studies find that for an additional cost higher rates may be achievable (den Elzen *et al.*, 2010; O'Neill *et al.*, 2010).

However, most studies of feasibility include a number of idealized assumptions, including availability of a wide range of mitigation technologies such as large-scale renewable and biomass energy, and carbon capture and storage (CCS). Most also assume universal participation in mitigation efforts beginning immediately, economically optimal reductions (i.e., reductions are made wherever they are cheapest), and no constraints on policy implementation. Any deviation from these idealized assumptions can significantly limit feasible mitigation reductions (Knopf *et al.*, 2010; Rogelj *et al.*, 2012). For example, delayed participation in reductions by non-OECD countries made concentration limits such as not exceeding 450 ppm CO_2eq (roughly consistent with a 50% chance of remaining below 2 °C relative to pre-industrial), and in some cases even 550 ppm CO_2eq, unachievable in some models unless temporary overshoot of these targets (Izrael and Semenov, 2006) were allowed (Clarke *et al.*, 2009), but not in others (Waldhoff and Fawcett, 2011). Technology limits, such as unavailability of CCS or limited expansion of renewables or biomass makes stabilization at 450 ppm CO_2eq (or 2 °C with a 50% chance) unachievable in some models (Krey and Riahi, 2009; van Vliet *et al.*, 2012). Similarly, if the political will to implement coordinated mitigation policies within or across a large number of countries were limited, peak emissions and subsequent reductions would be delayed (Webster *et al.*, 2010).

These considerations have led some analysts to doubt the plausibility of limiting warming to 2 °C (Anderson and Bows, 2008; Tol, 2009; Anderson and Bows, 2011). "Emergency mitigation" options have also been considered that would go beyond the measures considered in most mitigation analyses (Swart and Marinova, 2010). These include drastic emissions reductions achieved through limits on energy consumption (Anderson and Bows, 2011) or geoengineering through management of the earth's radiation budget (19.5.4; AR5 WGI Chapters 6, 7).

19.7.3. Avoiding Thresholds, Irreversible Change, and Large-Scale Singularities in the Earth System

Section 19.6.3.6 discussed the Reasons for Concern related to non-linear changes in the Earth system (“large-scale singular events”), whereby anthropogenic forcings might cause irreversible and potentially rapid transitions over a wide range of time scales (see, for example, WGI: SPM, TS, TFE5, and section 12.5, WGII: section 19.6.3, as well as Lenton *et al*., 2008). The risk of triggering such transitions generally increases with increasing anthropogenic climate forcings / climate change (Lenton *et al.*, 2008; Kriegler *et al.*, 2009; Levermann *et al.*, 2012). Reducing greenhouse gas emissions is projected to reduce the risks of triggering such transitions [*medium confidence*]. Adaptation could reduce their potential consequences, but the efficacy of adaptation might be limited, for example for rapid transitions (19.7.5).

Several studies have sought to identify levels of atmospheric greenhouse gas concentrations or global average temperature change that would limit the risks of triggering these transitions (e.g., Keller *et al.*, 2005, 2008; Kriegler *et al.*, 2009; Lenton *et al.*, 2008). Section 19.6.3.6 assesses evidence regarding the relationship between global average temperature and risks of disintegration of major ice sheets, loss of Arctic sea ice, shutdown of the Atlantic meridional overturning circulation (AMOC), carbon releases from temperature-related feedback processes, and regime shifts in ecosystems. Additional aspects of these risks are important to mitigation strategies. For example, it is important to distinguish between triggering and experiencing a threshold response because model simulations suggest that there can be sizeable delays between the two (e.g., Lenton *et al.*, 2008). The location of these trigger points can be difficult to determine from process-based models alone, as some of these models lack potentially important processes (see e.g., AR5 WGI Chapter 13). In this situation, expert elicitations can provide additional useful information for risk assessments. One such assessment based on expert elicitation (Lenton *et al.*, 2008) finds that limiting global mean temperature increase to approximately 3°C above recent (1980–1999) values would considerably reduce the risks of triggering some nonlinear responses. In general, there is *low confidence* in the location of such temperature limits due to disagreements among experts. Estimates of such temperature limits can change over time (Oppenheimer et al., 2008) and may be subject to overconfidence that can introduce a downward bias in risk estimates of low-probability events (Morgan and Henrion, 1990). The climate threshold responses can interact (e.g., Kriegler *et al*., 2009). Other climate change metrics (e.g., rates of changes or atmospheric carbon dioxide concentrations) can also be important in the consideration of response strategies aimed at reducing the risk of crossing thresholds (Lenton, 2011a; McAlpine *et al.*, 2010).

Several analyses have performed risk- and decision-analyses for specific thresholds, mostly focusing on a persistent weakening or collapse of the AMOC (Bahn *et al.*, 2011; McInerney *et al.*, 2012; Urban and Keller, 2010; Zickfeld and Bruckner, 2008). Experiencing AMOC collapse has been assessed as *very unlikely* in this century and there is *low confidence* in assessing the AMOC beyond the 21st century [AR5 WGI SPM]. However, due to lags in the ocean system, the probability of triggering an eventual collapse differs from that of experiencing such an outcome (Urban and Keller, 2010). A probabilistic analysis sampling a subset of the relevant uncertainties concluded that reducing the probability of a collapse within the next few centuries to one in ten requires emissions reductions of roughly 60% relative to a business-as-usual strategy by 2050 (McInerney and Keller, 2008). Bruckner and Zickfeld (2009) show that, under their worst-case assumptions about key parameter values, emissions mitigation would need to begin within the next two decades to avoid reducing the overturning rate by more than 50%.

Threshold risk estimates and evaluations of risk-management strategies are sensitive to factors such as the representation of uncertainties and the decision-making frameworks used (McInerney *et al.*, 2012; Polasky *et al.*, 2011). Several analyses have examined how the consideration of threshold events affects response strategies. For example, the design of risk-management strategies could be informed by observation and projection systems that would provide an actionable early warning signal of an approaching threshold response. Learning about key uncertain parameters (e.g., climate sensitivity or impacts of a threshold response) can considerably affect risk-management strategies and have a sizeable economic value of information (Keller *et al.*, 2004; Lorenz *et al.*, 2012). However, there is limited evidence about the feasibility and requirements for such systems due to the small number of studies and their focus on highly simplified situations (Keller and McInerney, 2008; Lenton, 2011b, Lorenz *et al.*, 2012). In some decision-analytic frameworks, knowing that a threshold has been crossed can lead to reductions in emissions mitigation and a shift of resources toward adaptation and/or geoengineering (Guillerminet and Tol, 2008; Keller *et al.*, 2004; Lenton, 2011b; Swart and Marinova, 2010).

19.7.4. Avoiding Tipping Points in Social/Ecological Systems

Tipping points (see Glossary) in socio-ecological systems are defined as thresholds beyond which impacts increase non-linearly to the detriment of both human and natural systems. These can be initiated rapidly, inducing a need for rapid response. For example, regime shifts have already occurred in marine food webs (Byrnes *et al.*, 2007; Alheit, 2009, Green *et al*., 2008, section 6.3.6) due to (observed) changes in sea surface temperature, changes in salinity, natural climate variability, and/or overfishing.

Because human and ecological systems are linked by the services that ecosystems provide to society (Lubchenko and Petes, 2010; McLeod and Leslie 2009), tipping points may be crossed when either the ecosystem services are disrupted and/or social/economic networks are disrupted (Renaud *et al.*, 2010). Climate change provides a stress that increases the risk that tipping points will be crossed, although they may be crossed due to other types of stresses even in the absence of climate change. For example, in dryland ecosystems overgrazing has caused grassland-to-desert transitions (Pimm, 2009). The likelihood of crossing tipping points due to climate change may be reduced by preserving ecosystem services through (i) limiting the level and rate of climate change [*medium confidence*] *and*/or (ii) removing concomitant stresses such as overgrazing, fishing, habitat destruction, and pollution. Most literature currently focuses on strategy (ii), and there is limited information about the exact levels and rates of climate change that specific coupled socio-economic systems can withstand. Examples of strategy (ii) include maintaining resilience of coral reefs, cephalopod or piscivorous seabird populations by removal of concomitant stress from fishing (Andre *et al*., 2010; Anthony *et al*., 2011; Sections 6.3.6, 30.6.2) or expanding protected area networks (Brodie *et al*., 2012). Removal of concomitant stress such as nutrient loading can reduce the chance of a regime shift (Jurgensone *et al*., 2011) in coral reef ecosystems (De'ath *et al.*, 2012). Sometimes management can reverse the crossing of a tipping point, e.g. by adding sediment to a submerged salt marsh (Stagg and Mendelssohn, 2010). Strategy (ii) is enhanced by resilience-based management approaches in ecosystems (Walker and Salt 2006; Lubchenko and Petes 2010; Allen *et al*. 2011; Selig *et al.*, 2012). A high level of biodiversity increases ecosystem resilience and can enable recovery after crossing a tipping point (Brierley and Kingsford, 2009; Lubchenko and Petes, 2010). Strategy (ii) generally becomes ineffective once climate changes beyond an uncertain and spatially variable threshold; also successive thresholds may be crossed as stress increases (Renaud *et al.*, 2010).

Monitoring that aims to detect a slow-down in the recovery of systems from small changes (van Nes and Scheffer, 2005) or to measure an appropriate indicator (Biggs *et al*., 2008) may give warning that a system is a approaching a regime shift, justifying intervention of type (ii) (Guttal and Jayaprakash, 2009; Brock and Carpenter, 2010). Such indicators have been identified for the desertification process in the Mediterranean (Alados *et al*., 2011) and for landscape fire dynamics (Zinck *et al.,* 2011; McKenzie and Kennedy, 2012).

19.7.5. Limits to Adaptation

Chapter 16.2 and 16.5 provide a thorough assessment of the literature on limits to adaptation. Discussions are beginning on the nature of such limits, e.g. in terms of different dimensions of the limits to adaptation, including financial or economic limits to adapt, but also social and political or cognitive limits of adaptation. Limits to adaptation (see e.g. Adger *et al.*, 2009) are also recognized in terms of specific geographies, for example small island developing states and their limited ability to adapt to increasing impacts of sea level rise, the limits to adaptation of urban agglomerations in low-laying coastal zones (see e.g. Birkmann *et al.*, 2010), or in relation to loss of water supplies as a result of glacier retreat (Orlove, 2009). Overall, the concept of limits to adaptation is closely related to key vulnerabilities and key risks including those identified in Table 19-4 and cross-chapter Box CC-KR, because this concept helps define residual risk.

Frequently Asked Questions

FAQ 19.1: Does science provide an answer to the question of how much warming is unacceptable?
[to be placed in Section 19.1.3]
No. Careful, critical scientific research and assessment can provide information to help society consider what levels of warming or climate change impacts are unacceptable. However, the answer is ultimately a subjective judgment that depends on values and culture, as well as socioeconomic and psychological factors, all of which influence how people perceive risk in general and the risk of climate change in particular. The question of what level of climate change impacts is unacceptable is ultimately not just a matter of the facts, but how we feel about those facts.

This question is raised in Article 2 of the UN Framework Convention on Climate Change (UNFCCC). The criterion, in the words of Article 2, is “dangerous anthropogenic interference with the climate system” - a framing that invokes both scientific analysis and human values.

Agreements reached by governments since 2009, meeting under the auspices of the UNFCCC, have recognized “the scientific view that the increase in global temperature should be below 2 degrees Celsius” (Chapter 19.1, UNFCCC, Copenhagen Accord). Still, as informed on the subject as the scientists referred to in this statement may be, theirs is just one valuable perspective. How each country or community will define acceptable or unacceptable levels, essentially deciding what is ‘dangerous’, is a societal judgment.

Science can certainly help society think about what is unacceptable. For example, science can identify how much monetary loss might occur if tropical cyclones grow more intense or heat waves more frequent, or identify the land that might be lost in coastal communities for various levels of higher seas. But “acceptability” depends on how each community values those losses. This question is more complex when loss of life is involved and yet more so when damage to future generations is involved. These are highly emotional and controversial value propositions that science can only inform, not decide.

The purpose of this chapter is to highlight key vulnerabilities and key risks that science has identified; however, it is up to people and governments to determine how the associated impacts should be valued, and whether and how the risks should be acted upon.

FAQ 19.2: How does climate change interact with and amplify pre-existing risks?
[to be placed in Section 19.3.2.4]
There are two components of risk: the probability of adverse events occurring and the impact or consequences of those events. Climate change increases the probability of several types of harmful events that societies and ecosystems already face, as well as the associated risks. For example, people in many regions have long faced threats associated with weather-related events like extreme temperatures and heavy precipitation (which can trigger flooding). Climate change will increase the likelihood of these two types of extremes as well as others. Climate

change means that impacts already affecting coastal areas, like erosion and loss of property in damaging storms, will become more likely due to sea level rise. In many areas, climate change increases the already high risks to people living in poverty or to people suffering from food insecurity or inadequate water supplies. Finally, climate and weather already pose risks for a wide range of economic sectors, including agriculture, fisheries, and forestry: climate change increases these risks for much of the world.

Climate change can amplify risks in many ways, including through indirect interactions with other risks. These are often not considered in projections of climate change impacts. For example, hotter weather contributes to increased amounts of ground level ozone (smog) in polluted areas, exacerbating an existing threat to human health, particularly for the elderly and the very young and those already in poor health. Also, efforts to mitigate or adapt to climate change can have negative as well as positive effects. For example, government policies encouraging expansion of biofuel production from maize have recently contributed to higher food prices for many, increasing food insecurity for populations already at risk, and threatening the livelihoods of those like the urban poor who are struggling with the inherent risks of poverty. Increased tapping of water resources for crop irrigation in one region in response to water shortages related to climate change can increase risks to adjacent areas that share those water resources. Climate change impacts can also reverberate by damaging critical infrastructure like power generation, transportation, or health care systems.

FAQ 19.3: How can climate change impacts on one region cause impacts on other distant areas?
[to be placed in Section 19.4.3.2]
People and societies are interconnected in many ways. Changes in one area can have ripple effects around the world through globally linked systems like the economy. Globalized food trade means that changed crop productivity as a result of extreme weather events or adverse climate trends in one area can shift food prices and food availability for a given commodity worldwide. Depletion of fish stocks in one region due to ocean temperature rise can cause impacts on the price of fish everywhere. Severe weather in one area that interferes with transportation or shipping of raw or finished goods, like refined oil, can have wider economic impacts.

In addition to triggering impacts via globally linked systems like markets, climate change can alter the movement of people, other species, and physical materials across the landscape, generating secondary impacts in places far removed from where these particular direct impacts of climate change occur. For example, climate change can create stresses in one area that prompt some human populations to migrate to adjacent or distant areas. Migration can affect many aspects of the regions people leave, as well as many aspects of their destination points, including income levels, land use and the availability of natural resources, and the health and security of the affected populations – these effects can be positive or negative. In addition to these indirect impacts, all regions experience the direct impacts of climate change.

Cross-Chapter Box

Box CC-KR. A Selection of the Hazards, Key Vulnerabilities, Key Risks, and Emergent Risks Identified in the WGII Contribution to the Fifth Assessment Report

The accompanying table provides a selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems which often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g. urbanization and other demographic changes) in combination and in specific development context (e.g. in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. A representative set of lines of sight is provided from across WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries. [NB: See tables file for the table embedded in Box CC-KR.]

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Table 19-1: Examples of global and national ecosystem service valuation studies. This table is not intended to be comprehensive. Furthermore, it encompasses studies based on a wide range of methodologies.

Ecosystem Service	**Region**	**Value**	**Currency**	**Citation**
Pollination of crops	Globe	153 bn	Euro	Gallai *et al*. 2008
Pollination of crops and wild plants	UK	430 m	£	NEA, 2011
Woodland cover increase from 6 to 12%	UK	680m	£	NEA, 2011
CO_2 fixation, O_2 release, nutrient recycling, soil protection, water holding capacity and environmental purification	Chinese terrestrial ecosystems	3×10^{13}	RMB/yr	Ke and Hong, 1999
Climate regulation provided by forests	US	1bn-6bn	$/yr	Krieger, 2001
Recreation provided by forests	US	1.3bn-110bn	$/yr	Krieger, 2001
Biodiversity supported by forests	US	5bn-54bn	$/yr	Krieger, 2001
Coral reef services	Australia	5.4bn	Au$	19.3.2.4, Box CC-CR
Coral reef services	Florida (USA)	1.6	$	19.3.2.4

Table 19-2: Emergent risks related to biofuel production as a mitigation strategy.

Issue number	**Issue description**	**Nature of emergent risk**	**Reference**
(i) Direct and/or indirect land use change (iLUC)	Potential for enhancement of greenhouse gas emissions	Mitigation benefit of biofuels reduced or negated	Wise et al., 2009, Melillo et al., 2009, Khanna et al., 2011
(ii) Policies targeting only fossil carbon	Biofuel cropping competes with agricultural systems and ecosystems for land and water	Mitigation benefit of policies reduced, harmful interactions with other key systems	Wise et al., 2009, Mellilo et al., 2009, Searchinger et al., 2008, Fargione et al., 2010
(iii) Food/fuel competition for land	Competition for land driving up food prices	Emergent risk of food insecurity due to mitigation-driven land use change	Hertel et al., 2010, Searchinger et al., 2008, Pimentel et al., 2009
(iv) Biofuels production affects water resources	Competition for water affects biodiversity and food cropping	Emergent risk of biodiversity loss and food insecurity due to mitigation-driven water stress	Fargione et al., 2010, Fingerman et al., 2010, Yang et al., 2012, Poudel et al., 2012
(v) Biofuels production affects biodiversity	Competition for land reduces natural forest and biodiversity	Emerging risk of biodiversity loss due to mitigation-driven land use change	Lapola et al., 2010, Koh et al., 2009, Fizherbert et al., 2008, Fletcher Jr. et al., 2011
(vi) Land conversion causes air pollution	Potential for increased production of tropospheric ozone from palm/sugarcane-induced LUC	Emergent risk of GHG-mitigation-driven plant and human health damage caused by tropospheric ozone	Hewitt et al., 2009, Cançado et al., 2006
(vii) Fertilizer application	Potential for increased emissions of N2O	Offsets some benefits of other mitigation measures	Donner and Kucharik, 2008, Searchinger et al., 2008, Fargione et al., 2010
(viii) Invasive properties of biofuel crops	Potential to become an invasive species	Unintended consequences that damage agriculture and/or biodiversity	Barney and Ditomaso 2008, DiTomaso et al., 2007, Raghu et al., 2006

Table 19-3: An assessment of the risks to ecosystem services posed by the impacts of ocean acidification on coral calcification and nitrogen fixation, based on the four criteria for key risks (19.2.2.2).

Criterion for key risk	**Coral calcification**	**Nitrogen fixation**
1. Magnitude of consequences for ecosystem services	Ecosystem services include supporting habitats, provisioning of fish, regulating shoreline erosion, and tourism. Potential magnitude of consequences is *medium* to *high* (Box CC-CR).	Ecosystem services include nitrogen cycling, which supports ecosystem structure and food chains (Hutchins et al., 2009). Potential magnitude of consequences has not been investigated.
2. Likelihood that risks will materialize and their timing	A reduction in coral calcification rate and an increase in reef dissolution rates are *very likely* (6.1.2), so that reefs will progressively shift toward net dissolution (*medium confidence*, Section 5.4.2.4; Box CC-CR; Box CC-OA)	Both increases and decreases in nitrogen fixation have been observed in various N2-fixing organisms (Section 6.3.2.2) but there is *limited in situ evidence* and *medium agreement* on how N_2-fixation rates will change in response to ocean acidification.
3. Irreversibility and persistence of ocean acidification impacts	Decreases in ocean pH will persist as long as atmospheric CO2 levels remain elevated. (AR5 WGI Section 3.8.2). Reductions in coral calcification will persist unless corals can physiologically adapt to maintain calcification rates. Reversibility of impacts on ecosystem services of coral reefs is unknown and depends on ecological factors such as hysteresis.	Decreases in ocean pH will persist as long as atmospheric CO2 levels remain elevated. (AR5 WGI Section 3.8.2). Reversibility and persistence of impacts on nitrogen fixation are unknown.
4. Limited ability to reduce the magnitude and frequency or nature of ocean acidification impacts	Reduction of ocean acidification will require global reductions in atmospheric CO2. Feasibility of mitigating ocean acidification at the local scale is unknown.	Reduction of ocean acidification will require global reductions in atmospheric CO2.

Table 19-4: A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems, and ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land-tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems which often provide important services to vulnerable communities, generate the context in which climatic change related harm and loss can occur. The table illustrates that current global megatrends (e.g. urbanization and other demographic changes) in combination and in specific development context (e.g. in low-lying coastal zones), can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. Roman numerals correspond with key risks listed in 19.6.2.1. A representative set of lines of sight is provided from across AR5 WGI and WGII. See Section 19.6.2.1 for a full description of the methods used to select these entries.

#	Hazard	Key vulnerabilities		Key risks	Emergent risks
i	Sea level rise, coastal flooding including storm surges. [AR5 WGI Sections 3.7.1, 13.5.1, Table 13-5; AR5 WGII Sections 5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, Box 25-1, Box 25-7, 26.7, 26.8, 29.3.1, 30.3.1]	High exposure of people, economic activity, and infrastructure in low-lying coastal zones and Small Island Developing States (SIDS). Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods. Insufficient local governmental attention to disaster risk reduction.	exposure social vulnerability institutional vulnerability	Death, injury, and disruption to livelihoods, food supplies, and drinking water. Loss of common-pool resources, sense of place, and identity, especially among indigenous populations in rural coastal zones.	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality.
ii	Warming, drought, and precipitation variability [AR5 WGI Section 11.3.2; AR5 WGII Sections 7.4, 7.5, 11.3, 11.6.1, 13.2.1, 13.2.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4]	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households.	social vulnerability institutional vulnerability	Risk of harm and loss of life due to reversal of progress in reducing malnutrition.	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality, and on-going food insecurity for the poor increases malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.
iii	Extreme precipitation and inland flooding. [AR5 WGI Section 11.3.2.5; AR5 WGII Sections 3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, Box 25-8, 26.3, 26.7, 26.8, 27.3.5]	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements. Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, culturally imposed gender roles.	exposure social vulnerability	Death, injury, and disruption of human security, especially among children, elderly, and disabled.	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high risk/high

		Inadequate governmental attention to disaster risk reduction.	institutional vulnerability		poverty spatial traps.
iv	Drought. [AR5 WGI Section 12.4.1, 12.4.5; AR5 WGII Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, 24.4]	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural-urban linkages.	social vulnerability institutional vulnerability	Insufficient water supply for people and industry yielding severe harm and economic impacts.	Interaction of urbanization, infrastructure insufficiency, groundwater depletion.
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water. Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources. Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods.	exposure social vulnerability institutional vulnerability	Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods particularly for those depending on water-intensive agriculture. Risk of food insecurity.	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in low and middle income countries. Potential tipping point in rain-fed farming system and/or pastoralism.
v	Novel hazards yielding systemic risks. [AR5 WGI Section 11.3.2; AR5 WGII Sections 8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, 26.8]	Populations and infrastructure exposed and lacking historical experience with these hazards. Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability.	exposure institutional vulnerability	Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on tele-communications. Collapse of health and emergency services in extreme events.	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
vi	Rising ocean temperature, ocean acidification, and loss of Arctic sea ice [AR5 WGI Section 11.3.3; AR5 WGII Sections 5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2.3, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, 30. 6, CC-OA, CC-CR]	High susceptibility of warm water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture.	environmental vulnerability economic vulnerability environmental vulnerability	Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms.	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk.

vii	Rising land temperatures, changes in precipitation patterns, and frequency and intensity of extreme heat [AR5 WGI Section 11.3.2.5; AR5 WGII Sections 4.3.4, FAQ 4.4, 19.3.2.1, 22.4.5.6, Table 23-2, 27.3.2.1, Box CC-WE]	Susceptibility of societies to loss of provisioning, regulation, and cultural services from terrestrial ecosystems. Susceptibility of human systems, agro-ecosystems and natural ecosystems to (i) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate (ii) loss of provision of food, livestock, fibre, bioenergy (iii) loss of recreation, tourism, aesthetic and heritage values, and biodiversity,	economic vulnerability environmental vulnerability	Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms.	Interaction of social-ecological systems with loss of ecosystem services upon which they depend.
viii	Increasing frequency and intensity of extreme heat, including urban heat island effect. [AR5 WGI Section 11.3.2; AR5 WGII Sections 8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8, CC-HS]	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures. Inability of local organizations which provide health, emergency and social services to adapt to new risk levels for vulnerable groups.	social vulnerability institutional vulnerability	Increased mortality and morbidity during periods of extreme heat.	Interaction of changes in regional temperature extremes, local heat island, and air pollution, with demographic shifts. Overloading of health and emergency services. Mortality, morbidity, and productivity loss among manual workers in hot climates.

Box CC-KR Table

Examples of Hazards/Stressors, Key Vulnerabilities, Key Risks and Emergent Risks (using input from chapter 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, 30)			
Hazard	**Key vulnerabilities**	**Key risks**	**Emergent risks**
Terrestrial and inland water systems (chapter 4)			
Rising air, soil, and water temperature [4.2.4, 4.3.2, 4.3.3]	Exceedance of eco-physiological climate tolerance limits of species (limited coping and adaptive capacities), increased viability of alien organisms.	Risk of loss of native biodiversity, increase in non-native organism dominance.	Cascades of native species loss due to interdependencies.
	Health response to spread of temperature-sensitive vectors (insects).	Risk of novel and/or much more severe pest and pathogen outbreaks.	Interactions between pest, drought and fire can lead to new risks and large negative impacts on ecosystems.
Change in seasonality of rain [4.3.3]	Increasing susceptibility of plants and ecosystem services, due to mismatch between plant life strategy and growth opportunities.	Changes in plant functional type mix leading to biome change with respective risks for ecosystems and ecosystem services.	Fire-promoting grasses grow in winter-rainfall areas and provide fuel in dry summers.
Ocean systems (chapter 6)			
Rising water temperature, increase of (thermal and haline) stratification, and marine acidification [6.1.1]	Tolerance limits of endemic species surpassed (limited coping and adaptive capacities), increased abundance of invasive organisms, high susceptibility and sensitivity of warm water coral reefs and respective ecosystem services for coastal communities. [6.3.1, 6.4.1]	Risk of loss of endemic species, mixing of ecosystem types, increased dominance of invasive organisms. Increasing risk of loss of coral cover and associated ecosystem with reduction of biodiversity and ecosystem services. [6.3.1]	Enhancement of risk due to interactions, e.g., acidification and warming on calcareous organisms. [6.3.5]
	New vulnerabilities can emerge due to shifted productivity zones and species distribution ranges, largely from low to high latitudes [6.3.4, 6.5.1], shifting fishery catch potential with species migration. [6.3.1, 6.5.2, 6.5.3]	Risks due to unknown productivity and services of new ecosystem types. [6.4.1, 6.5.3]	Enhancement of risk due to interactions of warming, hypoxia, acidification, new biotic interactions. [6.3.5, 6.3.6]
Expansion of oxygen minimum zones and coastal dead zones with stratification and eutrophication. [6.1.1]	Increasing susceptibility because hypoxia tolerance limits of larger animals surpassed, habitat contraction and loss for midwater fishes and benthic invertebrates. [6.3.3]	Risk of loss of larger animals and plants, shifts to hypoxia adapted, largely microbial communities with reduced biodiversity. [6.3.3]	Enhancement of risk due to expanding hypoxia in warming and acidifying oceans. [6.3.5]
Enhanced harmful algal blooms in coastal areas due to rising water temperature.	Increasing susceptibility and limited adaptive capacities of important ecosystems and	Increasing risk due to enhanced frequency of dinoflagellate blooms and	Disproportionate enhancement of risk due to interactions of various

[6.4.2.3]	valuable services due to already existing multiple stresses. [6.3.5, 6.4.1]	respective potential losses and degradations of coastal ecosystems and ecosystem services. [6.4.2]	stresses. [6.3.5]
Food production systems and food security (chapter 7)			
Rising average temperatures and more frequent extreme temperatures [7.1, 7.2, 7.4, 7.5]	Susceptibility of all elements of the food system from production to consumption, particularly for key grain crops.	Risk of crop failures, breakdown of food distribution and storage processes.	Increase in the global population to ca. 9 billion combined with rising temperatures and other trace gases such as ozone affecting food production and quality. Upper temperature limit to the ability of some food systems to adapt.
Extreme precipitation and droughts [7.4]	Crops, pasture, and husbandry are susceptible and sensitive to drought and extreme precipitation.	Risk of crop failure, risk of limited food access and quality.	Flood and droughts affect crop yields and quality, and directly affect food access in most developing countries. [7.4]
Urban areas (chapter 8)			
Inland flooding [8.2.3, 8.2.4]	Large numbers of people exposed in urban areas to flood events. Particularly susceptible are people in low-income informal settlements with inadequate infrastructure (and often on flood plains or along river banks). These bring serious environmental health consequences from overwhelmed, aging, poorly maintained and inadequate urban drainage infrastructure and widespread impermeable surfaces. Local governments are often unable or unwilling to give attention to needed flood-related disaster risk reduction. Much of the urban population unable to get or afford housing that protects against flooding, or insurance. Certain groups more sensitive to ill health from flood impacts – that may include increased mosquito and water borne diseases.	Risks of deaths and injuries and disruptions to livelihoods/incomes, food supplies and drinking water.	In many urban areas, larger and more frequent flooding impacting much larger population. No insurance available or impacts reaching the limits of insurance. Shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts and the creation of high risk/high poverty spatial traps.
Coastal flooding (including sea level rise and storm surge) [8.1.4, 8.2.3, 8.2.4]	High concentrations of people, businesses and physical assets including critical infrastructure	Risks from deaths and injuries and disruptions to livelihoods/incomes, food supplies and drinking water.	Additional 2 billion or so urban dwellers expected over the next 3 decades. Sea level rise means

	exposed in low-lying and unprotected coastal zones. Particularly susceptible is urban population that is unable to get or afford housing that protects against flooding or insurance. Local government unable or unwilling to give needed attention to disaster risk reduction.		increasing risks over time, yet with high and often increasing concentrations of population and economic activities on the coasts. No insurance available or reaching the limits of insurance; shift in the burden of risk management from the state to those at risk leading to greater inequality and property blight, abandonment of urban districts and the creation of high risk/high poverty spatial traps.
Heat and cold (including urban heat island effect) [8.2.3]	Particularly susceptible is a large and often increasing urban population of infants, young children, older age groups, expectant mothers, people with chronic diseases or compromised immune system in settlements exposed to higher temperatures (especially in heat islands) and unexpected cold spells. Inability of local organizations for health, emergency services and social services to adapt to new risk levels and set up needed initiatives for vulnerable groups.	Risk of mortality and morbidity increasing, including shifts in seasonal patterns and concentrations due to hot days with higher or more prolonged high temperatures or unexpected cold spells. Avoiding risks often most difficult for low-income groups.	Duration and variability of heat waves increasing risks over time for most locations due to interactions with multiple stressors such as air pollution.
Water shortages and drought in urban regions [8.2.3, 8.2.4]	Lack of piped water to homes of hundreds of millions of urban dwellers. Many urban areas subject to water shortages and irregular supplies, with constraints on increasing supplies. Lack of capacity and resilience in water management regimes including rural-urban linkages. Dependence on water resources in energy production systems.	Risks from constraints on urban water provision services to people and industry with human and economic impacts. Risk of damage and loss to urban ecology and its services including urban and peri-urban agriculture.	Cities' viability may be threatened by loss or depletion of freshwater sources – including for cities dependent on distant glacier melt water or on depleting groundwater resources.
Changes in urban meteorological regimes lead to enhanced air pollution [8.2.3]	Increases in exposure and in pollution levels with impacts most serious among physiologically susceptible populations. Limited coping and adaptive capacities, due to lacking implementation of pollution control legislation of urban governments.	Increasing risk of mortality and morbidity, lowered quality of life. These risks can also undermine the competitiveness of global cities to attract key workers and investment.	Complex and compounding health crises.
Geo-hydrological hazards	Local structures and	Risk of damage to	Potential for large local and

(salt water intrusion, mud/land slides, subsidence) [8.2.3, 8.2.4]	networked infrastructure (piped water, sanitation, drainage, communications, transport, electricity, gas) particularly susceptible. Inability of many low-income households to move to housing on safer sites.	networked infrastructure. Risk of loss of human life and property.	aggregate impacts. Knock on effects for urban activities and wellbeing.
Wind storms with higher intensity [8.1.4, 8.2.4]	Sub-standard buildings and physical infrastructure and the services and functions they support particularly susceptible. Old and difficult to retro-fit buildings and infrastructure in cities. Local government unable or unwilling to give attention to disaster risk reduction (limited coping and adaptive capacities).	Risk of damage to dwellings, businesses and public infrastructure. Risk of loss of function and services. Challenges to recovery, especially where insurance is absent.	Challenges to individuals, businesses and public agencies where the costs of retrofitting are high and other sectors or interests capture investment budgets; potential for tensions between development and risk reduction investments.
Changing hazard profile including novel hazards and new multi-hazard complexes [8.1.4, 8.2.4]	Newly exposed populations and infrastructure, especially those with limited capacity for multi-hazard risk forecasting and where risk reduction capacity is limited, e.g. where risk management planning is overly hazard specific including where physical infrastructure is predesigned in anticipation of other risks (e.g. geophysical rather than hydrometeorological).	Risks from failures within coupled systems, e.g. reliance of drainage systems on electric pumps, reliance of emergency services on roads and telecommunications. Potential of psychological shock from unanticipated risks.	Loss of faith in risk management institutions. Potential for extreme impacts that are magnified by a lack of preparation and capacity in response.
Compound slow-onset hazards including rising temperatures and variability in temperature and water [8.2.2, 8.2.4]	Large sections of the urban population in low- and middle-income nations with livelihoods or food supplies dependent on urban and peri-urban agriculture are especially susceptible.	Risk of damage to or degradation of soils, water catchment capacity, fuel wood production, urban and peri-urban agriculture and other productive or protective ecosystem services. Risk of knock-on impacts for urban and peri-urban livelihoods and urban health.	Collapsing of peri-urban economies and ecosystem services with wider implications for urban food security, service provision and disaster risk reduction.
Climate change induced or intensified hazard of more diseases and exposure to disease vectors [8.2.3, 8.2.4]	Large urban population that is exposed to foodborne and waterborne diseases and to malaria, dengue and other vector borne diseases that are influenced by climate change.	Risk due to increases in exposure to these diseases.	Lack of capacity of public health system to simultaneously address these health risks with other climate related risks like flooding.
Rural areas (chapter 9)			
Drought in pastoral areas [9.3.3.1, 9.3.5.2]	Increasing vulnerability due to encroachment on pastoral rangelands, inappropriate land policy, misperception	Risk of famine. Risk of loss of revenues from livestock trade.	Increasing risks for rural livelihoods through animal disease in pastoral areas combined with direct

	and undermining of pastoral livelihoods, conflict over natural resources, all driven by remoteness and lack of voice.		impacts of drought.
Effects of climate change on artisanal fisheries [9.3.3.1, 9.3.5.2]	Artisanal fisheries affected by pollution and mangrove loss, competition from aquaculture and the neglect of the sector by governments and researchers as well as complex property rights.	Risk of economic losses for artisanal fisherfolk, due to declining catches and incomes and damage to fishing gear and infrastructure.	Reduced dietary protein for those consuming artisinally-caught fish, combined with other climate-related risks.
Water shortages and drought in rural areas [9.3.5.1, 9.3.5.1]	Rural people lacking access to drinking and irrigation water. High dependence of rural people on natural resource-related activities. Lack of capacity and resilience in water management regimes (institutionally driven). Increased water demand from population pressure.	Risk of reduced agricultural productivity of rural people, including those dependent on rainfed or irrigated agriculture, or high-yield varieties, forestry and inland fisheries. Risk of food insecurity and decrease in incomes. Decreases in household nutritional status. [9.3.5.1]	Impacts on livelihoods driven by interaction with other factors (water management institutions, water demand, water used by non-food crops), including potential conflicts for access to water. Water-related diseases.
Human health (chapter 11)			
Increasing frequency and intensity of extreme heat	Older people living in cities are most susceptible to hot days and heat waves, as well as people with pre-existing health conditions. [11.3]	Risk of increased mortality and morbidity during hot days and heat waves. [11.4.1] Risk of mortality, morbidity and productivity loss, particularly amongst manual workers in hot climates.	The number of elderly people is projected to triple from 2010-2050. This can result in overloading of health and emergency services.
Increasing temperatures, increased variability in precipitation	Poorer populations are particularly susceptible to climate-induced reductions in local crop yields. Food insecurity may lead to undernutrition. Children are particularly vulnerable. [11.3]	Risk of a larger burden of disease and increased food insecurity for particular population groups. Increasing risk that progress in reducing mortality and morbidity from undernutrition may slow or reverse. [11.6.1]	Combined impacts of climate impacts, population growth, plateauing productivity gains, land demand for livestock, biofuels, persistent inequality, and on-going food insecurity for the poor.
Increasing temperatures, changing patterns of precipitation	Non-immune populations that are exposed to water- and vector-borne disease which are sensitive to meteorological conditions. [11.3]	Increasing health risks due to changing spatial and temporal distribution strains public health systems, especially if this occurs in combination with economic downturn. [11.5.1]	Rapid climate and other environmental change may promote emergence of new pathogens.
Increased variability in precipitation	People exposed to diarrhoea aggravated by higher temperatures, and unusually high or low precipitation. [11.3]	Risk that the progress to date in reducing childhood deaths from diarrhoeal disease is compromised. [11.5.2]	Increased rate of failure of water and sanitation infrastructure due to climate change leading to higher diarrhoea risk.
Livelihood and poverty (chapter 13)			
Increasing frequency and	Poorly endowed farmers	Risk of irreversible harm	Deteriorating livelihoods

severity of droughts, coupled with decreasing rainfall and/or increased unpredictability of rainfall [13.2.1.2; 13.2.1.4; 13.2.2.2]	(high and persistent poverty) particularly in drylands are susceptible to these hazards, since they have a very limited ability to compensate for losses in water-dependent farming systems and/or livestock.	due to short time for recovery between droughts, approaching tipping point in rain-fed farming system and/or pastoralism.	stuck in poverty traps, heightened food insecurity, decreased land productivity, outmigration, and new urban poor in LICs and MICs.
Floods and flash floods in informal urban settlements and mountain environments, destroying physical assets (e.g. homes, roads, terraces, irrigation canals) [13.2.1.1; 13.2.1.3; 13.2.1.4]	High exposure and susceptibility of people, particularly children and elderly as well as disabled in flood-prone areas. Inadequate infrastructure, culturally imposed gender roles, and limited ability to cope and adapt due to political and institutional marginalization and high poverty adds to the susceptibility of these people in informal urban settlements, limited political interest in development and building adaptive capacity.	Risk of a high morbidity and mortality to floods and flash floods. Factors that further increase risk may include a shift from transient to chronic poverty due to eroded human and economic assets (e.g. labor market); economic losses due to infrastructure damage	Exacerbated inequality between better-endowed households able to invest in flood-control measures and/or insurance and increasingly vulnerable populations prone to eviction, erosion of livelihoods, and outmigration.
Increased variability of precipitation; shifts in mean climate and extreme events [13.2.1.1; 13.2.1.4]	Limited ability to cope due to exhaustion of social networks, especially among the elderly and female-headed households; mobilization of labor and food no longer possible.	Hazard combines with vulnerability to shift populations from transient to chronic poverty due to persistent and irreversible socio-economic and political marginalization. In addition the lack of governmental support, as well as limited effectiveness of response options increase the risk.	Increasing yet invisible multidimensional vulnerability and deprivation at the convergence of climatic hazards and socio-economic stressors.
Successive and extreme events (floods, droughts) coupled with increasing temperatures and rising water demand [13, 2.1.1; 13.2.1.5]	Rural communities are particularly susceptible, due to the marginalization of rural water users to the benefit of urban users, given political and economic priorities (e.g. Australia, Andes, Himalayas, Caribbean).	Risk of loss of rural livelihoods, severe economic losses in agriculture and damage to cultural values and identity; mental health impacts (including increased rates of suicide).	Loss of rural livelihoods that have existed for generations, heightened outmigration to urban areas; emergence of new poverty in MICs and HICs.
Sea level rise [13.1.4; 13.2.1.1; 13.2.2.1; 13.2.2.3]	High number of people exposed in low-lying areas coupled with high susceptibility due to multidimensional poverty, limited alternative livelihood options among poor households, and exclusion from institutional decision-making structures.	Risk of severe harm and loss of livelihoods. Potential loss of common-pool resources; of sense of place, belonging, and identity, especially among indigenous populations.	Loss of livelihoods and mental health risks due to radical change in landscape, disappearance of natural resources, and potential relocation; increased migration.
Increasing temperatures and heat waves [13.2.2.4; 13.2.1.5; 13.2.2.3]	Agricultural wage labourers, small-scale farmers in areas with multidimensional	Risk of increased morbidity and mortality due to heat stress, among male and	Declining labor pool for agriculture coupled with new challenges for rural

	poverty and economic marginalization, children in urban slums, and the elderly particularly susceptible.	female workers, children, and the elderly, limited protection due to socio-economic discrimination and inadequate governmental responses.	health care systems in LICs and MICs; aging and low-income populations without safety nets in HICs at risk.
Increased variability of rainfall and/or extreme events (floods, droughts, heat waves) [13.2.1.1; 13.2.1.3; 13.2.1.4; 13.2.1.5]	People highly dependent on rain-fed agriculture particularly at risk. Persistent poverty among subsistence farmers and urban wage labourers who are net buyers of food with limited coping mechanisms.	Risk of crop failure, spikes in food prices, reduction in consumption to protect household assets, risk of food insecurity, shifts from transient to chronic poverty due to limited ability to reduce risks.	Food riots, child food poverty, global food crises, limits of insurance and other risk-spreading strategies.
Changing rainfall patterns (temporally and spatially)	Households or people with a high dependence on rain-fed agriculture and little access to alternative modes of income.	Risks of crop failure, food shortage, severe famine.	Coincidence of hazard with periods of high global food prices leads to risk of failure of coping strategies and adaptation mechanisms such as crop insurance (risk spreading).
Stressor from soaring demand (and prices) for biofuel feedstocks due to climate policies.	Farmers and groups that have unclear and/or insecure land tenure arrangements exposed to the dispossession of land due to land grabbing in developing countries.	Risk of harm and loss of livelihoods for some rural residents due to soaring demand for biofuel feedstocks and insecure land tenure and land grabbing.	Creation of large groups of landless farmers unable to support themselves. Social unrest due to disparities between intensive energy production and neglected food production.
Increasing frequency of extreme events (droughts, floods). For example if 1:20 year drought/flood becomes 1:5 year flood/drought.	Pastoralists and small farmers subject to damage to their productive assets (e.g. herds of livestock; dykes, fences, terraces).	Risk of the loss of livelihoods and harm due to shorter time for recovery between extremes. Pastoralists restocking after a drought may take several years; in terraced agriculture, need to rebuild terraces after flood, which may take several years.	Collapse of coping strategies with risk of collapsing livelihoods. Adaptation mechanisms such as insurance fail due to increasing frequency of claims.
Emergent risks and key vulnerabilities (chapter 19)			
Warming and drying (precipitation changes of uncertain magnitude) [AR5 WGI TS.5.3, WGI SPM, WGI 11.3, WGI 12.4]	Limits to coping capacity to deal with reduced water availability; increasing exposure and demand due to population increase; conflicting demands for alternative water uses; socio-cultural constraints on some adaptation options. [19.2.2, 19.6.1.1, 19.3.2.2 19.6.3.4]	Risk of harm and loss due to livelihood degradation from systematic constraints on water resource use that lead to supply falling far below demand. In addition limited coping and adaptation options increase the risk of harm and loss. [19.3.2.2, 19.6.3.4]	Competition for water from diverse sectors (e.g. energy, agriculture, industry) interacts with climate changes to produce locally severe shortages. [19.3.2.2, 19.6.3.4]
Changes in regional and seasonal temperature and precipitation over land [AR5 WGI TS.5.3, WGI SPM, WGI 11.3, WGI 12.4]	Communities highly dependent on ecosystem services [19.2.2.1, 19.3.2.1] which are negatively affected by changes in regional and seasonal temperature.	Risk of large-scale species richness loss over most of the global land surface. 57±6% of widespread & common plants and 34±7% of widespread & common animals expected to lose	Widespread loss of ecosystem services, including: *provisioning*, such as food and water; *regulating*, such as the control of climate and disease; *supporting*, such as

		≥50% of their current climatic range by the 2080s leading to loss of services. [19.3.2.1]	nutrient cycles and crop pollination; and *cultural*, such as spiritual and recreational benefit. [19.3.2.1, 19.6.3.4]
Africa (chapter 22)			
Increasing Temperature	Children, pregnant women, and those with compromised health status are particularly at risk for temperature-related changes in diarrheal and vector-borne diseases, and for temperature-related reductions in crop yields. Outdoor workers, older adults, and young children are most susceptible to hot weather and heat waves. [22.3.5.2, 22.3.5.4]	Risk of changes in the geographic distribution, seasonality, and incidence of infectious diseases, leading to increases in the health burden. Risk of increased burdens of stunting in children. Risk of increase in morbidity and mortality during hot days and heat waves.	Interactions among factors lead to emerging and re-emerging epidemics.
	Populations dependent on aquatic systems and aquatic ecosystem services that are sensitive to increased water temperatures.	Loss of aquatic ecosystems and risks for people who might depend on these resources; reduction in freshwater fisheries production. [22.3.2.2, 22.3.4.4]	Risk of loss of livelihoods due to interactions of loss of ecosystem services and other climate-related stressors on poor communities.
	Rural and urban populations whose food and livelihood security is diminished.	Risk of harm and loss due to increased heat stress on crops and livestock resulting in reduced productivity; Increased food storage losses due to spoilage. [22.3.4.1, 22.3.4.2]	Range expansion of crop pests and diseases to high elevation agroecosystems. [22.3.4.3]
Extreme Events, e.g. floods and flash floods (& drought)	Population groups living in informal settlements in highly exposed urban areas; women and children often the most vulnerable to disaster risk. [22.3.6, 22.4.3]	Increasing risk of mortality, harm and losses due to water logging triggered by heavy rainfall events.	Compounded risk of epidemics including diarrhoeal diseases (cholera).
	Susceptible groups include those who experience diminished access to food resulting from reduced capacity to transport, store, and market food, such as the urban poor.	Risk of food shortages and of damages to the food system due to storms and flooding.	Food price spikes due to convergence of climatic and non-climatic forces that reduce food access for the poor whose income is disproportionately spent on food. [22.3.4.5]
	Children, pregnant women, and those with compromised health status are particularly vulnerable to reduced access to safe water and improved sanitation and increasing food insecurity. [22.3.5.2, 22.3.5.3]	Risk of crop and livestock losses from drought. Risk of reduced water supply and quality for household use. [22.3.4.1, 22.3.4.2] Risk of increased incidence of food and waterborne diseases (e.g. cholera) and undernutrition. Risk of drinking water contamination due to heavy	Compound effects of high temperature and changes in rainfall on human and natural systems. Increased incidence of stunting in children. [22.3.5.3].

		precipitation events and flooding. [22.3.5.2]	
Europe (chapter 23)			
Extreme weather events [23.9]	Sectors with limited coping and adaptive capacity as well as high sensitivity to these extreme events, such as transport, energy and health are particularly susceptible.	Risk of new systemic threats due to stress on multiple and interconnected sectors. Risk of failure of service provision of one or more sectors.	Disproportionate intensification of risk due to increasing interdependencies.
Climate change increases the spatial distribution and seasonality of pests and diseases. [23.4.1, 23.4.3, 23.4.4]	High susceptibility of plants and animals that are exposed to pests and diseases.	Risk of increases in crop losses and animal diseases or even fatalities of livestock.	Increasing risks due to limited response options and various feedback processes in agriculture, e.g. use of pesticides or antibiotics to protect plants and livestock increases resistance of disease vectors.
Extreme weather events and reduced water availability due to climate change. [23.3.4]	Low adaptive capacity of power systems might lead to limited energy supply as well as higher supply costs during such extreme events and conditions.	Increasing risk of power shortages due to limited energy supply, e.g. of nuclear power plants due to limited cooling water during heat stress.	Continued underinvestment in adaptive energy systems might increase the risk of mismatches between limited energy supply during these events and increased demands, e.g. during a heat wave.
Asia (chapter 24)			
Rising average temperatures and more frequent extreme temperatures, as well as changing rainfall patterns (temporally and spatially).	Food systems and food production system for key grain crops, particularly rice and other cereal crop farming systems are highly susceptible. [24.4.4.3]	Risk of crop failures and lower crop yield also can increase the risk of major losses for farmers and rural livelihoods. [24.4.4.3]	Increase in Asian population combined with rising temperatures affecting food production. Upper temperature limit to the ability of some food systems to adapt could be reached.
Rising sea level	Paddy fields and farmers near the coasts are particularly susceptible. [24.4.4.3]	Risk of loss of arable areas due to submergence. [24.4.4.3]	Migration of farming communities to higher elevation areas entails risks for migrants and receiving regions.
Projected increase in frequency of various extreme events (heat-wave, floods and droughts) and sea level rise.	Increasing exposure due to convergence of livelihood and properties into coastal megacities. People in areas that are not sufficiently protected against natural hazards are particularly susceptible.	Risk of loss of life and assets due to coastal floods accompanied by increasing vulnerabilities.	Projected increase in disruption of basic services such as water supply, sanitation, energy provision, and transportation system, which themselves could increase vulnerabilities.
Australasia (chapter 25)			
Rising air and sea surface temperatures, drying trends, reduced snow cover, increased intensity of severe cyclones, ocean acidification [25.2, Table 25-1, Figure 25-4, AR5 WGI Chapter 14	Species that live in a limited climatic range and that suffer from habitat fragmentation as well as from external stressors (pollution, run-off, fishing, tourism, introduced	Risk of significant change in community composition and structure of coral reefs and montane ecosystems and risk of loss of some native species in Australia. [25.6.1, 25.6.2, 25.10.2]	Increasing risk from compound extreme events across time and space, and cumulative adaptation needs, with recovery and risk reduction measures hampered further by impacts

and Atlas]	predators and pests) are especially susceptible. [25.6.1, 25.6.2]		and responses reaching across different levels of government. [25.10.2, 25.10.3, Box 25-9]
Increased extreme rainfall related to flood risk in many locations [25.2, Table 25-1]	Adaptation deficit of existing infrastructure and settlements to current flood risk; expansion and densification of urban areas; effective adaptation includes transformative changes such as land-use controls and retreat. [25.3, Box 25-8, 25.10.2]	Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand. [Box 25-8, 25.10.2]	
Continuing sea level rise, with projections spanning a particularly large range and continuing beyond 2100, even under mitigation scenarios [25.2, Box 25-1, AR5 WGI Chapter 13]	Long-lived and high asset value coastal infrastructure, and low-lying ecosystems are highly susceptible. Expansion of coastal populations and assets into coastal zones increases the exposure. Conflicting priorities constrain adaptation options and limit effective response strategies. [25.3, Box 25-1]	Increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand, with widespread damages towards the upper end of projected ranges. [Box 25-1, 25.6.1, 25.6.2, 25.10.2].	
North America (chapter 26)			
Increases in frequency and/or intensity of extreme events, such as heavy precipitation, river and coastal floods, heat waves and droughts. [26.2.2, 26.3.1, 26.8.1]	Physical infrastructure in a declining state in urban areas particularly susceptible. Also increases in income disparities and limited institutional capacities might result in larger proportions of people susceptible to these stressors due to limited economic resources. [26.7, 26.8.2]	Risk of harm and loss in urban areas, particularly in coastal and dry environments due to enhanced vulnerabilities of social groups, physical systems and institutional settings combined with the increases of extreme weather events. [26.8.1]	Inability to reduce vulnerability in many areas results in increase in risk more so than change in physical hazard. [26.8.3]
Higher temperatures, decreases in runoff and lower soil moisture due to climate change [26.2, 26.3]	Vulnerability of small rural landholders, particularly in Mexican agriculture, and of the poor in rural settlements. [26.5, 26.8.2.2]	Risk of increased losses and decreases in agricultural production. Risk of food and job insecurity for small landholders and social groups in regions exposed to these phenomena. [26.5, 26.8.2.2]	Increasing risks of social instability and local economic disruption due to internal migration. [26.2.1, 26.8.3]
Wildfires and drought conditions [Box 26-2]	Indigenous groups, low-income residents in peri-urban areas, and forest systems. [Box 26-2, 26.8.2]	Risk of loss of ecosystem integrity, property loss, human morbidity and mortality due to wildfires. [Box 26-2, 26.8.3]	
Extreme storm and heat events, air pollution, pollen, and infectious diseases [26.6.1]	Susceptibility of individuals is determined by factors such as economic status, pre-existing illness, age, and access to assets. [26.6.1]	Increasing risk of extreme temperature-, storm-, pollen, and infectious diseases-related human morbidity or mortality. [26.6.2]	
River and coastal floods, and sea level rise [26.2.2,	Increasing exposure of populations, property, as	Risk of property damage, supply chain disruption,	Multiple risks from interacting hazards on

26.4.2, 26.8.1]	well as ecosystems, partly resulting from overwhelmed drainage networks. Groups and economic sectors that highly depend on the functioning of different supply chains; public health institutions that can be disrupted; and groups that have limited coping capacities to deal with supply chain interruptions and disruptions to their livelihoods are particularly susceptible. [26.7, 26.8.1]	public health, water quality impairment, ecosystem disruption, infrastructure damage, and social system disruption from urban flooding due to river and coastal floods and floods of drainage networks. [26.4.2, 26.8.1]	populations' livelihoods, infrastructure and services. [26.7, 26.8.3]
Central and South America (chapter 27)			
Reduced water availability in semi arid regions and regions dependent on glacier meltwater; flooding in urban areas due to extreme precipitation [27.2.1, 27.3.3]	Groups that cannot keep agricultural livelihoods and are forced to migrate are especially vulnerable. Limited infrastructure and planning capacity can further increase the lack of coping and adaptive capacities to rapid changes expected (precipitation), especially in large cities.	Risk of loss of human lives, livelihood and property.	Increase in infections diseases. Economic impacts due to reallocation of populations.
Ocean acidification and warming [27.3.3, CC-OA]	Coral reef systems.	Risk of loss of biodiversity (species) and risk of a reduced fishing capacity with respective impacts for coastal livelihoods.	Economic losses and impact on food (fishery) production in certain regions.
Extremes of drought/precipitation [27.2.1, 27.3.4]	Elevated CO_2 decreases nutrient contents in plants, especially nitrogen in relation to carbon in food products.	Risk of loss of (food) production and productivity in some regions where extreme events may occur. Need to adjust diet due to decrease in food quality (e.g. less protein due to lower nitrogen assimilation). Decrease in bioenergy production.	Strong economic impacts related to the need to move crops to more suitable regions. Teleconnections (related to food quality) related to the intense exportation of food by the region. Impacts on energy system and carbon emissions with consequent increase in fossil fuel demand.
Higher temperatures and humidity leads to a spread of vector-borne diseases in altitude and latitude [27.3.7]	People exposed and vulnerable to vector borne diseases and an increase in mosquito biting rates that increase the probability of human infections.	Risk of increase in morbidity and in disability-adjusted life years (DALYs); Risk of loss of human lives; Risk of decrease in school and labour productivity.	High economic impacts owing to the necessity to increase the financing of health programs, as well as the costs of DALYs, increase in hospitals and medical infrastructure adequate enough to cope with increasing disease incidence rates, and the spread of diseases to newer regions.
Polar Systems (chapter 28)			

Loss of multi-year ice and reductions in the spatial extent of summer sea ice [28.2.5, 28.3.2, 28.4.1]	Indigenous communities that dependent on sea ice for traditional livelihoods are vulnerable to this hazard, particularly due to loss of breeding and foraging platforms for marine mammals.	Risk of loss of traditional livelihoods and food sources.	Top down shifts in food-webs.
	Ecosystems are vulnerable due to the shifts in the distribution and timing of ice algal and ocean phytoplankton blooms.	Risk of disruption of synchronized timing of zooplankton ontogeny and availability of prey. Increased variability in secondary production while zooplankton adapt to shifts in timing. Risks also to local marine foodwebs.	Bottom up shifts in food webs. Potential changes in pelagic and benthic coupling.
Ocean acidification [28.2.2, 28.3.2]	Tolerance limits of endemic species surpassed. Impacts on exoskeleton formation for some species and alteration of physiological and behavioural properties during larval development.	Localized loss of endemic species, local impacts on marine foodwebs.	Localized declines in commercial fisheries. Local declines in fish, shellfish, seabirds and marine mammals.
Shifts in boundaries of marine eco-regions due to rising water temperature, shifts in mixed layer depth, changes in the distribution and intensity of ocean currents. [28.2.2, 28.3.2]	Marine organisms that are susceptible to spatial shifts are particularly vulnerable.	Risk of changes in the structure and function of marine systems and potentially species invasions.	Disputes over international fisheries and shared stocks
Declining sea ice, changes in snow and ice timing and state, decreasing predictability of weather. [28.1, 28.4.1]	Many traditional subsistence food sources – especially for indigenous peoples - such as Arctic marine and land mammals, fish and waterfowl. Various traditional livelihoods are susceptible to these hazards.	Risk of loss of habitats and changes in migration patterns of marine species.	Enhancement of risk to food security and basic nutrition – especially for indigenous peoples - from loss of subsistence foods and increased risk to subsistence hunters', herders', and fishers' health and safety in changing ice conditions.
Increased river and coastal flooding and erosion and thawing of permafrost [28.2.4, 28.3.1, 28.3.4]	Rural and remote communities as well as urban communities in low-lying Arctic areas are exposed. Susceptibility and limited coping capacity of community water supplies due to potential damages to infrastructure.	Community and public health infrastructure damaged resulting in disease from contamination and sea water intrusion.	Reduced water quality and quantity may result in increased rates of infection, other medical problems and hospitalizations.
Extreme and rapidly changing weather, intense weather and precipitation events, rapid snow and ice melt, changing river and sea ice conditions, permafrost thaw. [28.2.4]	People living from subsistence travel and hunting, herding and fishing, for example indigenous peoples in remote and isolated communities are particularly susceptible.	Accidents, physical/mental injuries, death, and cold-related exposure, injuries and diseases.	Enhanced risks to safe travel or subsistence hunting, herding, fishing activities affect livelihoods and wellbeing.

Diminished sea ice; earlier sea ice melt-out; faster sea ice retreat; thinner, less predictable ice in general; greater variability in snow melt/freeze; ice, weather, winds, temperatures, precipitation. [28.2.5, 28.2.6, 28.4.1]	Livelihoods of many indigenous peoples (e.g. Inuit and Saami) depend upon subsistence hunting and access to and favourable conditions for animals. These livelihoods are susceptible. Also marine ecosystems are susceptible (e.g. marine mammals).	Risk of loss of livelihoods and damage due to: (e.g., Inuit: more difficult access to marine mammals associated with diminishing sea ice) and (e.g., Saami: loss of access by reindeer to their forage under snow due to ice layers formed by warming winter temperatures and "rain on snow").	Enhanced risk of loss of livelihoods and culture of increasing numbers of indigenous peoples, exacerbated by increasing loss of lands and sea ice for hunting, herding, fishing due to enhanced petroleum and mineral exploration and increased maritime traffic.
Small Islands (chapter 29)			
Increases in intensity of tropical cyclones [AR5 WGI 14.6, 14.8.4]	Various countries and communities are vulnerable to these hazards due to their high dependence on natural and ecological systems for security of settlements and tourism [29.3.3.1], human health [29.3.3.2] and water resources [29.3.2].	Risk of loss of ecosystems, settlements and infrastructure, as well as negative impacts on human health and island economies. [Figure 29-4]	Increased risk of interactions of damages to ecosystems, settlements, island economies and risks to human life. [29.6, Figure 29-4].
Ocean warming and acidification leading to coral bleaching [29.3.1.2, 30.5.4.2, 30.5.6.1.1, 30.5.6.2]	Tropical island communities are highly dependent on coral reef ecosystems for subsistence life styles, food security, coastal protection and beach and reef-based tourist economic activity and hence are highly susceptible to the hazard of coral bleaching. [29.3.1.2, 30.6.2.1.2]	Risk of decline and possible loss of coral reef ecosystems through thermal stress. Risk of serious harm and loss of subsistence lifestyles. Risk of loss of coastal protection and beaches, risk of loss of tourist revenue. [29.3.1.1, 29.3.1.2]	Impacts on human health and loss of subsistence lifestyles. Potential increase in internal migration / urbanisation. [29.3.3.3, Chapter 9]
Sea level rise [29.3.1.1, 30.3.1.2; AR5 WGI 3.7.1]	Many small island communities and associated settlements and infrastructure are in low-lying coastal zones (high exposure) and are also vulnerable to increasing inundation, erosion and wave incursion. [5.3.2, 29.3.1.1, Figure 29-2]	Risk of loss and harm due to sea level rise in small island communities. Global Mean Sea Level is likely to increase by 0.35 to 0.70 m for RCP 4.5 during the 21st century, threatening low-lying coastal areas and atoll islands. [29.4.3, Table 29-1; AR5 WGI 13.5.1, Table 13.5]	Incremental upwards shift in sea-level baselines results in increased frequency and extent of marine flooding during high tides and episodic storm surges These events could render soils and fresh groundwater resources unfit for human use before permanent inundation of low-lying areas. [29.3.1.1, 29.3.2, 29.3.3.1, 29.5.1].
Regional Oceans (chapter 30)			
Increasing ocean temperatures. Increased frequency of thermal extremes	Corals and other organisms whose tolerance limits are exceeded are particularly susceptible (especially CBS, STG, SES and EUS ocean regions). [30.5.2, 30.5.4, 30.5.5, CC-CR, 30.5.6, CC-OA, 6.2.2.1, 6.2.2.2]	Risk of increased mass coral bleaching and mortality (loss of coral cover) with severe risks for coastal fisheries, tourism and coastal protection. [30.5.2, 30.5.3, 30.5.4, 30.5.5, Box CC-CR, 6.3.2. 6.3.5, 5.4.2.4, 7.2.1.2, 6.4.1.4, 29.3.1.2]	Loss of coastal reef systems, risk of decreased food security and reduced livelihoods, and reduced coastal protection. [30.6.2.1, 30.6.5, 7.2.1.2]

	Marine species and ecosystems as well as fisheries and coastal livelihoods and tourism that cannot cope or adapt to changing temperatures and changes in the distribution are particularly vulnerable, especially for HLSBS, CBS, STG, and EBUE. [30.5, CC-BIO, 6.3.2, 6.3.4, 7.3.2.6]	Risk for fishery and coastal livelihoods. Fishery opportunity changes as stock abundance may rise or fall; increased risk of disease and invading species impacting ecosystems and fisheries. [6.3.5, 6.4.1.1, 6.5.3, 7.3.2.6, 7.4.2, 29.5.3, 29.5.4]	Significant risk of fisheries collapse may develop as the capacity for fisheries to resist fundamental change to fishery composition as well as the increased migration of disease and other organisms is accelerated. [6.5.3, 7.5.1.1.3]
	Coastal ecosystems and communities that might be exposed to phenomena of elevated rates of microbial respiration leading to reduced oxygen at depth and increased spread of dead zones are particularly vulnerable (particularly for EBUE, SES, EUS).	Risk of loss of habitats and fishery resources as well as losses of key fisheries species. Oxygen levels decrease leading to impacts on ecosystems (e.g. loss of habitat) and organisms (e.g. physiological performance of fish) results in reduced capture of key fisheries species.	Increasing risk of loss of livelihoods.
	Deep sea life is sensitive to hazards and to change given the very constant conditions under which it has evolved. [30.1.3.1.3, 30.5.2, 30.5.5]	Risk of fundamental changes in conditions associated with Deep Sea (e.g. oxygen, pH, carbonate, CO_2, temperature) drive fundamental changes that result in broad scale changes throughout the ocean. [30.1.3.1.3, 30.5.2, 30.5.5, CC-UP, CC-NPP]	Changes in the deep ocean may be a prelude to ocean wide changes with planetary implications.
Rising ocean acidification	Reef systems, corals and coastal ecosystems that are exposed to a reduced rate of calcification and greater decalcification leading to potential loss of carbonate reef systems, corals, molluscs and other calcifiers in key regions, such as the CBS, STG [6.2.2.2]	Risk of the alteration of ecosystem services including risks to food provisioning with impacts on fisheries and aquaculture. [7.2.1.2, 7.3.2, 7.4.2, 6.2.5.3]	Income and livelihoods for communities are reduced as productivity of fisheries and aquaculture diminish. [7.5.1.1.3, 30.6]
	Marine organisms that are susceptible to changes in pH and carbonate chemistry imply a large number of changes to the physiology and ecology of marine organisms (particularly in CBS, STG, SES regions). [30.3.2.2, .2 .2, 6.3.4, 6.2.5]	Risk of fundamental shifts in ecosystems composition as well is organism function occur, leading to broad scale and fundamental change. Income and livelihoods from dependent communities are affected as ecosystem goods and services decline, with the prospect that recovery may take tens of thousands of years. [6.1.1.2]	Risk to ecosystems and livelihoods is increased by the potential for interaction among ocean warming and acidification to create unknown impacts. [CC-OA]
	Coastal systems are increasingly exposed to upwelling in upwelling systems which results in	Risk of loss and harm to fishery and aquaculture operations and respective livelihoods (e.g. oyster	Background pH and carbonate chemistry are also such that harmful conditions are always present (avoiding

	periods of high CO_2, low 0_2 and pH. [CC-UP, 6.2.2.2, 6.2.5.3]	cultivation) especially those exposed periodically to harmful conditions during elevated upwelling, which trigger adaptation responses. [30.6.2.1.4]	impacts via adaptation not possible any more. [30.6.2.1.4]
Increased stratification as a result of ocean warming; Reduced ventilation.	Ocean ecosystems are vulnerable due to the reduced regeneration of nutrients as mixing between the ocean and its surface is reduced (EUS, STG and EBUE). [30.5.2, 30.5.4, 30.5.5; 6.2, 6.3, 6.5]	Risk of productivity losses of oceans and respective negative impacts on fisheries. The concentration of inorganic nutrients in the upper layers of the ocean is reduced leading to lower rates of primary productivity. [CC-NPP]	Reduced primary productivity of the ocean impacts fisheries productivity leading to lower catch rates and effects on livelihoods. [6.4.1.1, CC-NPP]
	Ecosystems and organisms that are sensitive to decreasing oxygen levels. [30.5.2, 30.5.3, 30.5.5, 30.5.6, 30.5.7]	Increased risk of dead (hypoxic) zones reducing key ecosystems and fisheries habitat. [30.3.2.3, .1 .1 .3]	
Changes to wind, wave height and storm intensity.	Shipping and industrial infrastructure is vulnerable to wave and storm intensity. [30.6.2]	Risk of increasing losses and damages to shipping and industrial infrastructure.	Risk of accidents increases for enterprises such as shipping, as well as deep sea oil gas and mineral extraction.

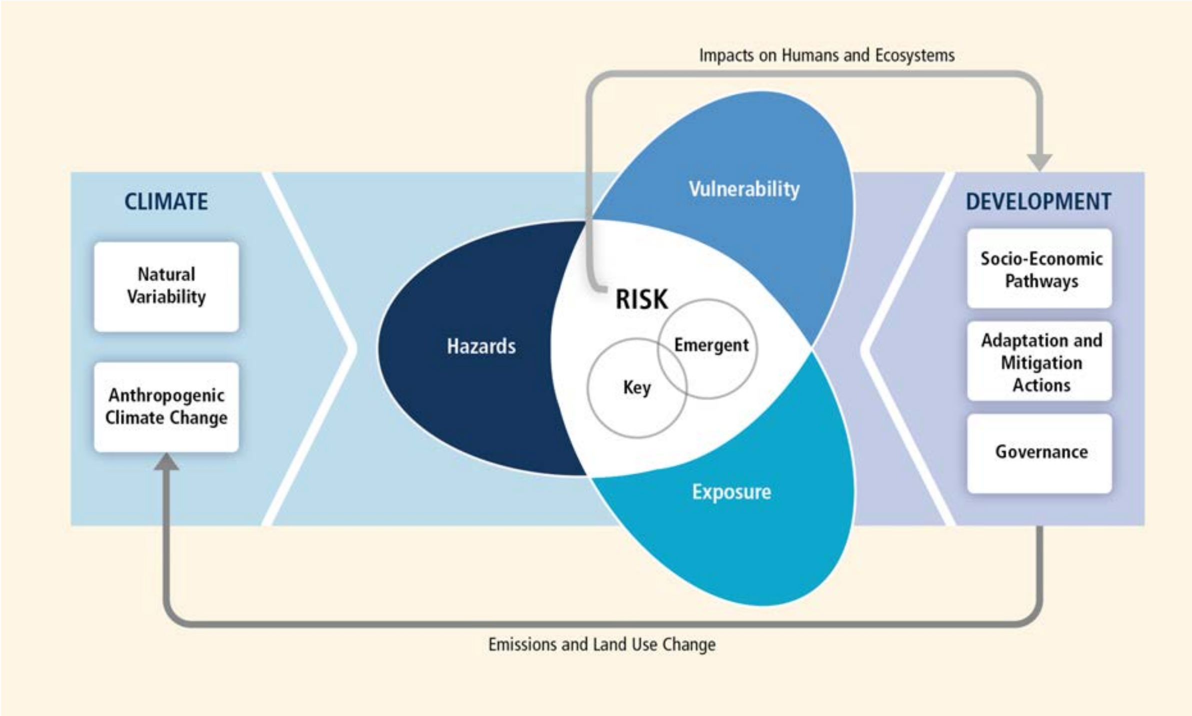

Figure 19-1: Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. It underscores that risks are a product of a complex interaction between physical hazards associated with climate change and climate variability on the one hand, and the vulnerability of a society or a social-ecological system and its exposure to climate-related hazards on the other. The definition and use of “key” and “emergent” are indicated in Box 19-2 and the Glossary. Vulnerability and exposure are, as the figure shows, largely the result of socio-economic development pathways and societal conditions (although changing hazard patterns also play a role, see 19.6.1.1). Changes in both the climate system (left side) and development processes (right side) are key drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk (modified version of Figure 1, IPCC 2012a).

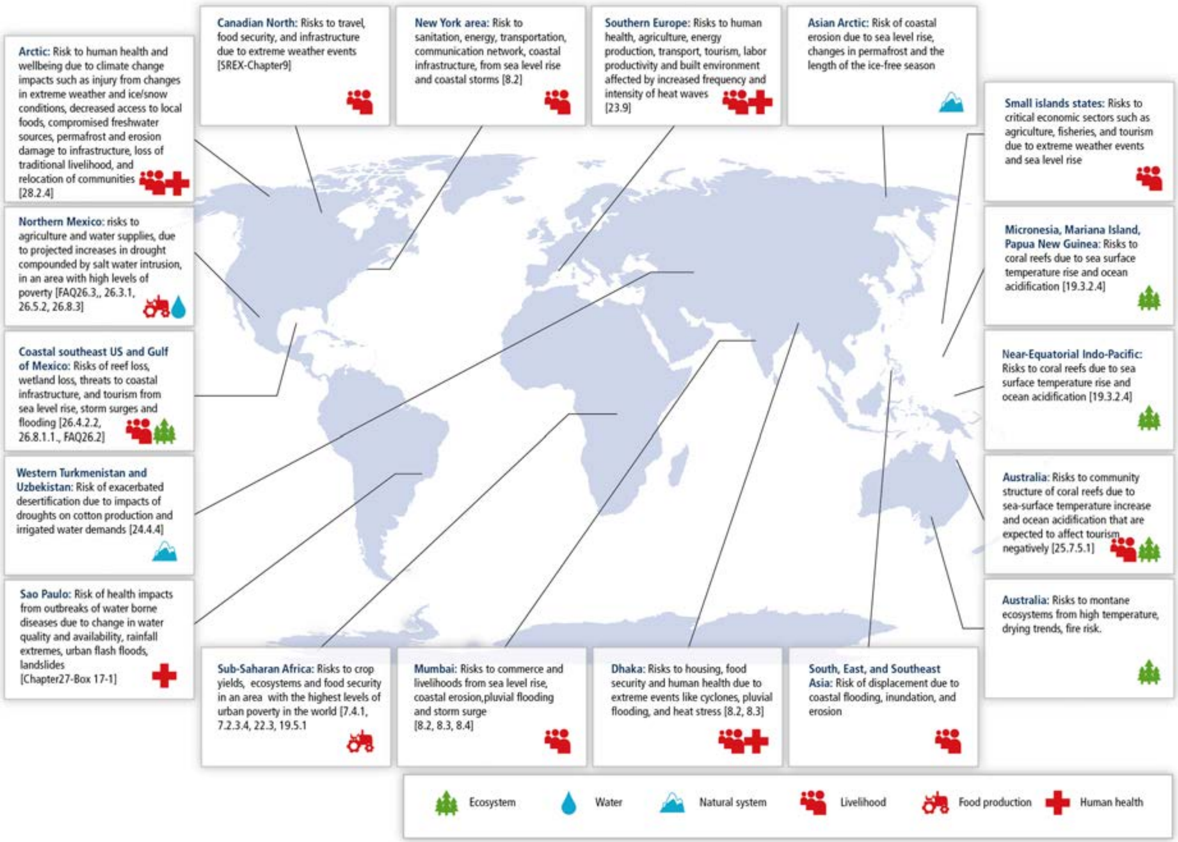

Figure 19-2: Some examples of areas of compound risk identified in this assessment. Symbols indicate one or two of the main sectors or systems subject to compound risk but in each case, additional sectors and systems are at risk.

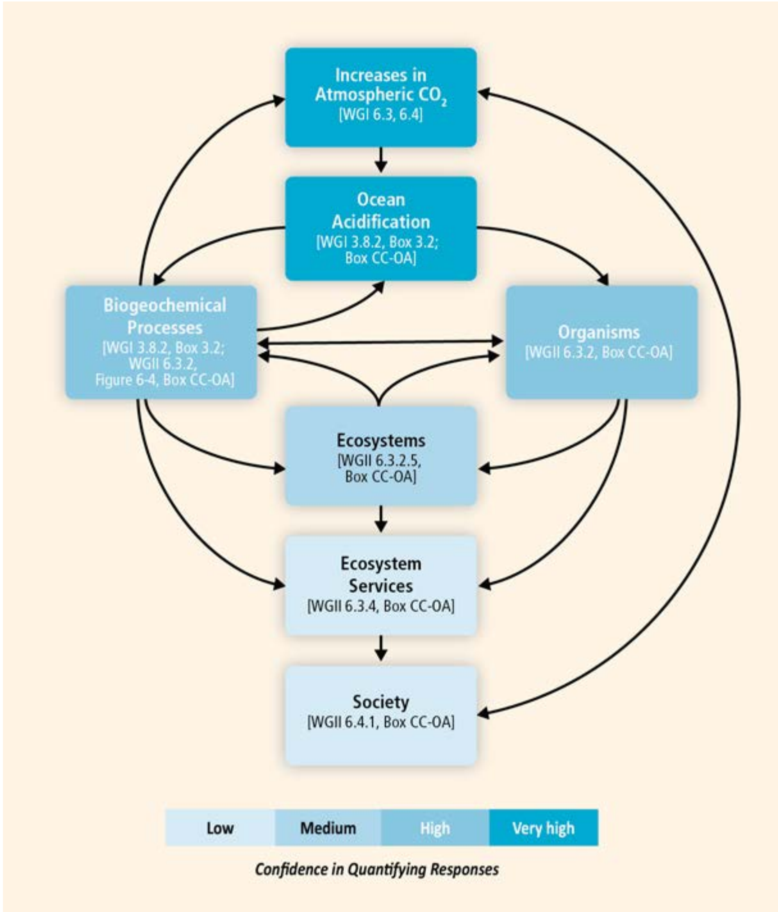

Figure 19-3: The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. The confidence in quantifying the impacts decreases along the pathway.

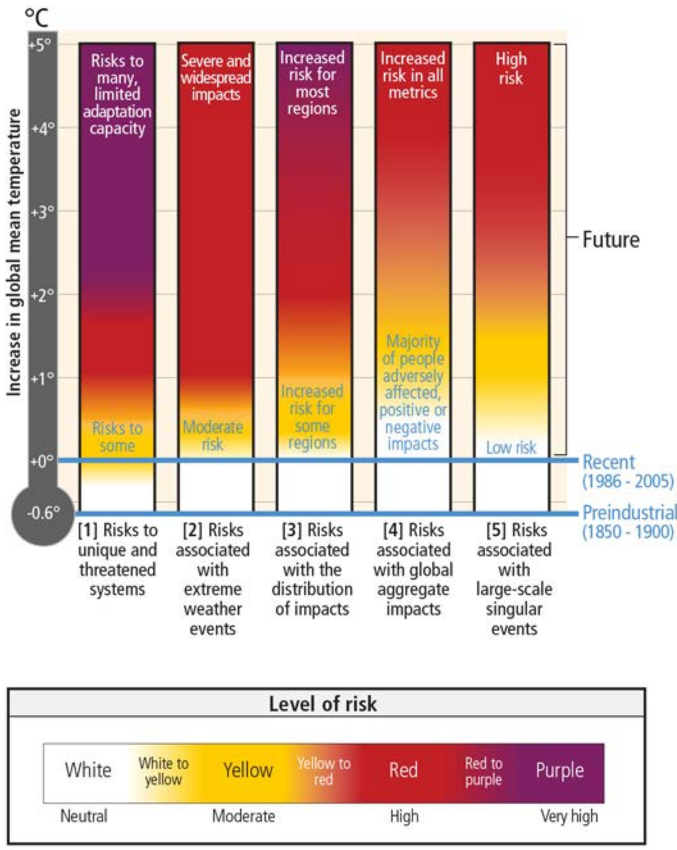

Figure 19-4: The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated from TAR and Smith *et al.* (2009). The color scheme indicates the additional risk due to climate change as described in the text. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual "reason." The transition from red to purple, introduced here, is defined by very high risk of severe impacts and the presence of significant irreversibilities or persistence of climate-related hazards combined with limited ability to adapt due to the nature of the hazard or impact. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. In general, assessment of RFCs takes autonomous adaptation into account, as was done previously (Smith *et al.*, 2001; Schneider *et al.*, 2007, AR4 WGII Chapter 19). In addition, this assessment took into account limits to adaptation in the case of RFC1, RFC3, and RFC5, independent of the development pathway. The rate and timing of climate change and physical impacts, not illustrated explicitly in this diagram, was taken into account in assessing RFC1 and RFC5. Comments superimposed on RFCs provide additional details which were factored into the assessment. The levels of risk illustrated reflect the judgments of Chapter 19 authors.

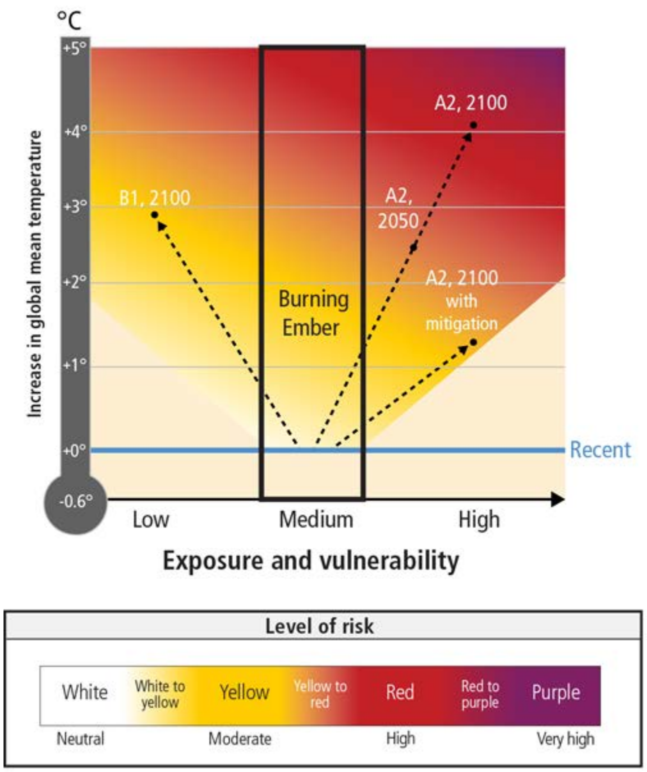

Figure 19-5: Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and exposure and vulnerability (E&V) of society. This figure is schematic; the degree of risk associated with particular levels of climate change or E&V has not been based on a literature assessment, nor associated with a particular RFC (the "burning ember" in the figure refers generically to any of the embers in Figure 19-4). The E&V axis is relative rather than absolute: "Medium" E&V indicates a future development path in which E&V changes over time are driven by moderate trends in socio-economic conditions. "Low" and "High" E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding exposure and vulnerability. Judgments made in other burning ember diagrams of the RFCs (Smith *et al.*, 2001, 2009) including Figure 19-4, which do not explicitly take changes in E&V into account, are consistent with Medium future E&V. Arrows and dots illustrate the use of SRES scenario-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socio-economic conditions over time. This figure does not explicitly address issues related to the rates of climate change or when impacts might be realized.

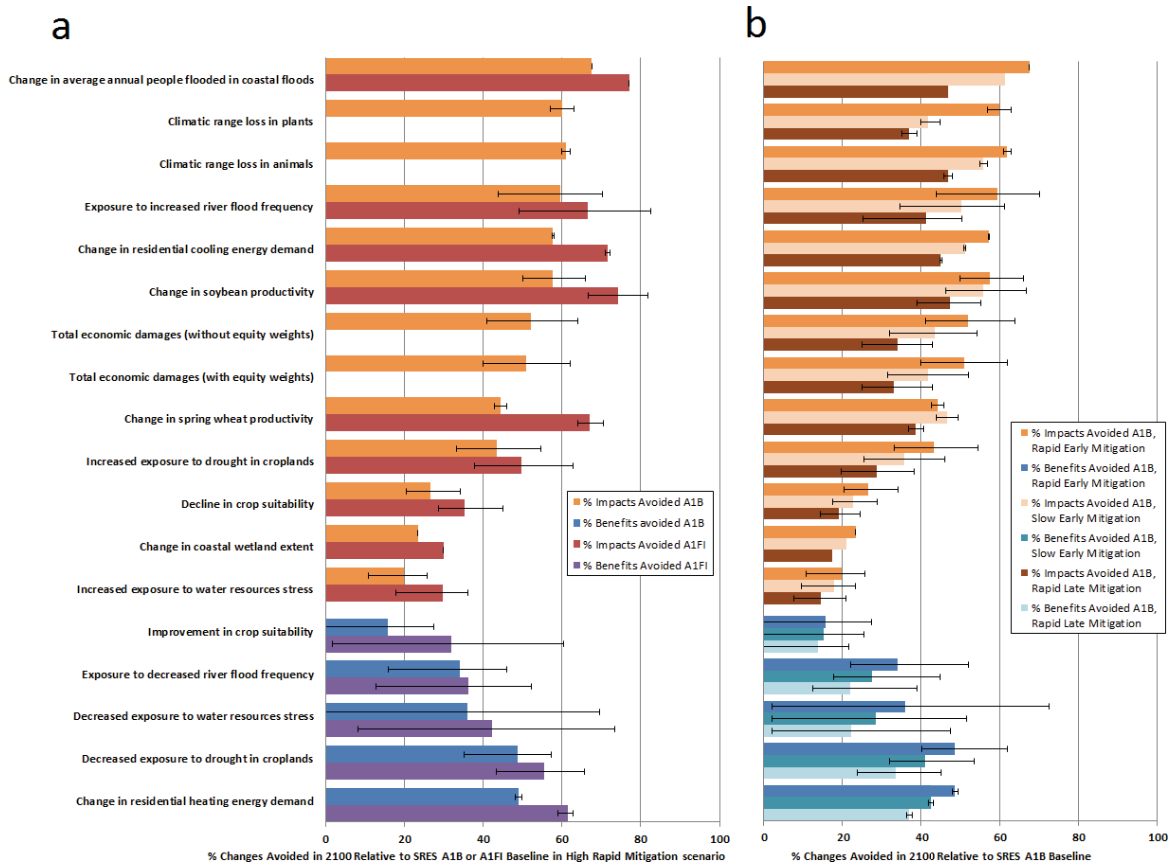

Figure 19-6: Panel **a**: Climate change impacts avoided by an early, rapid mitigation scenario in which global emissions peak in 2016 and are reduced at 5% thereafter, compared to two no-mitigation baseline cases SRES A1B (orange bars) and SRES A1FI (red bars). Impacts avoided are larger if the A1FI baseline scenario is used than if the A1B baseline is used, because greenhouse gas emissions in A1FI exceed those in A1B (see 19.7.1). Panel **b**: The dependence of the potential to avoid climate change impacts upon the timing of emission reductions is illustrated. Climate change impacts avoided by the same early, rapid mitigation scenario compared to the no-mitigation baseline case SRES A1B (orange bars) are shown. The information displayed is identical to the orange bars in panel a, but a comparison is now made with the impacts avoided from two other less stringent mitigation scenarios. Impacts avoided if global emissions peak in 2016 but are subsequently reduced more slowly (2% annually) are lower (pink bars compared to orange bars). However, if mitigation occurs later, so that global emissions do not peak until 2030, even if emissions are subsequently reduced at 5% annually, the avoided impacts are smaller than in either of the other two cases (brown bars compared to orange and pink bars). Both panels show the uncertainty range (error bars) due to regional climate change projected with 7 GCMs. Errors due to uncertainty within impacts models are not shown. Uncertainties associated with sea level rise related impacts are smaller because the models used encompass a narrow range of alternative sea level rise projections. Since increases and decreases in water stress, flood risks and crop suitability are not co-located and affect different regions, these effects are not combined. From Arnell *et al.*, 2013, Warren *et al*, 2013a; Warren *et al.*, 2013b.
[Illustration to be redrawn to conform to IPCC publication specifications.]

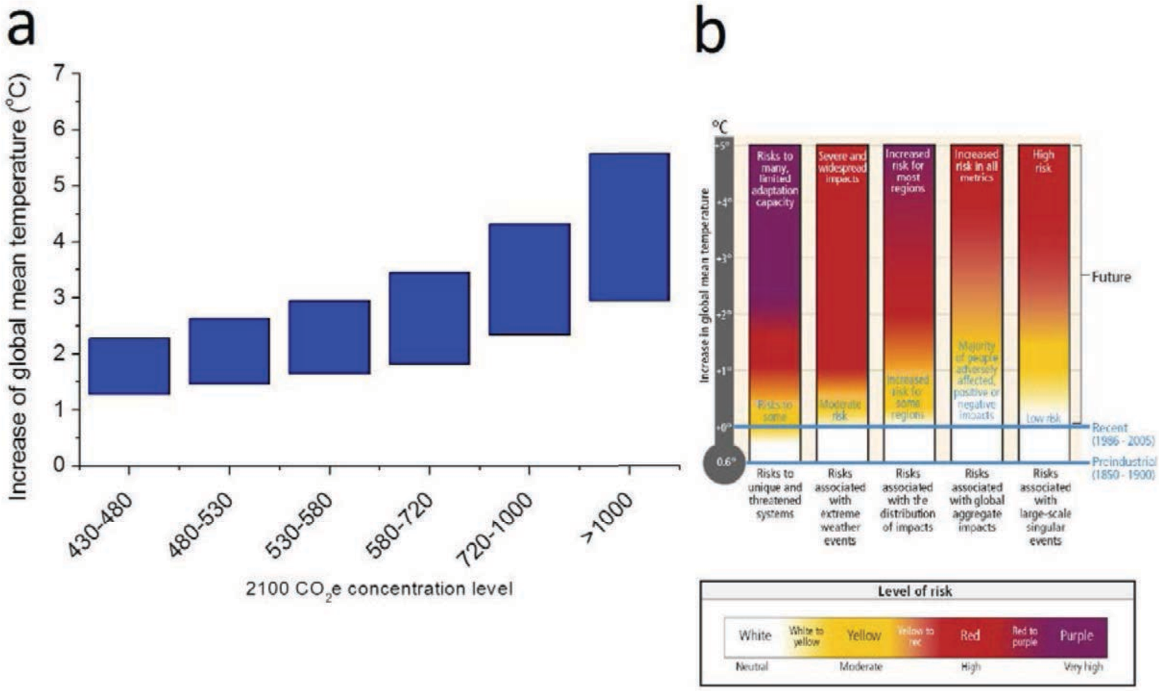

Figure 19-7: Relationship between mitigation scenarios considered in AR5 WGIII, in terms of their CO_2e concentrations and global temperature rise outcomes relative to pre-industrial times, and level of risk associated with Reasons for Concern. Panel **a** shows the projected increase in global mean temperature in 2100 compared to preindustrial, calculated using the MAGICC climate model for the scenarios defined in Chapter 6, Working Group III, indicating the uncertainty range resulting both from the range of emission scenario projections within each category and the uncertainty in the climate system as represented by MAGICC (data taken from Chapter 6 – AR5 WGIII). Panel **b** reproduces Figure 19-4 for ease of comparison. Note the different temperature baselines used in Figure 19-4. Beyond 2100, temperature, and therefore risk, decreases in most of the lowest three scenarios and increases further in most of the others.

[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 20. Climate-Resilient Pathways: Adaptation, Mitigation, and Sustainable Development

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Contents

Executive Summary

Climate change calls for new approaches to sustainable development that take into account complex interactions between climate and social and ecological systems. Climate-resilient pathways are development trajectories that combine adaptation and mitigation to realize the goal of sustainable development. They can be seen as iterative, continually evolving processes for managing change within complex systems.

This chapter integrates a variety of complex concepts in assessing climate-resilient pathways. It takes sustainable development as the ultimate goal, and considers mitigation as a way to keep climate change moderate rather than extreme. Adaptation is considered a response strategy to anticipate and cope with impacts that cannot be (or are not) avoided under different scenarios of climate change. In most cases, sustainable development will also involve capacities for implementing and sustaining appropriate risk management. Responses may differ from situation to situation, calling for a multi-scale perspective that takes the socioeconomic, cultural, biophysical, and institutional context into account. Nonetheless, most situations share at least one fundamental characteristic: threats to sustainable development are greater if climate change is substantial rather than moderate. Similarly, opportunities for sustainable development are greater if climate change is moderate rather than substantial.

Although findings from this chapter are based on a high level of consensus in source materials and in the expert communities, the amount of supporting evidence is relatively limited because so many aspects of sustainable development and climate change mitigation and adaptation have yet to be experienced and studied empirically. The task of this chapter is to suggest options to be considered for decision-making, both now and in the future, as elements of the evolving processes for a variety of locations and scales. This chapter's findings are as follows:

Climate change poses a moderate threat to current sustainable development and a severe threat to future sustainable development. (*high confidence*; *high agreement, medium evidence*). Some climate-related impacts on development are already being observed (e.g, changes in agriculture, increases in coastal vulnerability). Added to other stresses such as poverty, inequality, or diseases, the effects of climate change will make sustainable development objectives such as food and livelihood security, poverty reduction, health, and access to clean water more difficult to achieve for many locations, systems, and affected populations. [20.2.1]

Climate-resilient pathways include strategies, choices and actions that reduce climate change and its impacts. They also include actions to assure that effective risk management and adaptation can be implemented and sustained. (*high confidence*; *high agreement, medium evidence*). Adaptation and mitigation have the potential to both contribute to and impede sustainable development, and sustainable development strategies and choices have the potential to both contribute to and impede climate change responses. Both kinds of responses are needed, working together to reduce risks of disruptions from climate change. These actions, however, may introduce tradeoffs

between adaptation and mitigation, and between economic goals and environmental goals. In some cases, for example, adaptation may increase greenhouse gas emissions (e.g., increased fossil-based air conditioning in response to higher temperatures) and in some cases mitigation may impede adaptation (e.g., reduced energy availability in countries with growing populations). In many cases, strategies for climate changer responses and strategies for sustainable development are highly interactive. [20.3, 20.4]

The integration of adaptation and mitigation responses can in some cases generate mutual benefits, as well as introduce co-benefits with development policies. (*moderately high confidence*; *medium high agreement, medium evidence*). In many cases, reducing the risk of climate change can enhance capacities for management of other risks. Opportunities to take advantage of positive synergies may decrease with time, particularly if the limits to climate change adaptation are exceeded. [20.2.1, 20.3.2, 20.3.3, 20.5.1]

Prospects for climate-resilient pathways are related fundamentally to what the world accomplishes with climate change mitigation, but both mitigation and adaptation are essential for climate change risk management at all scales. (*high confidence*; *high agreement, medium evidence*). As the magnitude of climate change increases and the consequences become increasingly significant to many areas, systems, and populations, the challenges to sustainable development increase. Beyond some magnitudes and rates of climate change, the impacts on most systems would be great enough that sustainable development may no longer be possible for many systems and locations. At the local scale, governments, businesses, communities and individuals in many developing regions have limited capacities to mitigate climate change because they contribute very little to global emissions. They may also have relatively limited capacities to adapt for reasons of income, education, health, security, political power, or access to technology). At all scales, however, mitigation and adaptation actions are fundamental for effective implementation of climate risk management and reduction. [20.2.3, 20.3, 20.6.1]

To promote sustainable development within the context of climate change, climate-resilient pathways may involve significant transformations (*high confidence*; *high agreement, medium evidence*). Transformations in political, economic, and socio-technical systems can contribute to enhanced climate responses, both for mitigation and adaptation. Although transformations may be reactive, forced, or induced by random factors, they may also be deliberately created through social and political processes. Whether in relation to mitigation, adaptation, or sustainable development, it is possible to identify enabling conditions that support transformations. Nonetheless there are legitimate concerns about the equity and ethical dimensions of transformation. [20.5]

Strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve livelihoods, social and economic well-being, and responsible environmental management (*high confidence*; *high agreement, medium evidence*). Actions at the present time will emphasize co-benefits and iterative learning, with risk management strategies and capacities refined continually on the bases of growing evidence, knowledge, and experience. [20.6.2]

Delayed action in the present may reduce options for climate resilient pathways in the future (*high confidence*; *high agreement, medium evidence*). In some parts of the world, current failures to address effects of emerging climate stressors are already eroding the basis for sustainable development and offsetting previous gains. Opportunities to design and implement solutions that promote climate resilient pathways exists now, and they can capture development co-benefits of improving livelihoods, social and economic well-being. Current actions will emphasize climate risk management and iterative learning and transformation, on the basis of growing evidence, knowledge, and experience. [20.6.2]

More research about the relationship between mitigation, adaptation, and sustainable development is needed, as well as research on the relationship between incremental changes and more significant transformations for sustainable development (*high confidence*; *high agreement, robust evidence*). Priorities for research include improving understandings of benefits, costs, synergies, tradeoffs and limitations of major mitigation and adaptation options, along with implications for equitable development to facilitate decision-making about climate resilient pathways. (high confidence; high agreement, strong evidence).

20.1. Introduction

Following summaries of *what we know* about climate change impacts, vulnerabilities, and prospects for adaptation (Chapter 18) and of *what we should be most worried about* (Chapter 19), this concluding chapter summarizes what is currently known about options regarding *what to do* in responding to these risks and concerns.

In terms of "what to do" to address climate change and threats to development now and in the future, the chapter identifies and discusses climate-resilient pathways. Climate-resilient pathways are defined in this chapter as development trajectories that combine adaptation and mitigation with effective institutions to realize the goal of sustainable development. They are seen as iterative, continually evolving processes for managing change within complex socio-ecological systems; taking necessary steps to reduce vulnerabilities to climate change impacts in the context of development needs and resources, building capacity to increase the options available for vulnerability reduction and coping with unexpected threats; monitoring the effectiveness of vulnerability reduction efforts; and revising risk reduction responses on the basis of continuous learning. As such, climate-resilient pathways include two main categories of responses:

- Actions to reduce human induced climate change and its impacts, including both mitigation and adaptation towards achieving sustainable development
- Actions to assure that effective institutions, strategies, and choices for risk management will be identified, implemented, and sustained as an integrated part of achieving sustainable development.

In many cases, each of the two categories of responses has the potential to benefit the other as well, offering potentials for win-win kinds of integration, although mechanisms and institutions are needed to address cases where the two elements have negative effects on each other and to assure that positive synergies are realized. Because climate change challenges are significant for many areas, systems, and populations, climate-resilient pathways will generally require transformations – beyond incremental approaches – in order to assure sustainable development (see Sections 20.2.3.1 and 20.6.2; for related UNFCCC language, see Box 20-1**).**

Incremental responses to climate change address immediate and anticipated threats based on current practices, management approaches or technical strategies. These may involve developing energy-efficient vehicles to mitigate climate change, or building higher dykes to adapt to sea-level rise. Incremental responses are often referred to as business-as-usual approaches, as they do not challenge or disrupt existing systems (Kates et al, 2012). Transformative responses, in contrast, involve innovations that contribute to systemic changes by challenging some of the assumptions that underlie business-as-usual approaches (O'Brien, 2012). Transformational adaptations, for example, change the nature, composition, and/or location of threatened systems (Smit and Wandel, 2006; Stringer et al., 2009; NRC, 2010a; Pelling, 2010; IPCC SREX, 2012). Importantly, transformations of the systems, structures, relations, and behaviors that contribute to climate change and social vulnerability may also be necessary to reduce risks to sustainable development, as discussed in Section 20.5.2.

Conceptual understandings of sustainable development have developed considerably, particularly over the past two decades, as the short- and long-term implications of climate change and extreme events have become better understood, although empirical evidence of progress with sustainable development is often elusive. The discussion of sustainable development in the IPCC process has evolved since the First Assessment Report, which focused on the technology and cost-effectiveness of mitigation activities, and the Second Assessment Report (SAR), which included issues related to equity and to environmental and social considerations. The Third Assessment Report (TAR) further broadened the treatment of sustainable development by addressing issues related to global sustainability, and the Fourth Assessment (AR4) included chapters on sustainable development in both WG II and III reports, with a focus on both climate-first and development-first literatures.

This chapter recognises climate change as a threat to sustainable development, given growing evidence that the world is on a trajectory toward relatively major climate change. The chapter emphasises that, as a result, transformational changes are very likely to be required for climate resilient pathways – both transformational adaptations and transformations of social processes that make such transformational adaptations feasible. The chapter integrates a variety of complex issues in assessing climate-resilient pathways in a variety of regions at a variety of scales: sustainable development as the ultimate aim, mitigation as the way to keep climate change impacts moderate rather than extreme, adaptation as a response strategy the way to keep climate change impacts moderate rather than extreme or to cope with impacts that cannot be (or are not) avoided, and development pathways as contexts that shape choices and actions. It stresses needs and opportunities to make progress toward climate-resilient pathways now, rather than postponing responses to an indefinite future.

_____ START BOX 20-1 HERE _____

Box 20-1. Goals for Climate-Resilient Pathways

Climate resilient pathways are development trajectories of combined mitigation and adaptation to realize the goal of sustainable development that help avoid "dangerous anthropogenic interference with the climate system" as specified in Article 2 of the Convention.

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) outlines its ultimate objective as the, '*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*… in order to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner'. Article 3.4 of the Convention recognizes that '*Parties have a right to, and should promote sustainable development*'. Number of recent decisions by the Conference of the Parties (COP) to the UNFCCC has attempted to recognize the scientific view that the increase in global temperature should be below 2 degrees Celsius and encourage long-term cooperative action to combat climate change. The Decisions agreed in Cancun at COP 16 recognizes '… *deep cuts in global greenhouse gas emissions are required according to science*, and as documented in the Fourth Assessment Report of the IPCC, with a view to reducing global greenhouse gas emissions so as to hold the increase in global average temperature below 2°C above preindustrial levels…consistent with science…[and] also recognizes the need to consider… strengthening the long-term global goal on the basis of the best available scientific knowledge'. In the preamble of the Cancun Decisions highlights the central importance of the link between climate change and employment and *'Realizes that addressing climate change requires a paradigm shift towards building a low-carbon society that offers substantial opportunities and ensures continued high growth and sustainable development, based on innovative technologies and more sustainable production and consumption and lifestyles, while ensuring a just transition of the workforce that creates decent work and quality jobs.' (UNFCCC, 2011, Decision 1/CP16).* The 2011 COP in a decision known as the Durban Platform increases the strength of the language in the decision 1/CP.17 to conclude, '… *climate change represents an urgent and potentially irreversible threat to human societies and the planet* and thus requires to be urgently addressed … with a view to accelerating the reduction of global greenhouse gas emissions....*'* This decision was followed by the decisions adopted in Doha at the 18th Conference of the Parties that noted with grave concern the significant gap between the aggregate effect of Parties' mitigation pledges in terms of global annual emissions of greenhouse gases by 2020 and aggregate emission pathways consistent with having a likely chance of holding the increase in global average temperature below 2 °C or 1.5 °C above pre-industrial levels. As such, the current UNFCCC negotiations have adopted +2°C or 1.5 C as the desirable target upper limit and equated this with "dangerous" in Article 2.

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The chapter is organized in six parts: climate change as a threat to sustainable development, assessing links between sustainable development and climate change as well as defining climate resilient pathways (20.2), contributions to resilience through climate change responses (20.3), contributions to resilience through sustainable development strategies and choices (20.4), determinants of resilience in the face of serious threats (20.5), challenges in moving toward climate-resilient pathways (20.6), and priority gaps in knowledge (20.7). Several of the terms that are central to this chapter have been defined earlier in the Working Group II Fifth Assessment Report, including climate, adaptation, and mitigation. In addition, by "resilient" we mean a system's ability to anticipate, reduce, accommodate, and recover from disruptions in a timely, efficient, and fair manner (IPCC SREX, 2012). For literatures on "sustainable development," see the section below. A summary definition is development that achieves continuing improvements in human well-being and assures a sustainable relationship with a physical environment that is already under stress, reconciling tradeoffs among economic, environmental, and other social goals through institutional approaches that are equitable and participative in order themselves to be sustainable.

20.2. Climate Change as a Threat to Sustainable Development

Climate-resilient pathways bring together (a) sustainable development as the larger context for societies, regions, nations, and the global community with (b) climate change effects as threats to (and possibly opportunities for) sustainable development and (c) responses to reduce any effects that would undermine future development and even offset already achieved gains. Considering alternative climate-resilient pathways cannot be separated from levels of climate change. In principle, most climate change scientists, decisionmakers, and stakeholders agree that: (i) there is a level of climate change that is low enough that climate resilience for most systems could be achieved without enormous efforts and widespread transformational adaptation; (ii) there is a level of climate change that is high enough that climate resilience cannot be expected to cope with severe impacts on most systems (e.g., Rockstrom et al., 2009); and (iii) between those two levels the challenges to climate resilience grow as the level of climate change rises. Scientists do not, however, agree on what magnitude of climate change (e.g., average global warming) defines each of the two levels. Some experts support the view (Box 20-1 and Section 20.3.1) that any level above 2 degrees C would mean impacts that are incompatible with sustainable development (Metz et al., 2002**).** The Summary for Policymakers of the IPCC's Fourth Assessment Working Group II Report indicated that there is an approximate threshold between 2.5 and 3 degrees C of warming, above which impact concerns are severe but below which concerns are less severe (IPCC, 2007b: Figure SPM.2; also see Smith et al., 2009). Other scientists are unconvinced that system sensitivities to climate parameters such as temperature increase are understood well-enough to support any specific warming threshold (e.g., NRC, 2010c), and some scientists and policymakers are unconvinced that adaptive management and adaptive response capacities are well-enough understood to support determinations of limits to adaptation and resilience (Chapter 16). Most experts in all three groups, however, agree that prospects for climate-resilient development pathways are related fundamentally to what the world accomplishes with climate change mitigation (e.g., New et al., 2012).

20.2.1. Links between Sustainable Development and Climate Change

20.2.1.1. Objectives of Sustainable Development

Different actors have used the concept of sustainable development to pursue a variety of objectives in policy and practice worldwide, with the common denominator of delivering improved human well-being while sustaining environmental services (Sen, 1999; Morgan and Farsides, 2009; Von Bernard and Gorbaran, 2010). "Sustainable development" is a concept rooted in concerns about balance in the relationships between society and nature (e.g., Brown, 1981). The Brundtland Report (WCED, 1987: 43) defines the idea as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." It contains within it two key concepts of 'needs': in particular the essential needs of the world's poorest, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs (Rao, 2000). It stresses that equitable economic development is key to addressing environmental problems both in developing and developed regions in ways that are sustainable for the long term (Halsnaes et al., 2008; Lafferty and Meadowcroft, 2010).

Historically, policy and science have subsequently influenced the development of the concept. Concerns about declining environmental quality, and increasing population growth, coupled with increasing rates of consumption (energy, natural resources, input-intensive living standards), motivated changes in some countries, related for example to:

- Water and air quality standards
- Management of hazardous materials
- Changes in regulation (although some literature says that current institutional controls and linkages are counterproductive (Scrieciu et al., 2013; Barker, 2008; O'Hara, 2009)
- Agricultural and industrial practices
- Water and solid waste management
- A movement toward greater efficiency in resource use including recycling

- An emphasis on energy efficiency, progressing toward renewable energy as an alternative to non-renewable fossil fuel resources (Frey and Linke, 2002**)**.

In this context, global discourse and practice have helped to establish principles and aspirational plans. Examples include Agenda 21, which is a comprehensive plan of action adopted at the 1992 Earth Summit by more than 178 governments (Sitarz, 1994) and the 2012 “Rio+20” conference, which issued a statement urging countries to renew their commitment to sustainable development. Improved understandings of the short- and long-term implications of climate change and extreme events (IPCC FAR, SAR, TAR, AR4, SREX) have influenced conceptualizations of sustainable development and related objectives such as poverty reduction, health, livelihood and food security, and other aspects of human welfare related to the idea of “climate resilient development”. These discussions occurred against an emerging understanding of “rights to development” (e.g. UNFCCC Article 2), juxtaposed with the lack of consensus about justifiable patterns of consumption and a recognition that development processes have altered global environmental systems, including climates (Crutzen and Stoermer, 2000; IPCC, 2007a, IPCC SREX, 2012, Oliver-Smith et al., 2012). However, in practice some national authorities interpret sustainable development as pursuing current economic development (Arndt et al., 2012; Beg et al., 2002; Swart et al., 2003; Yohe, 2012), as many countries aspire to carbon intensive development models akin to the systems in place in most industrialized countries – from food production, trade, and transport to household consumption (Brown, 2011; Grist, 2008; Sanwal, 2012).

In contrast, to many observers carbon-intensive development models in industrialized and developing countries appear broadly inconsistent with objectives such as poverty reduction, improving human health, securing food and livelihoods associated with the idea of sustainable development (Marston, 2012; Grist, 2008; Ehrenfeld, 2008; also see Victor, 2008, and Victor and Rosenbluth, 2007), and with efforts to define and establish “safe operating spaces” for humanity (Röckstrom et al., 2009, Preston et al., 2013). While diverse interpretations of the concept are used, the literature suggests that many indicators of human welfare are already being compromised to some degree and at different scales by climate related stressors (see Section 20.2.1.2).

One way that sustainable development pathways can contribute to climate resilience is by pursuing consumption patterns that assure social and economic development while reducing use of natural resources and maintaining ecosystem services. It is possible that the desired objectives of consumption might be met in ways that require fewer resources and produce fewer emissions (Kates, 2000b; also see Leiserowitz et al., 2005). Ideas about equity and values play a role in sustainable development and how policy makers perceive tradeoffs in aims to improve human well-being. In many cases, growth in consumption that raises human well-being (such as food and health services), especially among populations with incomes rising from low levels, is a catalyst for economic and social development (Clark et al., 2008; Deaton, 2008). In contrast, for populations already at high consumption levels, increasing material consumption does not necessarily translate into higher well-being (Easterlin, 1974 and 2001; Adger, 2010; also see IPCC Working Group III: Chapter 4). This observation is reflected in research on subjective human happiness, satisfaction, and material comfort (DeLeire and Kalil, 2010; Cafaro, 2010; Huesemann, 2006; Dolan and White, 2007; Fleurbaey, 2009).

20.2.1.2. Risks and Threats Posed by Climate Change, interacting with Other Factors and Driving Forces

As the extent of implications of climate change become better-understood (Chapter 18) and as particular reasons for concern have begun to come into focus (Chapter 19), climate change has been increasingly seen as an issue for sustainable development – with the potential either to aid or impede its successful implementation (e.g., Halsnaes et al., 2008; Munasinghe, 2010).

The links between sustainable development and climate adaptation and mitigation are cross-cutting and complex. First, the impacts of climate change and ill-designed responses to these impacts, may derail current sustainable development policy and potentially offset already achieved gains. These impacts are expected to affect numerous sectors such as agriculture, forestry and energy; threaten coastal zones and other vulnerable areas; and pose critical challenges to governance and political systems (World Bank, 2010: 39-69; Adger et al., 2011; IPCC SREX, 2012; also see Box 20-2 below and Chapters18 and 19). Examples include poverty and livelihoods (Chapter 13), food security (Chapter 7), human security (Chapter 12), rural and urban areas (Chapters 8 and 9), and economic sectors (Chapters 10 and 17). For instance, effects of climate change on key ecological resources and systems can jeopardize sustainable development in systems closely dependent on natural capital. Moreover, although impacts will affect both developed and developing regions, the latter are considered especially problematic due to lower adaptive capacity (World Bank, 2010: Chapter 13; Lemos et al., 2013). Second, mitigation has the potential to keep these threats at a moderate rather than extreme level, and adaptation will enhance the ability of different systems to cope with the remaining impacts, therefore modulating negative effects on sustainable development (IPCC, 2007a).

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Box 20-2. Key Reasons for Concern about Climate Change Effects on Sustainable Development

Chapter 19 identifies a number of “Key Risks, Key Vulnerabilities, and Reasons for Concern” (see especially 19.6.3 and Table 19-4). Emergent risks from climate change related to sustainable development include losses of ecosystem services, challenges to land and water management, effects on human health, particular risks of severe harm and loss in certain vulnerable areas, increasing prices of food commodities on the global market, consequences for migration flows at particular times and places, increasing risks of flooding, risks of food insecurity, systemic risks to infrastructures from extreme events, loss of biodiversity, and risks for rural livelihoods. These risks differ according to the magnitude of climate change and both regional and socioeconomic differences in vulnerability. Some unique and threatened systems are at risk at current temperatures, with risks increasing at even relatively small increases in global mean temperature. Risks grow if the magnitude of warming increases.

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Third, many of the conditions that define vulnerability to climate impact and the ability to mitigate and adapt to them are firmly rooted in development processes (e.g., structural deficits and available assets and entitlements) (Brooks et al., 2005; Lemos et al., 2013; Chapter 15, Section 15.2.1). Indeed, climate change will act as a threat multiplier and will create new poor in low-income countries and middle to high-income countries (Chapter 13). Fourth, sustainable development intersects with many of the drivers of climate change, especially regarding energy production and consumption and the ability to mitigate emissions (IPCC SRREN, 2012; also see Chapter 9). Fifth, because several of the desirable characteristics of climate responses and sustainable development may overlap (e.g. implementation of no-regrets options, equitable distribution of resources, increased adaptive capacity and livelihood capitals, functioning ecosystems and maintained biodiversity), systems that prioritize sustainable development may be better at designing and implementing successful mitigation and adaptation (Forsyth, 2007; Brown, 2011).

Finally, climate mitigation and adaptation, if planned and integrated well, have the potential to create opportunities to foster sustainable development (see Section 20.3.3 below). Under the threat of climate change, sustainable development depends on changes in social awareness and values that lead to innovative actions and practices, including increased attention to both disaster risk management and climate change adaptation in anticipation of (and in response to) changes in climate extremes (IPCC SREX, 2012). Understanding how to enhance positive feedbacks between mitigation, adaptation, and sustainable development (e.g. win-win and triple win interventions) while minimizing potential trade-offs between them (see Section 20.3.3) is an essential part of planning for and pursuing climate-resilient pathways. In the following paragraphs, we discuss these links in light of empirical research and specific examples (Box 20-2; also see discussions of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) in Chapter 1). While some of the links described above have been contemplated in the scholarly literature, there remain considerable gaps on our knowledge base to inform climate-resilient pathways.

The relationship between climatic change and development policy has often been theorized as essentially twofold. On the one hand, climate change will affect development policy as needs to respond to negative, and perhaps positive, impacts arise (Schipper, 2007; Burton et al., 2002; Halsnaes and Verhagen, 2007; IPCC, 2007a). On the other hand, development policy critically shapes carbon emission paths, the ability to develop sustainable adaptation and mitigation options, and to build overall adaptive capacity (Bizikova et al., 2007; Garg et al., 2009; Metz and Kok, 2008; Lemos et al., 2013). Because of the recognized relationship between development and climate change drivers and responses, some authors have called for a “political economy of climate change” that takes into consideration ideas, power, and resources at different scales from the local to the global (e.g., Tanner and Allouche, 2011).

Enhancing resilience to respond to effects of climate change includes adopting good development practices that are consonant with building sustainable livelihoods and, in some cases, challenging current models of development (Boyd et al., 2008; McSweeny and Coomes, 2011). Moreover, promoting development pathways that are both equitable and sustainable is also a key to addressing climate change (Wilbanks, 2003; Nelson et al., 2007). In this sense, integrating sustainable development and overall climate change policy can be all the more relevant if "cross-linkages between poverty, the use of natural capital and environmental degradation" are recognized (Veeman and Politylo, 2003: 317; also see Matthew and Hammill, 2009). Especially in less developed regions, the relationship between vulnerability to climate impacts and development is often very close and mutually dependent as such realities as low per capita income and inequitable distribution of resources, lack of education, health care, and safety, and weak institutions and unequal power relations fundamentally shape sensitivity, exposure and adaptive capacity to climate impact (Garg et al., 2009; McSweeny and Coomes, 2011; Adger et al., 2003; Kates, 2000a; Lemos et al. 2013). In these regions, reducing risks that affect resource-dependent communities is increasingly viewed as a necessary but insufficient way to tackle the myriad of problems associated with climate change impacts (Jerneck and Olsson, 2008). Building the capacity of individuals, communities and governance systems to adapt to climate impacts is both a function of dealing with developmental deficits (e.g. poverty alleviation, reducing risks related to famine and food insecurity, enabling/implementing public health and mass education and literacy programs) and of improving risk management (e.g. alert systems, disaster relief, crop insurance, seasonal climate forecasts, risk insurance) (Mirza, 2003; Schipper and Pelling, 2006; IPCC SREX, 2012; Warner, Kreft, et al., 2012; Chapters 12 and 13). Hence, it is important not only to understand the relative importance of different kinds of interventions (climate and non-climate) in building adaptive capacity but also the potential positive and negative synergies between them (Lemos et al., 2013).

While research increasingly highlights the intersection between vulnerability, adaptive capacity, and developmental structural deficits (see chapter 13 for a detailed discussion), there is also growing recognition that the intractability of many of these problems may inhibit the development of climate-resilient pathways. For example, in Northeast Brazil, the fact that local traditional politics relied on patron-client relationships with drought-affected households to maintain power suggests that there was little incentive for policies that dramatically decreased their level of vulnerability (Tompkins et al., 2008). Omolo, 2010, argues that in the northwestern Kenya, in pastoralist societies of Turkana, in spite of increasing numbers of women headed households, participation of women in key decisions such as investment, resource allocation, and planning on where to move or settle in the aftermath of drought and floods is still quite low. A serious concern is that our inability to readily address these kinds of structural problems may limit options for future generations of marginalized social groups to be active agents of a climate resilient future. In this sense, it is critical to understand how existing path-dependent trajectories (e.g., socio-technical, behavioral, institutional) that form the contextual basis for climate change action at different scales (Burch, 2010) may inhibit (or help) the realization of future climate resilient pathways.

A number of studies recognize that not every possible response to climate change is consistent with sustainable development, since some strategies and actions may have negative impacts on the well-being of others and of future generations (Eriksen et al., 2011; Gardiner et al., 2010; see also Chapter 19, Section 19.3.2.5). For example, some mitigation interventions such as the subsidization of the ethanol industry in the US might compromise long-term resilience through both undesirable ecological effects (e.g. loss of crop diversity, soil erosion and aquifer depletion) and social effects (e.g. reduction of flexibility for alternative fuel development, potential for food insecurity (Adger et al., 2011). Likewise, in central Vietnam some responses to climate change impact, such as building dams to prevent flooding and saltwater intrusion and to generate power, threaten the livelihood of poor communities. First, the relocation of communities and the inundation of forestland to build dams limit households' access to land and forest products. Second, a government focus on irrigated rice agriculture can reduce poor households' ability to diversify their income portfolio, decreasing their long-term adaptive capacity (Beckman, 2011). Indeed, the consequences of responses to climate change, whether related to mitigation or adaptation, can negatively influence future vulnerability, unless there is awareness of and response to these interactions (Ericksen et al., 2011). Here, the role of values in responding to climate change becomes important from a variety of perspectives, including intergenerational, particularly when those currently in positions of power and authority assume that their prioritized values will be shared by future generations (O'Brien, 2009; Ericksen et al., 2011). Acknowledging the importance of intergenerational equity, it has been argued that participatory processes and 'deliberative democracy' can include the concerns, values and perceptions of a wide range of stakeholders, raising some of the ethical impacts attached to climate related risks (Backstrand, 2003; also see Deere-Birebeck, 2009). Such an approach could have a bearing on the way risks are assessed and addressed at the science-policy interface, with significant implications for sustainable development. For example, research by Wolf et al., 2009, on climate change responses in western Canada shows that individual quests to minimize their environmental impact and sense of responsibility (normatively defined as ecological citizenship) play an important role in the identification and implementation of sustainable responses to water scarcity. In contrast, inequitable distribution of power among those affected by climate impact can suppress innovative decisions about the future by limiting participation in designing solutions. In light of the complex interactions among climate change responses and sustainable development, there is a need for more holistic responses that place human well-being and security at the forefront, while building on existing strengths and capacities (Tompkins and Adger, 2004; O'Brien et al., 2010). This entails integrating multiple objectives and policy goals in order to promote responses to climate change that contribute to resilience and that are sustainable as social and policy conditions change (Meadowcroft, 2000; Tompkins and Adger, 2004; Pintér et al., 2011).

A reality in many countries may be that development in its many forms (economic, human and sustainable) can enhance the capacity to adapt (Lemos et al., 2013), while at the same time adding to greenhouse gas emissions. Yet, the World Development Report 2010 suggests that climate change responses have the potential to contribute to sustainable development as, for example, in the case of financial assistance with transition to low-carbon growth paths (World Bank, 2010) or in the case of mitigation policies that could increase income and/or enhance the quality of growth in vulnerable groups such as REDD+ (Reducing Emissions from Deforestation and Forest Degradation in Developing Countries). And while vulnerable sectors such as agriculture give us particular reasons for concern (see Box 20-2), they may offer opportunities in some instances to reduce climate related risks and threats by integrating both adaptation and mitigation strategies as a lever for reducing poverty and promoting climate resilient pathways. Particularly necessary is addressing institutional and social capacities for responding to both climate change impacts and mitigation responses. For example, Chhatre and Agrawal (2009), show that climate change mitigation can benefit livelihoods if ownership of forest commons is transferred to local communities.

Some interventions related to climate change responses aim to combine goals of sustainable development, climate change adaptation, and climate change mitigation into "win-win" or "triple win" approaches that highlight overlaps between these goals. Examples include mechanisms such as the Clean Development Mechanism (CDM) and Joint Implementation (JI) (e.g., Millar et al., 2007), which may seek to offset carbon emissions, build adaptive capacities of local communities, and provide sustainable development dividends despite mixed results in terms of accomplishing these goals in practice (Corbera and Brown, 2008). Specifically in the case of the CDM, robust empirical research shows overwhelming negative results in win-win terms—while the goal of offsetting carbon emissions has fared better, generating sustainable development dividend has been difficult. For example, after examining sixteen existing CDM projects around the world, Sutter and Parreno, 2007, found that whereas they could meet 72% of their emissions reduction goals, less than 1% might actually contribute significantly to sustainable development in the host country. Furthermore, their research suggests that there might be an actual tradeoff between the goals of efficient generation of certified emissions reduction (CERs) and the broader generation of the sustainable development dividend (also see Winkelman and Moore, 2011). Even when relatively successful, triple-win interventions may result in unequal distribution of benefits across mitigation, adaptation and sustainable development (Bryan et al., 2013). Because relationships among the three goals can lead to both positive and negative consequences, it is important to unravel conditions that lead to desirable outcomes (Chhartre and Agrawal, 2009) (see Section 20.3.3). Moreover, the fact that currently available institutional arrangements that attempt to combine mitigation and sustainable development (such as CDM) are not achieving win-win goals indicates the need for rapidly developing means for evaluating, changing and improving current policy instruments and mechanisms (Dovers and Hezri, 2010).

Given these connections, there is growing consensus in the literature about a need to integrate development and climate policies; however, the means to achieve this integration differ and are not without controversy (see, for example, Seballos and Kreft, 2011). An approach often described in the literature is mainstreaming, where governments incorporate climate-related concerns into existing policy (Dovers and Hezri, 2010). A major factor constraining the 'mainstreaming' of climate adaptation into development is the disconnect between access to globally available adaptation funds and developing countries' own development agendas (Hardee and Mutunga, 2009; Seballos and Kreft, 2011). This disconnect can potentially inhibit the development of robust local organizations and institutions that effectively integrate or mainstream climate change considerations into development priorities. In particular, research focusing on the National Adaptation Programmes of Action (NAPAs) and the Strategic Programmes for Climate Resilience (SPCRs), designed to support least developed countries to mainstream adaptation, shows that lack of coordination between government sectors, lack of technical capacity and discrepancies between long term development goals and short term adaptation interventions still constrain mainstreaming efforts (Chapter 15: Section 15.2; Saito, 2013). Even where climate-related initiatives and programs are reasonably well-coordinated, bureaucratic complexities can cause communities to be overlooked (Chukwumerije and Schroeder, 2009). For example, in Mexico, despite the governmental discourse supporting climate change policy, actual implementation of mitigation and adaptation actions have been constrained by lack of resources and institutional coordination and limited societal involvement (Sosa-Rodriguez, 2013). Other factors -- such as lack of financial and human resources, unclear distribution of costs and benefits, fragmented management, mismatches in scale of governance and implementation, lack and unequal distribution of climate information, lack of institutional memory, and trade-offs with other priorities – may also limit the smooth mainstreaming of climate adaptation action into development (Agrawala and van Aalst, 2008; Bizikova et al., 2007; Eakin and Lemos, 2006; Kok et al., 2008; Metz and Kok, 2008, Sietz et al., 2011). Finally, empirical evidence suggests that the relationship between development variables and climate change responses can be a mixture of positives and negatives, if development variables are not managed well (Garg et al., 2009). For example, in a study of the relationship between malaria incidence, development and climate variables in India, Garg et al., 2009, found that while some development interventions such as building irrigation canals and dams can, in some cases, increase the incidence of malaria and water-borne diseases (when they exacerbate potential breeding grounds for malarial parasites), others such as higher per capita income can reduce negative health impacts of climate change significantly – although the distribution of benefits can differ between types of interventions (also see Campbell-Landrum and Woodruff, 2006). Understanding how development variables intersect with climate responses is especially important because governments and other actors rarely make decisions in isolation; rather they respond to multiple stressors both in rural and urban environments (Agrawal, 2008; Eakin, 2005; Wilbanks and Kates, 2010; Lemos et al., 2013). Moreover, some evidence suggests that, in practice, decisionmakers (from heads of households to policy-makers) often do not place climate change at the top of their priority list of critical issues to address (Garg et al., 2007; Kok et al., 2008), although this situation seems to be changing. Moreover the increasing importance of climatic change in shaping social and governmental policy agendas has resulted a growing number of examples of specific interventions to respond to climate change, both in developed and developing regions (Ayers and Huq, 2009; Burch, 2010; Bierbaum et al., 2013; for examples of adaptation planning see Chapter 15, especially Section 15.2, and Chapter 14, especially Section 14.3).

20.2.3. Climate-Resilient Pathways

20.2.3.1. Framing Climate-Resilient Pathways

Climate-resilient pathways integrate current and evolving understandings of climate change consequences and conventional and alternative development pathways to meet the goals of sustainable development (see IPCC Working Group III: Chapter 4). They can be seen as development trajectories that include both mitigation and adaptation, as well as effective development institutions. Climate resilient pathways represent iterative processes for managing change within complex systems, where unintended consequences are common due to feedbacks, teleconnections, cross-scale linkages, thresholds, and non-linear effects (Folke et al., 2002; Scheffer et al., 2009; Lenton, 2011a). Climate-resilient pathways recognize that increasing atmospheric concentrations of greenhouse gases can lead to impacts that have long-term implications for sustainable development. The observed and projected impacts of climate change on poverty and livelihoods, food and water security, health, and human security are well-documented in this report (see Chapters 11, 12, 13).

The pursuit of climate-resilient pathways involves identifying vulnerabilities to climate change impacts; assessing opportunities for reducing risks; and taking actions that are consistent with the goals of sustainable development.

These actions may involve a combination of incremental and transformative responses that take into account: 1) current and anticipated changes in both climate averages and extremes; 2) the dynamic development context that influences social vulnerability, risk perception, conflict resolution, and resilience; and 3) recognition of human agency and capacity to influence the future. This last point is significant, as humans have the capacity to manage risk and to decrease vulnerability through both mitigation and adaptation, as well as through choices of development goals and strategies (IPCC SREX, 2012**)**.

Climate resilient pathways call for decisions and actions that take into account both short- and long-term time horizons. In the short term, society will have to adapt to changes in the climate that are linked to past emissions, and both incremental and transformative adaptation may thus be significant. Mitigation responses taken in the short term will have a strong influence on climate-resilient pathways for sustainable development in the future, shaping needs for transformative adaptation over a long time horizon. Considering the potential for non-linear impacts associated with increasing global temperatures, the threats to sustainable development are likely to become greater over time (Wilbanks et al., 2007; Stafford et al., 2010; Chapter 12). Discussions of climate-resilient pathways thus cannot be separated from levels of climate change.

20.2.3.2. Elements of Climate-Resilient Pathways

If climate change continues on its current path toward relatively significant impacts (NRC, 2010b), climate-resilient pathways will become increasingly challenging, requiring explicit attention to responses in virtually all regions, sectors, and systems in order to avoid disruptions of development processes. Climate-resilient pathways include two overarching attributes: (1) actions in order to reduce climate change and its impacts, including both mitigation and adaptation, and (2) actions to assure that effective risk management institutions, strategies, and choices can be identified, implemented, and sustained as an integrated part of development processes (Edenhofer et al., 2012). Box 20-3 lists a number of attributes of climate-resilient pathways categorized into awareness and capacity, resources and practices. Each of the items is amenable to strategy development in appropriate national, regional, and local contexts. For example, in many cases effective response to extreme events can benefit both from iterative problem-solving and bottom-up engagement in risk management, and from human development to enhance capacities for risk management and adaptive behavior (Tompkins et al., 2008). Folke (2006) characterizes resilience as a process of innovation and development. Pathways should therefore be continuously moving toward a more adapted and less vulnerable state; in some instances, there may be stages of slow development followed by periods where progress increases speed. Further, the nonlinearity, variability and uncertainty of climate impacts necessitates a system that allows for the flexibility to adapt to unexpected and even extreme events (Holling, 1973). This is especially true in light of political, economic or resource constraints, where pathways at the local level will need to not only be flexible but also practical and feasible in both the short term and long term. One of the most challenging aspects of climate-resilient pathways is that they exist in distinctive local contexts, where they are shaped by external linkages that connect them across geographic scales and time. For example, resilience cannot be achieved in a few privileged places if it is not achieved in other connected places, because instabilities in adversely impacted situations will spill over to other situations through such effects as resource supply constraints, conflict, migration, or disease transmission (Wilbanks, 2009; IPCC SREX, 2012: Chapter 7).

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Box 20-3. Selected Elements of Climate-Resilient Pathways

Awareness and capacity

- A high level of social awareness of climate change risks
- A demonstrated commitment to contribute appropriately to reducing net GHG emissions, integrated with national development strategies
- Institutional change for more effective resource management through collective action
- Human capital development to improve risk management and adaptive capacities
- Leadership for sustainability that effectively responds to complex challenges

Resources

- Access to scientific and technological expertise and options for problem-solving, including effective mechanisms for providing climate information, services and standards
- Access to financing for appropriate climate change response strategies and actions
- Information linkages in order to learn from experiences of others with mitigation and adaptation

Practices

- Continuing development and evaluation of institutionalized vulnerability assessments and risk management strategy development, and refinement based on emerging information and experience
- Monitoring of emerging climate change impacts and contingency planning for responding to them, including possible needs for transformational responses
- Policy, regulatory, and legal frameworks that encourage and support distributed voluntary actions for climate change risk management
- Effective programs to assist the most vulnerable populations and systems in coping with impacts of climate change

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Climate resilient pathways are in fact a process, not an outcome (Manyena, 2006), involving both incremental and transformational changes. The pathways therefore need to be built on a foundation of constantly advancing knowledge, where information is adjusted based on changing scientific knowledge climate parameters and altering social, economic and natural resource situations (Berkes, 2007). While some measures will be reactive, the main elements of a pathway are intentional and proactive: anticipating future change and developing appropriate plans and responses. Although payoffs from specific long-term pathways may be unknown, strategies and actions can be pursued now that will contribute significantly to moving toward climate-resilient pathways while helping to improve human livelihoods, social and economic well-being, and responsible environmental management (Section 20.6.2).

20.3. Contributions to Resilience through Climate Change Responses

Climate change responses include mitigation, adaptation, and integrated mitigation and adaptation strategies. Related to these responses but generally considered a separate response issue is “geoengineering” (Box 20-4, after Section 20.3.2).

20.3.1. Mitigation

In IPCC’s assessment reports, mitigation is the subject of Working Group III, to which the reader is referred for comprehensive information about options and strategies for reducing GHG emissions and increasing GHG uptakes by the earth system. For this chapter, the issue is how climate change mitigation relates to sustainable development, which was addressed by Chapter 12 of Working Group III’s Fourth Assessment Report (IPCC 2007a) and is also the focus of Chapter 4 of its Fifth Assessment Report, including attention to equity issues.

In general terms, mitigation is recognized to be important for sustainable development in two ways (Riahi, 2000). First, it reduces the rate and magnitude of climate change, which reduces climate-related stresses on sustainable development, including effects of climate extremes and extreme events (IPCC SREX, 2012; Section 20.2; Box 20-1; Washington et al., 2009; Lenton, 2011b). Perspectives among countries and other parties about mitigation targets differ as to whether they should be framed in terms of an aspirational ceiling on average global warming, such as 2 degrees or 1.5 degrees C, or in terms of an aspirational ceiling on the greenhouse gas concentration level in the atmosphere, such as 450 parts per million; and they differ in how to make progress toward stabilization. But recent observations of the rate of increase in global greenhouse emissions (e.g., Peters et al., 2013) suggest that the challenge of stabilizing greenhouse gas emission and/or concentrations is growing (for further information about international accords, national pledges and inventory reports, and continuing negotiations, along with summaries of current and projected progress with mitigation, see the Working Group III Fifth Assessment Report).

Second, trajectories for technological and institutional change in order to reduce net GHG emissions interact with development pathways. In some cases, national pledges to achieve mitigation targets (e.g., Figure 20-1) may be congruent with sustainable development in urban settings, such as green growth strategies that reduce local and regional air pollution, enhancing prospects for multi-level governance and integrated management of resources, and encouraging broader participation in development processes (Seto et al., 2010; Lebel, 2005). In other cases, such effects as higher energy prices associated with transitions from fossil fuels to renewable energy sources have the potential to have adverse effects on local and regional economic and social development (IPCC SRREN, 2012: Chapter 9).

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Box 20-4. Considering Geoengineering Responses

If climate change mitigation leads to socially unacceptable pain and distress, policymakers may be faced with demands to find further ways to reduce climate change and its effects.

Such options include intentional large-scale interventions in the earth system either to reduce the sun’s radiation that reaches the surface of the earth or to increase the uptake of carbon dioxide from the atmosphere. An example of the former is to inject sulfates into the stratosphere. Examples of the latter include facilities to scrub carbon dioxide from the air and chemical interventions to increase uptakes by oceans, soil, or biomass (UK Royal Society, 2009; Chapter 19; IPCC Working Group III: Chapter 6; and Working Group I, Chapters 6 and 7).

Discussions of geoengineering have only recently become an active area of discourse in science, despite a longer history of efforts to modify climate (Schneider, 1996, 2009; Keith, 2000; Crutzen, 2006). Many of the possible options are known to be technically feasible, but their costs, effectiveness, and side-effects are exceedingly poorly understood (NRC, 2010b; MacCracken, 2011; Vaughan and Lenten, 2011; Goes et al., 2011). For example, some interventions in the atmosphere might not be unacceptably expensive in terms of direct costs, but they might affect the behavior of such earth system processes as the Asian monsoons (Robock et al., 2008; Brovkin et al., 2009). Some interventions to increase carbon uptakes, such as scrubbing carbon dioxide from the earth’s atmosphere, might be socially acceptable but economically very expensive. Moreover, it is possible that optimism about geoengineering options might invite complacency regarding mitigation efforts.

In any case, implications for sustainable development are largely unknown. Even though some views have been expressed that geoengineering is needed now in order to avoid irreversible impact such as the loss of ocean corals (while many governments have not begun to consider it at all), several countries consider it a research priority rather than a current decision-making option (NRC, 2010b). The challenge is to understand what geoengineering options would do to moderate global climate change and also to understand what their ancillary effects might be. This would allow policymakers in the future to respond if severe disruptions appear and, as a result, there is a need to consider rather dramatic technology alternatives. Some observers propose that research efforts should include limited experiments with geoengineering options, but agreement has not been reached about criteria for determining what experiments are appropriate or ethical (e.g., Blackstock and Long, 2010; Gardiner, 2010).

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The challenge for climate-resilient pathways is to identify and implement mixes of technological and governance options that reduce net carbon emissions and at the same time support sustainable economic and social growth in a context where rising demands for economic and social development need to be combined with technology transitions without disrupting the development process. For example, strategies such as increasing carbon uptakes and decreasing carbon losses in the soil through better agricultural management practices – which can reduce net emissions – can improve soil water storage capacity. Practices such as conservation tillage can also increase water retention in drought conditions and help to sequester carbon in soils **(**Halsnaes et al., 2008**).** In many cases, however, this challenge remains very difficult to meet.

[INSERT FIGURE 20-1 HERE
Figure 20-1: Pledges by Annex 1 and Annex 2 countries in response to the Copenhagen Accord. Sources: http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php, http://unfccc.int/meetings/cop_15/copenhagen_accord/items5265.php.]

Mitigation and development also interact in a third way in that different groups and countries' ability to implement mitigation critically depends on their "mitigative capacity" (Yohe, 2001): their "ability to reduce anthropogenic greenhouse gas emissions or enhance natural sinks" and the "skills, competencies, fitness, and proficiencies that a country has attained which can contribute to GHG emissions mitigation" (Winkler et al., 2007). Here, many of the determinants of mitigative capacity are fundamentally shaped by different countries' level of development, including their current level of emissions, their stock of human, financial and technological capital, such as the ability to pay for mitigation; the magnitude and cost of available abatement opportunities; the regulatory effectiveness and market rules; the education and skills base; the suite of mitigation technologies available; the ability to absorb new technologies; and the level of infrastructure development (see Box 20-4).

20.3.2. Adaptation

Adaptation is the subject of four chapters of this Working Group II Fifth Assessment Report (14-17), to which the reader is referred for comprehensive descriptions of concepts, options, strategies, and examples of adaptation practices. For this section, we focus on the intersection between adaptation and sustainable development. Overall, climate adaptation and sustainable development are linked in several ways: first, many of the determinants of adaptive capacity to respond to climate impact and indicators of sustainable development overlap; second, adaptive capacity building may critically contribute to the well-being of both social and ecological systems; and third, building adaptive capacity within a sustainable development framework may require transformational changes (Dovers and Hezri, 2010; Lemos et al., 2013; Kates et al., 2012).

Around the globe, the ability of communities and individuals to respond to climate change in predicated on a number of capacities (e.g. human capital, information and technology, material resources and infrastructure, organizational and social capital, political capital, wealth and financial capital, institutions and entitlements) that typically overlap with indicators of development (Smit and Pilifozofa, 2001; Yohe and Tol, 2002; Eakin and Lemos, 2006). However, building these capacities both in developed and less developed regions has implications for sustainable development because it might increase the consumption of materials and create potential negative effects on ecosystems (e.g. building of new infrastructure and increasing consumption). In terms of governance, climate change adaptation and sustainable development share many characteristics (e.g. issues of spatial and temporal scales, uncertainty, poorly defined jurisdictions (Dovers and Hezri, 2010), and designing and implementing successful interventions require different kinds of capacities, including political and administrative structures (Wilbanks et al., 2007; Eakin and Lemos, 2006).

Building adaptive capacity may critically contribute to the improvement of the well-being of both social and ecological systems by bettering livelihoods and reducing pressure on the environment, especially in less developed regions (see Section 20.40.3). Regarding social systems, it is important to consider not only the factors that enable the building of different capacities (e.g. institutions and governance) but also how to guarantee that those who need it the most have access to them (Gupta et al., 2010; Nelson et al., 2007). It is also vital to understand how different capacities influence each other, positively and negatively (Lemos et al., 2013) and how they may affect the long-term resilience of social-ecological systems (Adger et al., 2011; Box 20-5). Indeed, adaptation can be important in reducing stresses on development processes, especially in vulnerable areas where it can help to promote and support sustainable development. For example, where adaptation planning stimulates participatory social processes, including equity and legitimacy, as well as discussions regarding different adaptation options, it can encourage communities to think more clearly about broader sustainable development goals and pathways (NRC, 2010a).

Given recent trends in GHG emissions and projections of climate futures that suggest impacts of climate change will be serious and widespread (e.g., Auerswald et al., 2011; Smith et al., 2011), adaptation may require considering transformational changes, in which potentially impacted systems move to fundamentally new patterns, dynamics, and/or locations (Schipper, 2007; Kates et al., 2012; Park et al., 2012; Marshall et al., 2012). Desirable adaptation strategies may vary according to specific kinds climate change threat, location, impacted system, the geographical scale of attention, and the time frame of strategic risk management planning (Heltberg et al., 2009; Thomalla et al., 2006; NRC, 2010a). Transformational adaptation policy at different scales needs to take into consideration the goals of sustainable development, both by fostering positive synergies and by avoiding negative feedbacks between them. This is especially important because some adaptation options might lead to inequitable and unsustainable outcomes, and some adaptations at one scale may negatively affect vulnerability in another (Thomas and Twyman, 2005; Eriksen et al., 2011; Eriksen and Brown, 2011; see also Sections 20.3.3 and 20.4.4 and Chapter 14 for a more detailed discussion). For example, in the U.S. building adaptive capacity for water management through drought preparedness plans at one scale (the state level) may constrain the flexibility of managers at lower scales (community water systems) to successfully respond to drought (Engle, 2013).

Indeed, adaptation pathways can foster food and water security, human health, and air and water quality and natural resource management, while promoting gender equality and other desirable outcomes consistent with sustainable development goals. However, creating the conditions for the emergence of such outcomes will require better integration in the implementation of policies and programs at all scales. By selecting materials not harmful to the environment, promoting the conservation of energy, water and other resources, promoting re-use and recycling, minimizing waste generation, protecting habitat and addressing needs of marginalized groups, adaptation can contribute to win-win and triple win options that can support a diverse array of development goals (Bizikova et al., 2007; Seto et al., 2010; see also Section 20.3.3, Chapter 15 Section 15.3.1, and UNFCCC, 2011).

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Box 20-5. Case Studies from China

Water-saving irrigation has enhanced climate change adaptation capacity, improved ecosystem services, and promoted regional sustainable development in China.

- **Water-Saving Irrigation Measures in Cropland Adaptation to Climate Change**. Water-saving irrigation is one effective measure to deal with the water scarcity and food security issues caused by climate change (Hanjra and Qureshi, 2010; Tejero et al., 2011). Given an increase in non-agricultural water consumption, China's agriculture could be faced with a severe shortage of water resources (Xiong et al., 2010). Through water-saving irrigation practices, water saved from 2007-2009 added up to 30.7-34.92 $10^9 m^3$ for each year, which accounted for 5.6%-11.8% of the national total water consumption and saved about 9.59-20.85 Mt of standard coal and reduced 21.83-47.48 Mt CO_2 emissions. Therefore, water saving irrigation has had a positive effect in dealing with climate change and sustainable development (Zhou et al., 2012).

	2007	***2008***	***2009***
Water saved (Btu^2)	19.37 - 40.86	19.86 - 41.55	22.58 - 57.25
Energy saved (Mt)	2.92 - 6.39	3.08 - 6.72	3.57 - 7.73
CO_2 emission reduction (Mt)	6.66 - 14.58	7.02 - 15.31	8.15 - 17.59

- **Water-Saving Irrigation Measures in Alpine Grassland for Adapting to Climate Change** In recent years, the rise in precipitation and temperature results has led to the melting of glaciers and expansion to inland high mountain lakes, contributing to alpine grassland degradation in Northern Tibet (Gao et al., 2010). Among many grassland protection measures, alpine grassland water saving irrigation measures could be effective in redistributing and making full use of increased precipitation and lake water in the dry period, which would reduce the negative effects of climate change and make full use of favourable conditions (Editorial Board of National Climate Change Assessment, 2011; Gao et al., 2012). A three-year demonstration of alpine grassland water saving irrigation measures showed that alpine grassland primary productivity nearly doubled while the number of plant species increased from 91 to 129, helping to protect and restore the alpine grassland ecosystem and ecosystem services and to promote regional socioeconomic sustainable development in Northern Tibet (Gao et al., 2012).

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20.3.3. Integrating Climate Change Adaptation and Mitigation for Sustainable Risk Management

Because both adaptation and mitigation are parts of climate-resilient pathways, and because each benefits from progress with the other (e.g, 20.2), integrating the two kinds of climate change responses within the broader context of sustainable development has been suggested as an aspirational goal (Wilbanks et al., 2007; Bizikova et al., 2010), especially when policy attention and financial commitments to climate change responses must consider the pursuit of both adaptation and mitigation. In practice, however, mitigation and adaptation tend to involve different time frames, communities of interest, and decision-making responsibilities (IPCC, 2007a; Wilbanks et al., 2007).

Integration of climate change responses with development processes is a further aspirational goal. Recent research suggests that mitigation and adaptation are likely to be more effective when they are designed and implemented in the context of other interventions within the broader context of sustainability and resilience (Wilbanks and Kates, 2010; Asian Development Bank, 2012). Moreover, studies focusing on the intersection between sustainable development and climate policy point out that integration between the two is a desirable although complex path (20.2.1.2; Halsnaes et al., 2008; Wilson and McDaniels, 2007; Ayers and Huq, 2009; Robinson et al., 2006; Swart and Raes, 2007; Beg et al., 2002). Wilson and McDaniels suggest three reasons to integrate across adaptation, mitigation and sustainable development: (1) many dimensions of the *values* that are important for decision-making are common to all three decision contexts; (2) impacts from any one of the three decision contexts may have important *consequences* for the other contexts; and (3) the *choice among alternatives* in one context can be a means for achieving the underlying values important in the other contexts.

A key factor in integrating climate change adaptation and mitigation into sustainable risk management is to understand the processes of decision-making at different scales. The distribution of costs and benefits of mitigation and adaptation differ -- e.g., mitigation benefits are more global, adaptation benefits are often more localized, the research and policy discourses are often unrelated, and the constituencies and decisionmakers are often different (mitigation may involve powerful industrial stakeholders from the energy sector concentrated at higher levels of decision-making, while adaptation may involve more dispersed stakeholders at the local level across sectors) (Wilbanks et al., 2007). To significantly reduce total global emissions, mitigation decisions must be taken either by major emitters, or by groups of countries. At the national and international level, direct responsibilities to curb the main drivers of global climate change are dispersed across countries (Banerjee, 2012). In contrast, adaptation often falls to practitioners where local responsibility is clearer, although it often depends on support from national and global scale (Tanner and Allouche, 2011).

In many cases, the challenge of fostering synergies while avoiding negative feedbacks often comes into focus in place-based discussions of climate change responses and development objectives such as localities and small regions (Wilbanks, 2003; Bulkeley and Schroeder, 2012; Dang et al., 2003). Globally, a particular hurdle is the practice of applying available mitigation resources only for reducing emissions beyond that which would have occurred without those resources ("*additionality*"), when access to resources for adaptation efforts should take into account the critical role of *co-benefits* in supporting development in other ways while at the same time reducing vulnerabilities to climate change impacts (NRC, 2010a; also see Section 20.4.1).

Choices in integrating adaptation and mitigation will vary according to the circumstances of each country and each locality (De Boer et al., 2010; Wilbanks, 2003). In highly vulnerable countries, adaptation may be seen as the highest priority because there are immediate benefits to be obtained by reducing vulnerabilities to current climate variability and extremes as well as future climate changes. In the case of developed countries, adaptation initiatives have often been seen as a lower priority because it is perceived that there is abundant adaptive capacity (Naess et al., 2005). Yet major losses and damages in some industrialized countries related to climatic variability and extremes challenge this perception (e.g., Hurricane Sandy, tornadoes, and drought in the US in 2011 and 2012). Mitigation may be seen as more acute political question—involving well-organized stakeholders concerned about costs—in countries that contribute a large proportion of GHG emissions (e.g., NRC, 2011), and it may be seen as an investment opportunity for the domestic private sector.

As indicated above, one emerging strategy to integrate climate and development policies is the design of "win-win" and "triple-win" interventions that seek to achieve an appropriate mix of mitigation and adaptation within the context of sustainable development (Pyke et al., 2007; Swart and Raes, 2007). Swart and Raes suggest a number of factors that should be taken into consideration when evaluating combined adaptation and mitigation policy designs, including: (1) *avoiding trade-offs* - when designing policies for mitigation or adaptation, (2) *identifying synergies,* (3) *enhancing response capacity,* (4) *developing institutional links* between adaptation and mitigation - e.g. in national institutions and in international negotiations, and (5) *mainstreaming* adaptation and mitigation considerations into broader sustainable development policies. Box 20-5 provides a case study of an initiative in China that has been a winner for both climate change responses and regional sustainable development The potential for climate-resilient pathways may already be limited, however, in part because of path dependency stemming from choices on mitigation, adaptation, and political interpretations and subsequent choices around "sustainable" development (Barker, 2008; Swart et al., 2003); and in many cases interventions have not delivered win-win results, which raises questions about the actual attainability of win-win strategies given legal, political, economic, and/or institutional obstacles **(**Warner, van der Geest, et al., 2012; 20.2.1.2).

In synthesizing evidence from a series of empirical articles focusing on the intersection between mitigation and adaptation (M&A), Wilbanks and Sathaye (2007) argue that mitigation and adaptation pathways might be alternatives in reducing costs, complementary and reinforcing to each other (e.g., improvements in building energy efficiency), or competitive and mutually contradictory (e.g., coastal protection vs. reductions in sea level rise). In Bangladesh, for example, waste-to-compost projects contribute to mitigation through reducing methane emissions; to adaptation through soil improvement in drought-prone areas; and to sustainable development through the preservation of ecosystem services (Ayers and Huq, 2009; also see Vergara et al., 2012, regarding possible development benefits of mitigation and adaptation in Latin America and the Caribbean). Land management and forestry activities contribute to ecosystem-based mitigation, for example through the reduction of emissions from deforestation and forest degradation, and adaptation, for example through the conservation of hydrological services provided to people facing water problems, as well as renewable energy (see several cases of ecosystem-based adaptation in Pramova et al., 2012). However, tradeoffs are also possible, for example if ecosystem management for mitigation purposes reduces the livelihood opportunities and the adaptive capacity of local people (Locatelli et al., 2011). The scale of these examples is often local, however, and longer-term success of these pathways will depend on the broader context of mitigation and facilitation of adaptation options (Metz et al., 2002).

When integrating across the goal of finding climate resilient pathways (and win-win solutions), decisionmakers often need to address issues of scale, along with trade-offs in values such as economic profitability versus stability of food and livelihood security (e.g. in agricultural policy), relationships between development ends and means, uncertainty and path dependencies, and institutional complexity (Klein et al., 2005; Tol, 2004; Wilson and McDaniels, 2007). They also need to consider the possibility of ancillary co-benefits, complementarities and potential contradictions, opportunity costs, and unknown negative and positive feedbacks (for example interactions among options and paybacks (NRC, 2010a; Kok et al., 2008; Wilbanks and Sathaye, 2007; Swart and Raes, 2007; Rosenzweig and Tubiello, 2007; IPCC, 2007a: Chapter 18). Current research is examining tradeoffs and complementarities between mitigation and adaptation in different sectors. In the energy sector, for instance, Kopytko and Perkins (2011) have examined to what extent the siting of nuclear power plants might constrain future adaptation to sea-level rise. Others ask about such issues as adaptation implications of the production of biofuels (La Rovere et al., 2009); agriculture and water (Rounsevell et al., 2010; Turner et al., 2010; Rosenzweig and Tubiello, 2007; Falloon and Betts, 2010; Shah, 2009); conservation (Rounsevell et al., 2010; Turner et al., 2010); use of mitigation programs to finance adaptation (Hof et al., 2009); and the urban environment (Biesbroek et al., 2009; Hamin and Gurran, 2009; Roy, 2009; Romero-Lankao and Wilbanks, 2011; and Viguié and Hallegatte, 2012).

20.4. Contributions to Resilience through Sustainable Development Strategies and Choices

Although climate change responses can contribute significantly to climate-resilient development pathways, some of the key elements of resilience lie in sustainable development implementation, which can make resilience either more or less achievable. Examples of ways that development strategies and choices can contribute to climate resilience include being capable of resolving tradeoffs among economic and environmental goals (e.g., Bamuri and

Opeschoor, 2007), assuring effective institutions in developing, implementing, and sustaining resilient strategies, and enhancing the range of choices through innovation (e.g., Hallegatte, 2009; Chuku, 2009; Folke et al., 2002).

20.4.1. Resolving Tradeoffs between Economic and Environmental Goals

Sustainable development pathways will be more climate-resilient if they develop and utilize socioeconomic and institutional structures that are effective in resolving tradeoffs among social, economic, and environmental goals – a central tenet of sustainable development (Section 20.2.1.1). As climate change poses risks to goals such as poverty reduction, food and livelihood security, human health, and economic prosperity (Chapter 19), societies face the task of defining how to manage these risks and what levels of risk without compromising what they value most and what defines their societies. The management of risk – and the weighting of various categories of risk – depends on social definitions of what consequences are acceptable, tolerable, or intolerable (Chapter 16).

There is a longstanding assumption that economic growth is in conflict with environmental management (Victor and Rosenbluth, 2007; Hueting, 2010). Much of this thinking can be traced back to Malthus and his assertions that population growth (and associated consumption) would expand at an increasing rate until the limits of the earth's capacity were reached (Malthus, 1798). The very idea of sustainable development itself springs from a need to respond to such Malthusian ideas. The views expounded in the Brundtland Report, for example, are that development should not be unconstrained but should rather be modified into a "sustainable" form (WCED, 1987). Views about relationships between economic growth and environmental protection range widely from arguments that sustainable development is inconsistent with continued economic growth (e.g., Robinson, 2004) to arguments that economic growth and associated technological innovation can enhance options for environmental management (Lovins and Cohen, 2011). Relationships between affluence and environmental protection are complex, as poverty can lead to land degradation and affluence can afford support for nature preservation, while economic growth is built on levels of resource extraction and use that require significant changes in environments. Sustainable development cannot escape continuing tensions between economic growth and environmental management goals, where strongly held views across society often differ so fundamentally that conflict results unless social processes and institutional mechanisms are effective in resolving a host of tradeoffs (Boyd et al., 2008), with both values and processes varying according to development context.

Examples of frameworks of thought often related to addressing tradeoffs are multi-metric valuation and co-benefits (see also Ness et al., 2007, regarding tools for sustainability assessment; Pew Center, 2010; Bizikova et al., 2008: Appendix 1):

- *Multi-metric valuation*. In evaluating development pathways, there are often needs to combine a number of dimensions associated with different valuation metrics and information requirements, such as monetary measures of returns and non-monetary metrics of risk. Fields ranging from aquatic ecology to risk assessment and financial management have developed tools for such complex valuations, including graphical mapping (e.g., UNFCCC, 2011; Moed and Plume, 2011; Rose, 2010; Sheppard and Meitner, 2005) and the construction of multi-metric indexes (e.g., Johnston et al., 2011). Multi-metric indicators have been widely studied and critiqued, and they are an active topic of research (e.g., Drouineau et al., 2012; Schoolmaster, 2013). A key challenge is weighting different valuations being combined quantitatively, which may be addressed in part by constructing multiple indices. More commonly in collective decision-making, however, analytical-deliberative group processes are used to evaluate, weight, and combine different dimensions and metrics qualitatively (NRC, 1996).
- *Co-benefits*. An issue in both climate and development policy, related in some cases to access to financial support (e.g., Miller, 2008), is the fact that a specific resilience-enhancing action may have benefits for both development and for addressing concerns about climate change. International funding for mitigation projects has often adopted the concept of "additionality," which takes the position that financial support should be limited to those climate change response benefits that are *in addition to* what would be happening in development processes otherwise (e.g., Muller, 2009). This general concept (e.g., "incremental" costs and benefits) has been applied in financial support for adaptation as well. A co-benefits approach, on the other hand, takes the position that actions which benefit *both* development and climate change responses simultaneously should be encouraged and that a combination of both kinds of benefits should increase the

attractiveness of a proposed action (Section 20.3.3). Co-benefits of mitigation actions, such as health benefits, have been extensively analyzed (e.g., WHO, 2011; Netherlands Environmental Assessment Agency, 2009; EPA, 2012; and Younger et al., 2008); and they are being actively explored for adaptation as well (e.g., UNFCCC, 2011; NRC, 2010a).

As an example of co-benefits, such mechanisms as REDD+ have the potential to achieve both carbon emissions reduction and to benefit livelihoods of those living in forested areas, as well as supporting benefits to social equity (Anglesen et al., 2009; UNEP, 2013). As one instance, the government of Ethiopia has recognized the multiple benefits that can be derived from REDD+ and has incorporated a REDD+ initiative in critical sectors of the economy in order to develop an environmentally sustainable growth path in Ethiopia (FDRE, 2011).
Tools for analyzing such issues are associated with research on "externalities" (e.g., Baumol and Oates, 1989; Klenow and Rodriguez-Clare, 2005; also see Chapter 17 and multi-metric valuations above), but participative planning and decision-making usually incorporate a co-benefits perspective as a matter of course.

In practice, tradeoffs between different development goals (Stoorvogel et al., 2004) may or not be resolved in coherent ways (Metz et al., 2002). In many cases, resolutions emerge through untidy social processes of evolution and attrition, reflecting dynamics of values, power, control, and surprises, rather than through formal analysis (Bizikova et al., 2008). In some cases, tradeoffs are addressed with the assistance of scenario development, the creation of descriptive narratives, and other projections of future contingencies (IPCC SREX: Chapter 8), along with participative vulnerability assessments (NRC, 2010a).

20.4.2. Assuring Effective Institutions in Developing, Implementing, and Sustaining Resilient Strategies

Climate resilient pathways will benefit from institutions that are effective and flexible in the face of a wider range of challenges, of which climate change is only one (Gupta et al., 2010). Governance systems, including public and private organizations, will need resources (e.g. human, financial, political, technological) to enable vulnerable societies that are sensitive to the impacts of climate change to transform their lives. Effective management of natural capital and ecosystem goods and services can only be accomplished where there are strong institutions as stewards and a regulatory force to ensure that vulnerable communities are protected from climate shocks and stresses and that growth from climate change is inclusive (Mitchell and Tanner, 2006). Moderating the impacts of climate change will also require strong a foundation in science and technology; but the deployment of science and relevant technologies cannot take place in a vacuum. It will need effective institutional arrangements to bolster both adaptation and mitigation demands and to combine technology options with local knowledge (20.4.3).

"Institutions" refer not only to formal structures and processes but also to the rules of the game and the norms and cultures that underpin environmental values and belief systems. Ostrom (1986) defines institutions as the rules, norms and practices defining social behavior in a particular context, the action arena. Institutions define roles and provide social context for action and structure social interactions (Hodgson, 2003). Definitions of sustainability are largely shaped by institutional values, cultures and norms. Institutions also critically influence our ability to govern and manage the resources and systems that shape adaptation, mitigation and sustainable development. Fostering climate-resilient pathways requires strong institutions that are able to create an enabling environment through which adaptive and mitigative capacities can be built (Gupta et al., 2010; IPCC, 2007a: Chapter 20). Implicit in institutional resilience is the capacity of the exposed unit and the players within an action arena to devise rules that allows them to recover from environmental shocks, and equally ones that provides incentives and benefits that equitably distributes resources across social groups (McSweeny and Coomes, 2011; Handmer and Dovers, 1996). Hence, the trajectory to a climate resilient pathway requires institutional arrangements that foster innovation, monitoring, and evaluation of strategies for managing climate impacts and reducing risks.

Transformative action within a framework of climate resilient pathways is rooted in strong and viable institutions and in an institutional context that adaptively manages the allocation of resources and processes of change. Institutions at different levels are the object of societal pressures and challenges relating to environmental change. Local institutions are particularly adroit in coping with multiple changes. These changes often force local actors and organizations to rethink their institutional arrangements and make adjustments that will allow them to cope with multiple vulnerabilities (McSweeny and Coomes, 2011), and their bottom-up initiatives are critically important to climate-resilient pathways. Organizational mechanisms are central to building linkages between local level adaptation action and national level planning; however, in six cases studies in West Africa and Latin America, Agrawal et al. (2011) found that while these connections are missing in almost all the countries studied, external policy support can catalyze adaptation action through three types of intervention mechanisms: information, incentives, and institutions.

Local institutions crucially influence the ability of communities to adapt and benefit from adaptation and mitigation programs in rural and urban settings (Agrawal, 2008; Chhartre and Agrawal, 2009; Corbera and Brown, 2008). For instance, institutions tend to play an influential role in shaping farmers' decisions and helping them make strategic choices with several implications for livelihoods and sustainable development (Agrawal, 2008). In rural areas, current socioeconomic dynamics, rapid population growth, commercialized agriculture, new agricultural trends and technological advancements in agriculture have meant that local organizations and actors have seen a change in their role managing environmental resources; local institutions are themselves in a state of flux as they are subjected to uncertainties in climatic condition (Senaratne and Wickramasinghe, 2010*)*. However, in developing countries, particularly in Africa, where traditional knowledge could moderate this uncertainty, it is often not recognized as a reference point for managing climate risks and emerging threats. In Kenya, the importance of indigenous knowledge, given increased uncertainty and climate related risks, has compelled national agencies such as the Kenyan Meteorological Agencies and vulnerable groups such as the indigenous communities commonly known as rainmakers to form strategic reciprocal links. By working closely together to calibrate their forecasts and test the efficacy of the results against climate change impacts on agricultural productivity, the two groups have been able to demonstrate the benefits of western science and traditional knowledge systems to increase effectiveness (Ziervogel and Opere, 2010). In integrating different kinds of knowledge, participatory processes, which call for a deliberative form of decision making among stakeholders are well suited to the governance culture necessary for effective adaptation and mitigation. However, findings in the literature regarding the effectiveness of participatory processes are mixed. For example while some scholars have argued that deliberative democracy methods can bring diverse stakeholders and kinds of knowledge (e.g., lay, expert and indigenous) together thus putting in place a more communicative model of science delivery (Benn et al., 2009), empirical research shows that stakeholder participation does not always lead to consensus (Rowe and Frewer, 2004; Bell et al., 2011; also see Salter et al., 2010).

In addition, better institutions are needed to handle the large flows of funds and other resources that are associated with managing and improving the delivery systems that will allow people and organizations to take advantage of opportunities that will trigger a set of actions to combat the negative impacts of climate change. The complexity of different resource flows and distributional effects related to adaptation and mitigation is at the heart of the sustainable development debate, with numerous implications for equity and justice (O'Brien and Leichenko, 2003; Roberts and Parks, 2006). The nature and dynamics of climate change call for flexibility to 'allow society to modify its institutions at a rate commensurate with the rapid rate of environmental change' (Gupta et al., 2008). Here, institutional 'renewal' is essential to achieve a degree of social cohesion and transformation.

An institutional response to climate change is even more fundamental in common pool property resources such as freshwater, especially because in a changing climate, many river basins are subjected to increased precipitation or water scarcity that affects both their ecosystems and the resources that support the livelihoods of those communities dependent on them. The quality and performance of the organizations and mechanisms created to manage these resources are largely shaped by the rules they follow and the suitability of these rules to the social ecological system in which they are embedded (Bisaro et al., 2010). Indeed, a climate-resilient pathway is one that will not only manage biophysical changes, but address inherent institutional asymmetries that can further reinforce current inequalities in the way common pool resources are managed. In this context, the monitoring and mediation capacities and the degree to which resource management organizations are embedded at different scales across the governance regime will largely shape its adaptive capacity and sustainability. Thus, the vulnerability of large river basins will largely depend not only on the changing biophysical conditions, but also on institutional architecture that is put in place to manage risks and build resilience. For example, Schlager and Heikkila, 2011, argue that compacts that have fixed allocation rules tend to exhibit greater vulnerability to climate change mainly because the system is far too rigid and does not allow for much flexibility in dealing with the changing hydrologic regime. States such as

Colorado in the United States have dealt with water scarcity more efficiently mainly because users of the basin have access to venues that allow them to design and review current rules (Schlager and Heikkila, 2011).

Common problems with institutional arrangements for adaptively managing natural resources include a frequent incompatibility of current governance structures with many of those that may be necessary for promoting social and ecological resilience'. For example, some major tenets of traditional management styles have 'in many cases operated through exclusion of users and the top-down application of scientific knowledge in rigid programmes' (Tompkins and Adger, 2004: 10).

20.4.3. Enhancing the Range of Choices through Innovation

Finally, climate resilience will in most cases depend on innovation, developing new ideas and options or adapting robust familiar ideas and options to meet emerging new needs and to respond to surprises (also see IPCC Working Group III: Chapter 6). As indicated in the previous section, integrated strategies for climate resilience can benefit from considering possibilities to develop new options through social, institutional, and technological innovation. For example, if a climate-resilient pathway for a particular region calls for coping with greater water scarcity, innovations might consider changes in water rights practices, improving the understanding of groundwater dynamics and recharge, improving technologies and policies for water-use efficiency improvements, and in coastal areas the development of more affordable technologies for desalination (NRC, 2010a; Lebel, 2005). One key issue for risk management, therefore, is assessing needs for and possible benefits from targeting innovation efforts on critical vulnerabilities.

Innovations can include both technological and social changes, which in many cases are closely related (Rohracher, 2008; Raven et al., 2010), as technology and society evolve together (Kemp, 1994). An important characteristic of such socio-technical transitions are the interactions and conflicts between new, emerging systems and established regimes, with strong actors defending business as usual (IPCC SREX, 2012; Kemp, 1994; Perez, 2002).

Effective use of innovations depends on more than idea and/or technology development alone. Unless the innovations, the skills required to use them, and the institutional approaches appropriate to deploy them are effectively transferred from providers to users, effects of innovations – however promising – are minimized (IPCC SREX, 2012). Challenges in putting science and technology to use for sustainable development have received considerable attention (e.g., Nelson and Winter, 1982; Patel and Pavit, 1995; NRC, 1999; International Council for Science, 2002; and Kristjanson et al., 2009). These studies emphasize the wide range of contexts that shape both barriers and potentials and the importance of "co-production" of knowledge, integrating general scientific knowledge with other forms of knowledge (e.g., local, indigenous, practical knowledge, experience, and expertise). If obstacles related to intellectual property rights can be overcome, however, the growing power of the information technology revolution could accelerate the transfer of technologies and other innovations (linked with local knowledge) in ways that would be very promising for strengthening local resilience (Wilbanks and Wilbanks, 2010).

New technologies have the potential to allow a number of developing countries to benefit from a knowledge in ways that will given them considerable advantage in building the relevant social and institutional infrastructure in order to sustain a climate-resilient pathway. Advances in mobile technologies in developing countries, for example, have increased the accessibility of farmers to critical information related to disease surveillance, information related to agricultural inputs, and market prices for crops (Juma, 2011; Hazell et al., 2010). Biotechnology applications in biological system have the potential to lead to increased food security and sustainable forestry practices, as well as improving health in developing countries by enhancing food nutrition.

20.5. Determinants of Resilience in the Face of Serious Threats

Climate change is not the only type of change occurring in the 21st century. Many households, communities, organizations, countries and regions are confronting a confluence of economic, political, demographic, social, cultural and environmental changes. Issues such as poverty, economic crisis, increasing inequality, and violent conflict often draw attention away from concerns about climate change, the loss of biodiversity and ecosystem services, and other global environmental issues. However, the impacts of climate change and extreme events can exacerbate food insecurity, slow down the pace of poverty reduction in urban areas, influence human health, and jeopardize sustainable development (chapters 11, 12 and 13). Resilience is a concept that takes into account how systems, communities, sectors, or households deal with disturbance, uncertainty and surprise over time, and it is characterized by both adaptability and transformability (Walker and Salt, 2006; Folke et al., 2010; Westley et al., 2011). The sections below consider two important components of climate resilient pathways: transformational adaptation in response to the impacts of climate change, and transformational change to reduce vulnerability and the risk of high magnitude climate change.

20.5.1. Relationships between the Magnitude and Rate of Climate Change and Requirements for Transformational Adaptation

The timing and ambition levels of global greenhouse gas mitigation efforts will influence the magnitude and rate of climate change and its impacts, particularly in the second half of the 21st century and beyond (Kriegler et al., 2012; Rogelj et al., 2013; Peters et al., 2013; Box 20-3). Model results based on integrated scenarios that take into account geophysical, technological, social and political uncertainties indicate that reaching the often-discussed limit of a 2°C average global temperature increase call for mitigation of emissions through increased energy efficiency and lower energy demand well before 2020 (Rogelj et al., 2013; Peters et al., 2013; Section 20.6.1).

If the magnitude and rate of climate change is kept minimal or moderate, incremental adaptation may be a sufficient response to consequences in many locations and contexts. However, in cases where vulnerability is currently high, transformational adaptation may be needed to respond to changes in climate and climate variability. In the absence of ambitious mitigation efforts, the impacts of climate change can be expected to increase dramatically from the second half of the 21st century onward (see Chapter 19). In this case, transformational adaptation may be required in advance of disruptive impacts to reduce risks and vulnerabilities (Kates et al., 2012).

This distinction between incremental and transformational adaptation is significant: incremental adaptation can be considered extensions of actions and behaviors that already are in place to reduce losses or enhance benefits associated with climate change, often where the goal is to maintain the essence and integrity of an existing system or process at a given scale (Kates et al., 2012; Park et al., 2012). Transformational adaptation, in contrast, includes actions that change the fundamental attributes of a system in response to actual or expected impacts of climate change. These may involve adaptations at a larger scale or greater intensity than previously experienced; adaptations that are new to a region or system; or adaptations that transform places or lead to a shift in the location of activities (Kates et al., 2012). Such transformations are expected to occur when the rate and magnitude of climate change threatens to overwhelm the resilience of existing systems, or when vulnerability is high (Kates et al., 2012). Transformational adaptation often occurs in continuous interaction with incremental adaptations (Park et al., 2012, see IPCC SREX, 2012: Figure 8-1).

Although thresholds or tipping points in complex systems are difficult to predict, studies from a variety of disciplines indicate some generic properties associated with transitions between different states, including an increase in recovery times from disturbances such as extreme weather events (Scheffer et al., 2009; Lenton, 2011a). The risks associated with a high magnitude and rate of climate change and its impacts on natural and managed resources and systems are considerable. The limits to adaptation, discussed in Chapter 16, suggest that transformational change may be a requirement for sustainable development in a changing climate (Westley et al., 2011; O'Brien, 2013).

20.5.2. Elements of and Potentials for Transformational Change

Transformational change can be considered a means of reducing risk and vulnerability, not only by adapting to the to the impacts of climate change, but also by challenging the systems and structures, economic and social relations, and beliefs and behaviors that contribute to climate change and social vulnerability. In cases where current development pathways are considered as the root causes of climate risk and vulnerability, transformation of wider political, economic and social systems may be necessary (Pelling, 2010; IPCC SREX, 2012; Lemos et al., 2013).

Transformation is defined as a change in the fundamental attributes of a system, often based on altered paradigms, goals, or values. It can occur in technological, biological or financial systems, or regulatory, legislative, or administrative regimes (see glossary). Transformations can occur quite suddenly, in response to a specific event or a momentous incident, or they may emerge gradually over time (Loorbach, 2007). Transformational change is often difficult to order or plan, and there are many social, political, and cultural barriers and resistances. Transformational change can threaten vested interests, or prioritize the interests of some over the well-being of others, and it is never a neutral process (Meadowcroft, 2009; Smith and Stirling, 2010). While not every transformation is considered ethical, equitable or sustainable, it is possible to promote deliberate transformations that reduce climate risk and vulnerability and contribute to global sustainability (Folke et al., 2010; O’Brien, 2013; Kates et al., 2012).

There is an extensive literature on transitions and transformations covering a variety of sectors and factors that influence changes in systems and behaviors (Calvin et al., 2009; Berkhout et al., 2010; Shove and Walker, 2010; Pelling 2010; Geels, 2002; IPCC Working Group III: Chapter 6). Transformations can be promoted by creating enabling conditions, which include a supportive social environment, information flows, and access to options, resources, and incentives for change (Kates et al., 2012). Transformations can also be stimulated through rules and regulations that necessitate innovations, alternative options or new behaviors. Finally, transformations may result when alternative systems and structures eventually make old ones seem outdated. Often, dramatic focal events can draw attention to the need for change and mobilize groups or networks to advocate transformational change (Hernes, 2011).

Transformation processes are linked to learning, leadership, empowerment and collaboration within and across institutions, organizations and groups (IPCC SREX, 2012: Chapter 8; Heifetz et al., 2010; Kates et al., 2012; O’Brien 2013). Other key elements associated with transformations include adaptable institutions (cultural, economic and governance), all types of capital, diversity in landscapes, seascapes and institutions, learning platforms, collective action and networks, as well as reflexivity and the capacity to take different perspectives (Loorbach 2007; Folke et al., 2010; Westley et al., 2011; Schlitz et al., 2010). Many of the elements of climate-resilient pathways discussed in Box 20-3 can, in fact, support transformation.

Transformations can take place within diverse realms or spheres (see Figure 20-2). Within each sphere, there exist both catalysts and constraints to transformation. The core of transformational change occurs in what is labelled in Figure 20-2 as the “practical sphere.” Here, measures such as technological innovations and economic incentives are used to influence sustainable behaviors and responses. The outcomes of transformations in this sphere are observable and measurable; many sustainability policies and initiatives target transformations in this sphere. However, these transformations are often constrained by larger systems and structures, including financial, political, legal, social, economic, ecological and cultural systems that define the boundaries for action. The “political sphere” is where systems and structures are transformed (intentionally or unintentionally) through politics and social movements, or through changes in social and cultural norms and power relations. Systems and structures often reflect dominant cultural beliefs and worldviews, and it is here where value conflicts may be experienced or resolved. A third sphere of transformation is the “personal sphere,” which includes individual and collective beliefs, values, and worldviews, as well as the dominant paradigms. Transformations in this sphere can influence systems, structures, behaviors and responses, and thus they represent important leverage points for sustainability. Attention to transformations in all three spheres is considered necessary in response to the observed and anticipated impacts of climate change (Beddoe et al., 2009; O’Brien and Sygna 2013).

[INSERT FIGURE 20-2 HERE
Figure 20-2: The three spheres of transformation. Transformational change may be an effective leverage point for promoting climate-resilient pathways for sustainable development. This figure depicts three interacting spheres or realms where transformational changes towards sustainability may be initiated. Transformations in the outer two spheres can have a large influence on behaviors and technical responses, contributing to non-linear transformations to sustainability. Source: O'Brien and Sygna, 2013.]

20.6. Toward Climate-Resilient Pathways

20.6.1. Alternative Climate-Resilient Pathways

Climate-resilient pathways consist of future trajectories of development that combine adaptation and mitigation in the context of sustainable development implementation. At any scale (local or regional) there are multiple paths leading to the same total amount of climate resilience: alternative stable states (Holling, 1973). At any time along a pathway, more or less resilience maybe observed at specified points within the system (or locality), while the total amount of resilience within the entire system remains unchanged (Folke, 2006). Each potential alternative pathway can be strengthened and evaluated based on certain risk management characteristics/elements, the capacity nto: a) foresee risk/vulnerability, b) decrease climate change impacts, c) respond rapidly to unpredictable, uneven and extreme events, d) include considerable amounts of proactive adaptation, and e) evolve in support of societal advancement and balanced environmental management.

Many of the choices involved in framing and supporting attempts to increase and sustain climate resilience are made largely at global and national levels, but many of the actions to sustain resilience are made at local levels. The global pathways that emerge are accumulations of these local and national choices. In these processes, path dependence is strong enough such that risk management decisions in the near term are more likely to lead to resilience if long term objectives are included as well as a wider spatial scale up to and including the global level.

A central issue in considering alternative pathways is the extent to which they may fail to meet a criterion of climate resilience. Or to put the question more simply, “are there any boundaries on the envelope of climate resilience”? The answer is highly scale dependent. We have a carbon legacy in the atmosphere, and total prevention/avoidance of impacts is now unachievable (Dickinson, 2007). At any level of stabilization of GHG concentrations, with even the strongest emissions reduction targets, some localities or systems or populations will be vulnerable to disruptions because there is in effect no limit below which universal prevention of residual loss and damages can be assured. Transformational change will therefore need to be a key component in nearly all alternative climate resilient pathways.

In the event that global surface mean temperatures rise through +2^{o}C to +4^{o}C and higher (Schneider, 2009; New et al., 2012; Anderson and Bows, 2008), sustainability will become significantly more difficult to achieve (food security is a notable example: Chapter 7). For example, a business-as-usual future society where unsustainable development paths are the norm, where technology transfer between countries is lacking, population growth increases rapidly, GHG emission go unabated, and institutions and governance structures are ineffective at creating effective climate change policies, would almost certainly result in losses so widespread that development pathway would not be resilient (Riahi et al., 2011; Arnell et al., 2013). A pathway that included these elements would fall outside the ‘boundaries of the envelope of climate resilience’.

Within these boundaries, climate-resilient pathways can be made up of a collective of alternative choices at the regional level, where they are dependent upon specific demographics, potentials for economic development and growth, ecological and ecosystem services, access to natural resources, institutional and governance structures, and technological development and transfer. This concept at the global level offers a conceptual framework for considering alternative mixes of actions in support of climate resilience. Pathways can be developed to illustrate a range or possible futures, as a basis for discussion, following different yet distinct storylines. These dimensions can then be related to socioeconomic challenges confronting climate change mitigation and adaptation (as one aspect of sustainable development). One such pathway could have relatively limited challenges to both adaptation and mitigation, while another has substantial challenges to both adaptation and mitigation. Any pathway characterised by low challenges to both has a high potential to be more climate- resilient at the global scale and in many local or national situations. A pathway characterised by high challenges to both adaptation and mitigation has a high potential to be less climate-resilient at the global scale and in many localities and countries.

20.6.2. Implications for Current Sustainable Development Strategies and Choices

Decisionmakers face an array of choices in their efforts to define and implement pathways that will help to improve human well-being now and in the future in the face of climate change and other stressors.

Although payoffs from specific long-term pathways may be uncertain at this time, growing evidence (IPCC 2007; Chapters 8 – 13, 16, 17, 18 and 19) suggests that decision points and actions are at hand now. Climate-resilient development pathways are not only about actions taken in the future, but they are also about strategies and choices that are taken today. In fact, damage and loss patterns are not limited to future vulnerabilities; in many areas they are impeding food production and other essential development services in ways that deepen and widen poverty (Chapter 13), contribute to involuntary migration (Chapter 12; Warner and Afifi, forthcoming), and pressure food production and food prices (Chapters 7 and 17; Warner, van der Geest, 2013).

In this sense, delaying action in the present may reduce options for climate resilient pathways in the future. In some parts of the world, inadequate efforts to address effects of emerging climate stressors are already eroding the basis for sustainable development. New studies find that among people who who attempt to cope with current stresses, most experienced negative residual impacts and as a consequence faced eroding household income and food security, health, education opportunities, more likely to migrate, and losing housing and livelihood assets (Warner and van der Geest, 2013; Rabbani et al., 2013, Yaffa, 2013, Monnereau and Abraham, 2013, Traore et al., 2013). For example, in the Punakha district in Bhutan, 87% of households that adopted coping measures reported that they were still experiencing adverse effects of changing monsoon patterns despite the adaptation measures (Kusters and Wangdi, 2013). Evidence (Chapters 7, 8, 12, 13, 16, 19) suggests that waiting to take more effective action may reduce the range of choices for climate resilient pathways in the future (NRC, 2011b).

More generally, IPCC SREX, 2012, makes the case that a window of opportunity exists now for considering possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. It suggests that a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways. In this sense, strategies and actions can be pursued now that will move toward climate-resilient pathways while at the same time helping to improve human livelihoods, social and economic well-being, and responsible environmental management.

As policy makers explore what pathways to pursue, they will increasingly face questions about managing discourses about what societal objectives to pursue unchanged, where compromises in objectives are tolerable, and what consequences including loss and damage may be associated with different pathways. In considering possible needs for transformational pathways (Section 20.5), extreme weather occurrences such as major floods, wildfires, cyclones and heat waves may focus societal attention on vulnerabilities and stressors and provide a “policy window” for major changes (Kingdon, 1995; Birkland, 2006; Kates et al., 2012). Discussions of transformation may require broader-based social discourse (Pelling et al., 2007) and iterative institutional learning (Berkhout et al., 2006), on the basis of growing evidence, knowledge, and experience. Systems to monitor emerging stresses and threats will aid decisionmakers at different scales to evaluate alternative pathways (Kates et al., 2012).

20.7. Priority Research/Knowledge Gaps

Because integrating climate change mitigation, climate change adaptation, and sustainable development is a relatively new challenge, research should be a very high priority indeed in order to inform strategies and actions. The most salient research need is to improve the understanding of how climate change mitigation and adaptation can be combined with resilient sustainable development pathways in a wide variety of regional and sectoral contexts (Wilbanks, 2010). One starting point is simply improving the capacity to characterize benefits, costs, potentials, and limitations of major mitigation and adaptation options, along with their external implications for equitable development, so that integrated climate change response strategies can be evaluated more carefully (Wilbanks et al., 2007; NRC, 2011). What are the major tradeoffs? What are the potential synergies? How do implications of integrated mitigation/adaptation strategies vary with location, climate change risks and vulnerabilities, scale, and development objectives and capacities? (e.g., Hugé et al., 2011). In these regards, the best of global science needs to be combined with national and local expertise to advance knowledge related to climate-resilient pathways.

Related to this general priority are at least three specific research needs:

- Advances in conceptual and methodological understandings of, and tools to support research on, multiple drivers of development pathways and climate change impacts; possible feedback effects among mitigation, adaptation, and development; possible thresholds/tipping points that could cause particular challenges for development; and possible transformations to reduce losses and damages and support sustainable development (NRC, 2009, 2010a; Section 20.5).
- Advances in knowledge about how to respond sustainably to climate change extremes and extreme events, when and where they pose development challenges that would appear to require transformative changes in affected human and/or environmental systems. What might the response options be, and how can they be facilitated where they merit consideration? (e.g., Pelling, 2010; Lemos et al., 2013).
- Research on how to reconcile the importance of synergies between climate change adaptation and mitigation actions with widespread use of the concept of "additionality." For example, how might criteria be established for access to financial support for adaptation that incorporates the development importance of co-benefits? Such research could inform discourses about differences between adaptation and development in ways that enable the flow of financial resources to support adaptations (NRC, 2010a).

Further research needs include:

- Research attention to potentials for technological and institutional innovations to ease threats to sustainable development from climate change impacts and responses. In other words, how might climate change responses represent opportunities for innovative development paths? How might technological development be part of a strategy for development/climate change response integration? (Wilbanks, 2010)
- Research on strategies for institutional development, including improving understandings of how social institutions affect resource use (NRC, 2009), improving understandings of risk-related judgment and decision-making under uncertainty (NRC, 2009), and best practices in creating institutions that will effectively integrate climate change responses with sustainable development characteristics such as participation, equity, and accountability
- Research on strategies for the implementation of adaptive management and risk reduction for development. Examples of important research needs include improving the understanding of respective roles and interactions between autonomous response behavior and policy initiatives, improving the body of empirical evidence about how to implement changes that are judged to be desirable: e.g., adaptive management and governance capacity, and improving the understanding of differences between retrofitting older infrastructures (the challenge in many industrialized countries) and designing new infrastructures (the challenge in many rapidly developing countries) (IPCC SREX, 2012: Chapter 8).
- Research to improve the understanding of how to build social inclusiveness into development/climate change response integration. As suggested above, research is needed on issues of social values/climate justice/equity/participation and how they intersect with the deployment of mitigation, adaptation interventions and sustainable development policy in different regional/sociopolitical contexts (IPCC SREX, 2012: Chapter 8).
- Research on factors that influence deliberate transformations that are ethical, equitable, and sustainable (O'Brien, 2012; Kates et al., 2012).
- The development of structures for learning from emerging integrated climate change response/development experience: e.g., approaches and structures for monitoring, recording, evaluating, and learning from experience, identifying "best practices" and their characteristics (NRC, 2010a; IPCC SREX, 2012: Chapter 8; Hilden, 2011).

Finally, it is very possible that progress with global climate change mitigation will not be sufficient to avoid relatively high levels of regional and sectoral impacts, and that such conditions would pose growing challenges to the capacity of adaptation to avoid serious disruptions to development processes. If this were to become a reality later in this century, one response could be a rush toward geoengineering approaches. In preparation for such a contingency, and perhaps as an additional way to show how important progress with mitigation will be in framing prospects for sustainable development in many contexts, there is a very serious need for research on geoengineering costs, benefits, risks, a wide range of possible impacts, and fair and equitable structures for global policymaking and decision-making (UK Royal Society, 2009; Kates et al., 2012).

But a fundamental aim of research to improve capacities for climate-resilient pathways for sustainable development is to avoid such an unfortunate outcome. It seeks to do so by strengthening the base of knowledge that underlies and supports effective actions by viewing climate change mitigation, climate change adaptation, and sustainable development in an integrative and mutually supportive way.

Frequently Asked Questions

FAQ 20.1: What is a climate-resilient pathway for development? *[to be placed before Box 20-1]*
A climate-resilient pathway for development is a continuing process for managing changes in the climate and other driving forces affecting development, combining flexibility, innovativeness, and participative problem-solving with effectiveness in mitigating and adapting to climate change. If effects of climate change are relatively severe, this process is likely to require considerations of transformational changes in threatened systems if development is to be sustained without major disruptions.

FAQ 20.2: What do you mean by" transformational changes"? *[to be placed after Box 20-1]*
Transformational change is a fundamental change in a system, its nature, and/or its location that can occur in human institutions, technological and biological systems and elsewhere. It most often happens in responding to significantly disruptive events or concerns about them. For climate-resilient pathways for development, transformations in social processes may be required in order to get voluntary social agreement to undertake transformational adaptations that avoid serious disruptions of sustainable development.

FAQ 20.3: Why are climate-resilient pathways needed for sustainable development? *[to be placed in Section 20.2]*
Sustainable development requires managing many threats and risks, including climate change. Because climate change is a growing threat to development, sustainability will be more difficult to achieve for many locations, systems, and populations unless development pathways are pursued that are resilient to effects of climate change.

FAQ 20.4: Are there things that we can be doing now that will put us on the right track toward climate-resilient pathways? *[to be placed in Section 20.6.2]*
Yes. Climate-resilient pathways begin now, because it is time to consider possible strategies that would increase climate resilience while at the same time helping to improve human livelihoods and social and economic well-being. Combining these strategies with a process of iterative monitoring, evaluation, learning, innovation, and contingency planning will reduce climate change disaster risks, promote adaptive management, and contribute significantly to prospects for climate-resilient pathways.

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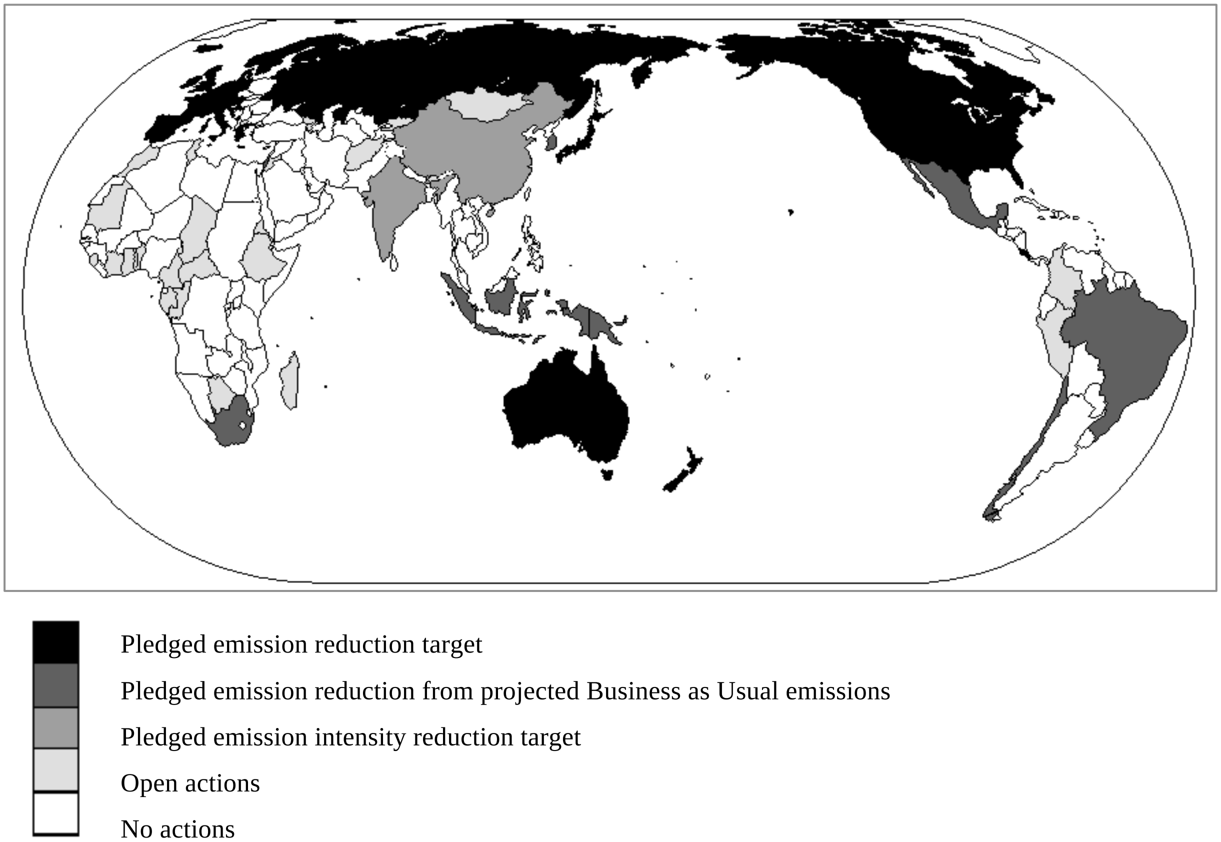

Figure 20-1: Pledges by Annex 1 and Annex 2 countries in response to the Copenhagen Accord. Sources: http://unfccc.int/meetings/copenhagen_dec_2009/items/5264.php, http://unfccc.int/meetings/cop_15/copenhagen_accord/items5265.php.
[Illustration to be redrawn to conform to IPCC publication specifications.]

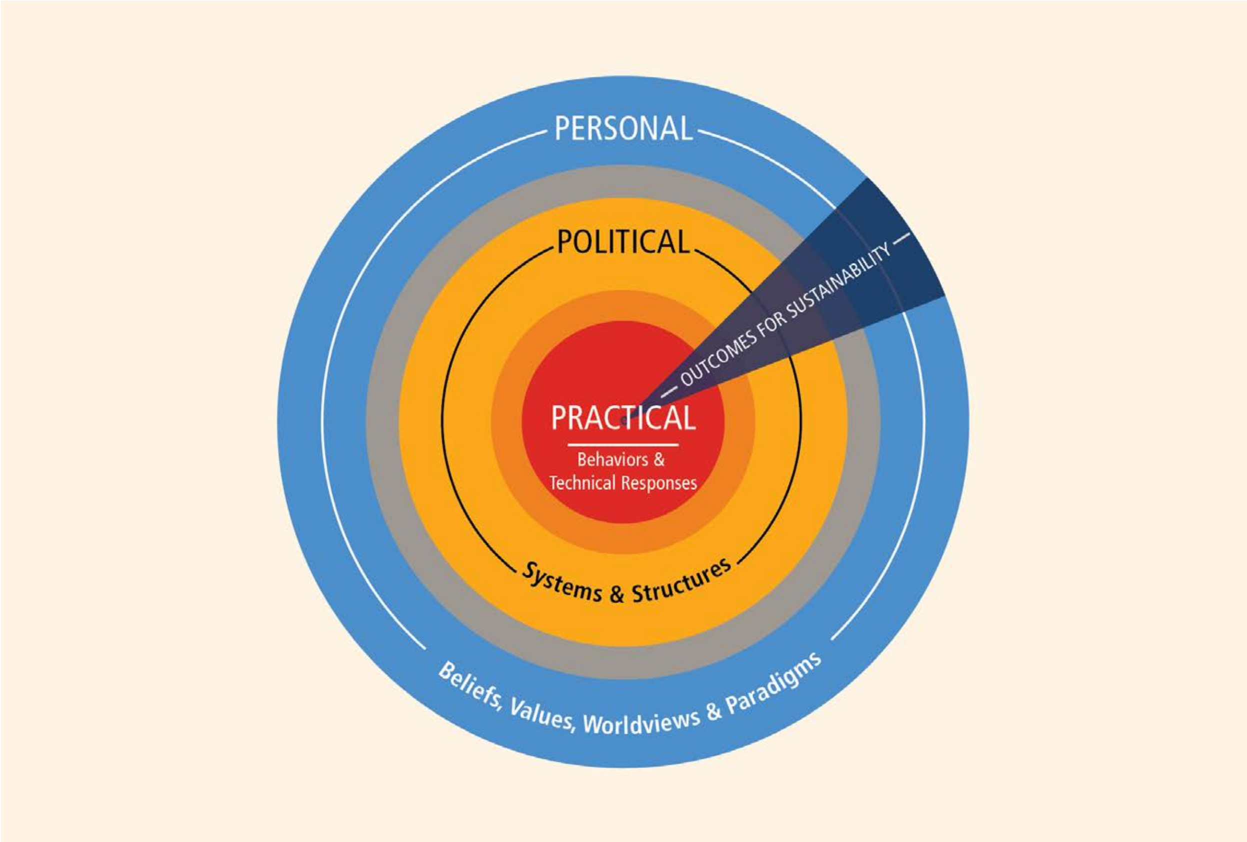

Figure 20-2: The three spheres of transformation. Transformational change may be an effective leverage point for promoting climate-resilient pathways for sustainable development. This figure depicts three interacting spheres or realms where transformational changes towards sustainability may be initiated. Transformations in the outer two spheres can have a large influence on behaviors and technical responses, contributing to non-linear transformations to sustainability. Source: O'Brien and Sygna, 2013.

Chapter 21. Regional Context

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Contents

Executive Summary

There has been an evolution in the treatment of regional aspects of climate change in IPCC reports from a patchwork of case examples in early assessments towards recent attempts at a more systematic coverage of regional issues at continental and sub-continental scales (21.2.2). Key topics requiring a regional treatment include: changes in the climate itself and in other aspects of the climate system (such as the cryosphere, oceans, sea level and atmospheric composition), climate change impacts on natural resource sectors and on human activities and infrastructure, factors determining adaptive capacity for adjusting to these impacts, emissions of greenhouse gases and aerosols and their cycling through the Earth system, and human responses to climate change through mitigation and adaptation.

A good understanding of decision-making contexts is essential to define the type and scale of information on climate change related risks required from physical climate science and impacts, adaptation and vulnerability assessments (21.2.1) (*high confidence*). This is a general issue for all impacts, adaptation and vulnerability assessments, but is especially important in the context of regional issues. Many studies still rely on global datasets, models and assessment methods to inform regional decisions. However, tailored regional approaches are often more effective in accounting for variations in trans-national, national and local decision-making contexts, as well as across different groups of stakeholders and sectors. There is a growing body of literature offering guidance on how to provide the most relevant climate risk information to suit specific decision-making scales and processes.

A greater range of regional scale climate information is now available which provides a more coherent picture of past and future regional changes with associated uncertainties (21.3.3). More targeted analyses of reference and projected climate information for impact assessment studies have been carried out. Leading messages include:

- Significant improvements have been made in the amount and quality of climate data that are available for establishing baseline reference states of climate-sensitive systems (21.5.3.1). These include new and improved observational datasets, rescue and digitisation of historical datasets, and a range of improved global reconstructions of weather sequences.
- A larger set of global and regional (both dynamical and statistical) model projections allow a better characterization of ranges of plausible climate futures than in the AR4 (21.3.3), and more methods are available to produce regional probabilistic projections of changes for use in IAV assessment work (21.5.3).
- Better process understanding would strengthen the emerging messages on future climate change where there remains significant regional variation in their reliability (21.3.3).
- Confidence in past climate trends has different regional variability and in many regions there is higher confidence in future changes, often due to a lack of evidence on observed changes (21.3, Box 21-4).

In spite of improvements, the available information is limited by the lack of comprehensive observations of regional climate, or analyses of these, and different levels of confidence in projected climate change (*high confidence*). Some trends that are of particular significance for regional impacts and adaptation include (21.3.3.1; WG I SPM):

- The globally averaged combined land and ocean surface temperature data show a warming of 0.85 [0.65 to 1.06] °C, over the period 1880–2012. There is regional variation in the global trend, but overall the entire globe has warmed during the period 1901-2012. (WGI SPM) Future warming is *very likely* to be larger over land areas than over oceans. (WGI SPM)
- Averaged over mid-latitude land areas, precipitation has increased since 1901(*medium confidence* before and *high confidence* after 1951), but for other regions there is low confidence in the assessment of precipitation trends (WGI SPM).
- There are *likely* more land regions where the number of heavy precipitation events has increased than where it has decreased. The frequency or intensity of heavy precipitation events has *likely* increased in North America and Europe. In other continents, confidence in changes in heavy precipitation events is at most *medium*. The frequency and intensity of drought has *likely* increased in the Mediterranean and West Africa and *likely* decreased in central North America and north-west Australia.
- The annual mean Arctic sea ice extent decreased over the period 1979–2012 with a rate that was *very likely* in the range 3.5 to 4.1% per decade. Climate models indicate a nearly ice-free Arctic Ocean in September before mid-century is *likely* under the high forcing scenario RCP8.5 (*medium confidence*).
- The average rate of ice loss from glaciers worldwide, excluding those near the Greenland and Antarctic ice sheets, was *very likely* 275 [140 to 410] Gt yr^{-1} over the period 1993-2009. By the end of the 21st century, the volume of glaciers (excluding those near the Antarctic ice sheet), is projected to decrease by 15 to 55% for RCP2.6, and by 35 to 85% for RCP8.5, relative to 1986-2005 (*medium confidence*).
- The rate of global mean sea-level rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010, under all RCP scenarios (21.3.3.5; WG I SPM). By the end of the 21st century it is *very likely* that sea level will rise in more than about 95% of the ocean area, with about 70% of the global coastlines projected to experience a sea level change within 20% of the global mean change. Sea-level rise along coasts will also be a function of local and regional conditions, including land subsidence or uplift and patterns of development near the coast.

There is substantial regional variation in observations and projections of climate change impacts, both because the impacts themselves vary, and because of unequal research attention (21.3.1). Evidence linking observed impacts on biological, physical and (increasingly) human systems to recent and ongoing regional temperature and (in some cases) precipitation changes have become more compelling since the AR4. This is due both to the greater availability of statistically robust, calibrated satellite records, and to improved reporting from monitoring sites in hitherto under-represented regions, though the disparity still remains large between data rich and data-poor regions. Regional variations in physical impacts such as vegetation changes, sea-level rise, and ocean acidification are increasingly well documented, though their consequences for ecosystems and humans are less well studied or understood. Projections of future impacts rely primarily on a diverse suite of biophysical, economic and integrated models operating from global- to site-scales, though some physical experiments are also conducted to study processes in altered environments. New research initiatives are beginning to exploit the diversity of impact model projections, through cross-scale model inter-comparison exercises.

There are large variations in the degree to which adaptation processes, practices and policy have been studied and implemented in different regions (21.3.2) (*high confidence*). Europe and Australia have had extensive research programs on climate change adaptation, while research in Africa and Asia has been dominated by international partners and relies heavily on case studies of community-based adaptation. National adaptation strategies are common in Europe, and adaptation plans are in place in some cities in Europe, the Americas and Australasia, with agriculture, water and land use management the primary sectors of activity. However, it is still the case that implementation lags behind planning in most regions of the world.

Contested definitions and alternative approaches to describing regional vulnerability to climate change pose problems for interpreting vulnerability indicators (21.3.1.2; 21.5.1.1). There are numerous studies that use indicators to define aspects of vulnerability, quantifying these across regional units (e.g. by country or municipality), often weighting and merging them into vulnerability indices and presenting them regionally as maps. However, methods of constructing indices are subjective, often lack transparency and can be difficult to interpret. Moreover, indices commonly combine indicators reflecting current conditions (e.g. of socio-economic capacity) with other indicators describing projected changes (e.g. of future climate or population), and have failed to reflect the dynamic nature of the different indicator variables.

Hotspots draw attention, from various perspectives and often controversially, to locations judged to be especially vulnerable to climate change (21.5.1.2). Identifying hotspots is an approach that has been used to indicate locations that stand out in terms of impacts, vulnerability or adaptive capacity (or combinations of these). The approach exists in many fields and the meaning and use of the term hotspots differs, though their purpose is generally to set priorities for policy action or for further research. Hotspots can be very effective as communication tools, but may also suffer from methodological weaknesses. They are often subjectively defined, relationships between indicator variables may be poorly understood and they can be highly scale-dependent. In part due to these ambiguities, there has been controversy surrounding the growing use of hotspots in decision making, particularly in relation to prioritising regions for climate change funding.

Cross-regional phenomena can be crucial for understanding the ramifications of climate change at regional scales, and its impacts and policies of response (21.4) (*high confidence*). These include global trade and international financial transactions, which are linked to climate change as a direct or indirect cause of anthropogenic emissions, as a predisposing factor for regional vulnerability, through their sensitivity to climate trends and extreme climate events, and as an instrument for implementing mitigation and adaptation policies. Migration is also a cross-regional phenomenon, whether of people or of ecosystems, both requiring trans-boundary consideration of their causes, implications and possible interventions to alleviate human suffering and promote biodiversity.

Downscaling of global climate reconstructions and models has advanced to bring the climate data to a closer match for the temporal and spatial resolution requirements for assessing many regional impacts, and the application of downscaled climate data has expanded substantially since AR4 (21.3.3; 21.5.3). This information remains weakly coordinated, and current results indicate that high resolution downscaled reconstructions of the current climate can have significant errors. The increase in downscaled data sets has not narrowed the uncertainty range. Integrating these data with historical change and process based understanding remains an important challenge.

Characterization of uncertainty in climate change research on regional scales has advanced well beyond quantifying uncertainties in regional climate projections alone, to incorporating uncertainties in simulations of future impacts as well as considering uncertainties in projections of societal vulnerability (21.3.3, 21.5.3, 21.5.1. 21.5.2). In particular, intercomparison studies are now examining the uncertainties in impacts models (e.g., AgMIP and ISIMIP) and combining them with uncertainties in regional climate projections. Some results indicate that a larger portion of the uncertainty in estimates of future impacts can be attributed to the impact models applied rather than to the climate projections assumed. In addition, the deeper uncertainties associated with aspects of defining societal vulnerability to climate change related to the alternative approaches to defining vulnerability are becoming appreciated. As yet there has been little research actively to quantify these uncertainties or to combine them with physical impact and climate uncertainties.

Studies of multiple stressors and assessments of potential global and regional futures using scenarios with multiple, non-climate elements are becoming increasingly common (21.5.3.2; 21.5.3.3). Non-climatic factors relevant to assessing a system's vulnerability generally involve a complex mix of influences such as environmental changes (e.g. in air, water and soil quality, sea level, resource depletion), land use and land cover changes, and socio-economic changes (e.g. in population, income, technology, education, equity, governance). All of these non-climate factors have important regional variations. There is significant variation in vulnerability due to variability in these factors.

21.1. Introduction

This chapter serves as an introduction to Part B of this volume. It provides context for an assessment of regional aspects of climate change in different parts of the world, which are presented in the following nine chapters. While the main focus of those chapters is on the regional dimensions of impacts, adaptation and vulnerability, this chapter also offers links to regional aspects of the physical climate reported by Working Group I and of mitigation analysis reported by Working Group III. The chapter frames the discussion of both global and regional issues in a decision-making context. This context identifies different scales of decisions that are made (e.g. global, international, regional, national, subnational, local) and the different economic or impact sectors that are often the objects of decision-making (e.g. agriculture, water resources, energy).

Within this framing, the chapter then provides three levels of synthesis. First there is an evaluation of the state of knowledge of changes in the physical climate system, and associated impacts and vulnerabilities, and the degree of confidence that we have in understanding those on a regional basis as relevant to decision-making. Second, the regional context of the sectoral findings presented in Part A of this volume is discussed. Third, there is an analysis of the regional variation revealed in subsequent chapters of Part B. In so doing, the goal is to examine how the chapters reflect differences or similarities in how decision-making is being addressed by policy and informed by research in different regions of the world, and whether there is commonality of experience among regions that could be useful for enhancing decisions in the future.

Having analyzed similarities and differences among IPCC regions, the chapter then discusses trans-regional and cross-regional issues that affect both human systems (e.g. trade and financial flows) and natural systems (e.g. ecosystem migration). Finally, the chapter evaluates methods of assessing regional vulnerabilities and adaptation, impact analyses, and the development and application of baselines and scenarios of the future. These evaluations provide guidance for understanding how such methods might ultimately be enhanced, so that the confidence in research about possible future conditions and consequences might ultimately improve.

21.2. Defining Regional Context

The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather and longer-term climate trends – are regional or local in their occurrence, character and implications. Moreover, the decisions that are or could be taken on the basis of climate change science play out on a range of scales, and the relevance and limitations of information on both biophysical impacts and social vulnerability differ strongly from global- to local-scale, and from one region to another. Explicit recognition of geographical diversity is therefore important for any scientific assessment of anthropogenic climate change. The following sections emphasize some of the crucial regional issues to be pursued in Part B of this report.

21.2.1. Decision-Making Context

A good understanding of decision-making contexts is essential to define the type and resolution and characteristics of information on climate change related risks required from physical climate science and impacts, adaptation and vulnerability assessments (e.g. IPCC, 2012a). This is a general issue for all impacts, adaptation and vulnerability assessments (cf. the chapters in Part A), but is especially important in the context of regional issues. Many studies still rely on global datasets, models and assessment methods to inform regional decisions. However, tailored regional approaches are often more effective in accounting for variations in trans-national, national and local decision-making contexts, as well as across different groups of stakeholders and sectors. There is a growing body of literature offering guidance on how to provide the most relevant climate risk information to suit specific decision-making scales and processes (e.g., Willows and Connell, 2003; ADB, 2005; Kandlikar *et al.*, 2011).

Table 21-1 illustrates the range of actors involved in decision-making to be informed by climate information at different scales in different sectors, ranging from international policy makers and agencies, to national and local government departments, to civil society organizations and the private sector at all levels, all the way to communities and individual households. The table illustrates how policy makers face a dual challenge in achieving policy integration – vertically, through multiple levels of governance, and horizontally, across different sectors (policy coherence).

[INSERT TABLE 21-1 HERE
Table 21-1: Dimensions of the institutions and actors involved in climate change decision-making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decison-making domains are illustrative. Modified and extended from Mickwitz (2009).]

Many climate change risk assessments have traditionally been undertaken either in the context of international climate policy-making (especially the United National Framework Convention on Climate Change – UNFCCC), or by (or for) national governments (e.g. CCRA, 2012; SEI, 2009; GCAP, 2011; Roshydromet, 2008). In those cases, climate risk information commonly assumes a central role in the decision-making, for instance to inform mitigation policy, or for plans or projects designed specifically to adapt to a changing climate. In recent years, increasing attention has been paid to more sector- or project-specific risk assessments, intended to guide planning and practice by a range of actors (e.g. Liu *et al.*, 2008; Rosenzweig *et al.*, 2011). In those contexts, climate may often be considered as only one contributor among a much wider set of considerations for a particular decision. In such cases, there is uncertainty about not only the future climate, but also many other aspects of the system at risk. Moreover, while analysts will seek the best available climate risk information to inform the relative costs and benefits of the options available to manage that risk, they will also need to consider the various constraints to action faced by the actors involved.

Some of these decision-making contexts, such as the design of large infrastructure projects, may require rigorous quantitative information to feed formal evaluations, often including cost-benefit analysis (e.g. PriceWaterHouseCoopers, 2010; and see chapter 17). Others, especially at local level, such as decision-making in traditional communities, are often made more intuitively, with a much greater role for a wide range of social and cultural aspects. These may benefit much more from experience-based approaches, participatory risk assessments or story-telling to evaluate future implications of possible decisions (e.g. Van Aalst *et al.*, 2008, World Bank, 2010). Multi-criteria analysis, scenario planning, and flexible decision paths offer options for taking action when faced with large uncertainties or incomplete information, and can help bridge adaptation strategies across scales (in particular between the national and local level). In most cases, an understanding of the context in which the risk plays out, and the alternative options that may be considered to manage it, are not an afterthought, but a defining feature of an appropriate climate risk analysis, which requires a much closer interplay between decision-makers and providers of climate risk information than often occurs in practice (e.g., Cardona *et al.*, 2012; Hellmuth *et al.*, 2010; Mendler de Suarez *et al.*, 2012).

The different decision-making contexts also determine the types of climate information required, including the climate variables of interest and the geographic and time scales on which they need to be provided. Many climate change impact assessments have traditionally focused on changes over longer time horizons (often out to 2100, though recently studies have begun to concentrate more on mid-century or earlier). In contrast, most decisions taken today have a planning horizon ranging from a few months to about two decades (e.g. Wilby et al., 2009). For many such shorter-term decisions, recent climate variability and observed trends are commonly regarded as sufficient to inform adaptation (e.g. Hallegatte, 2009). However, in so doing, there is often scope to make better use of observed climatological information as well as seasonal and maybe also decadal climate forecasts (e.g. Wang *et al.*, 2009;

Ziervogel *et al.*, 2010; Mehta *et al.*, 2011; Kirtman *et al.*, 2014., HLT, 2011). For longer-term decisions, such as decisions with irreversible long-term implications and investments with a long investment horizon and substantial vulnerability to changing climate conditions, longer-term climate risk information is needed (e.g. Reeder and Ranger, 2010). However, while that longer-term information is often used simply to plan for a best-guess scenario to optimize for most probable conditions, there is increasing attention for informing concerns about maladaptation (Barnett and O'Neill, 2010) and sequencing of potential adaptation options in a wider range of possible outcomes, requiring a stronger focus on ranges of possible outcomes and guidance on managing uncertainties, especially at regional, national and sub-national levels (Hall *et al.*, 2012; Gersonius *et al.*, 2013).

Section 21.3 summarizes different approaches that have been applied at different scales looking at vulnerabilities and impacts, adaptation, and climate science in a regional context, paying special attention to information contained in the regional chapters.

21.2.2. Defining Regions

There has been an evolution in the treatment of regional aspects of climate change in IPCC reports (Table 21-2) from a patchwork of case examples in the First Assessment Report (FAR) and its supplements, through to attempts at a more systematic coverage of regional issues following a request from governments, beginning with the Special Report on the Regional Impacts of Climate Change in 1998. That report distilled information from the Second Assessment Report (SAR) for ten continental scale regions, and the subsequent Third (TAR) and Fourth (AR4) assessments each contained comparable chapters on impacts, adaptation and vulnerability in the Working Group (WG) II volumes. WG I and III reports have also addressed regional issues in various chapters, using different methods of mapping, statistical aggregation and spatial averaging to provide regional information.

[INSERT TABLE 21-2 HERE
Table 21-2: Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SR). Major assessments are subdivided by the three Working Group reports, each described by generic titles.**]**

Part B of this WG II Fifth Assessment (AR5) is the first to address regional issues treated in all three WGs. It comprises chapters on the six major continental land regions, Polar Regions, Small Islands and The Ocean. These are depicted in Figure 21-1.

[INSERT FIGURE 21-1 HERE
Figure 21-1: Specification of the world regions described in chapters 22-30 of this volume.]

Some of the main topics benefiting from a regional treatment are:

- *Changes in climate*, typically represented over sub-continental regions, a scale at which global climate models simulate well the pattern of observed surface temperatures, though more modestly the pattern of precipitation (Flato *et al.*, 2014). While maps are widely used to represent climatic patterns, regional aggregation of this (typically gridded) information is still required to summarise the processes and trends they depict. Examples, including information on climate extremes, are presented elsewhere in this chapter, with systematic coverage of all regions provided in supplementary material. Selected time series plots of temperature and precipitation change from an atlas of global and regional climate projections accompanying the WG I report (Collins *et al.*, 2014b) can also be found in several regional chapters of this volume. In Figure 21-1, the sub-continental regions used for summarising climate information are overlaid on a map of the nine regions treated in Part B.
- *Changes in other aspects of the climate system*, such as the cryosphere, oceans, sea level, and atmospheric composition. A regional treatment of these phenomena is often extremely important to gauge real risks, for example when regional changes in land movements and local ocean currents counter or reinforce global sea level rise (Nicholls *et al.*, 2013).
- *Climate change impacts* on natural resource sectors, such as agriculture, forestry, ecosystems, water resources and fisheries, and on human activities and infrastructure, often with regional treatment according

to biogeographical characteristics (e.g. biomes, climatic zones, physiographic features such as mountains, river basins, coastlines or deltas, or combinations of these).

- *Adaptive capacity*, which is a measure of society's ability to adjust to the potential impacts of climate change, sometimes characterised in relation to social vulnerability (Füssel, 2010), and sometimes represented in regional statistics through the use of socio-economic indicators.
- *Emissions* of greenhouse gases and aerosols and their cycling through the Earth system (Blanco et al., 2014; Ciais *et al*., 2014).
- *Human responses to climate change through mitigation and adaptation*, which can require both global and regional approaches (e.g. Stavins *et al.*, 2014; Agrawala *et al.*, 2014; Somanathan *et al.*, 2014; and see chapters 14 to 16).

Detailed examples of these elements will be referred to throughout this chapter and the regional chapters that follow. Some of the more important international political groupings that are pertinent to the climate change issue are described and catalogued in Supplementary material (section SM21.1). Table SM21-1 in section SM21.1 lists UN member states and other territories, their status in September 2013 with respect to some illustrative groupings of potential relevance for international climate change policy making, and the regional chapters in which they are considered in this report.

Finally, new global socioeconomic and environmental scenarios for climate change research have emerged since the AR4 that are richer, more diverse and offer a higher level of regional detail than previous scenarios taken from the IPCC Special Report on Emissions Scenarios (SRES). These are introduced in Box 21-1.

_____ START BOX 21-1 HERE _____

Box 21-1. A New Framework of Global Scenarios for Regional Assessment

The major socio-economic driving factors of future emissions and their effects on the global climate system were characterized in the TAR and AR4 using scenarios derived from the IPCC Special Report on Emissions Scenarios (SRES – IPCC, 2000). However, these scenarios are becoming outdated in terms of their data and projections, and their scope is too narrow to serve contemporary user needs (Ebi *et al*., 2013). More recently a new approach to developing climate and socio-economic scenarios has been adopted in which concentration trajectories for atmospheric greenhouse gases and aerosols were developed first (Representative Concentration Pathways or RCPs – Moss et al., 2010), thereby allowing climate modeling work to proceed much earlier in the process than for SRES. Different possible Shared Socio-economic Pathways (SSPs), intended for shared use among different climate change research communities, were to be determined later, recognizing that more than one socio-economic pathway can lead to the same concentrations of greenhouse gases and aerosols (Kriegler *et al.,* 2012).

Four different RCPs were developed, corresponding to four different levels of radiative forcing of the atmosphere by 2100 relative to pre-industrial levels, expressed in units of Wm^{-2}: RCP 8.5, 6.0, 4.5, and 2.6 (van Vuuren et al., 2012). These embrace the range of scenarios found in the literature, and all except RCP 8.5 also include explicit stabilization strategies, which were missing from the SRES set. An approximate mapping of the SRES scenarios onto the RCPs on the basis of a resemblance in radiative forcing by 2100 is presented in chapter 1 (this volume), pairing RCP 8.5 with SRES A2 and RCP 4.5 with B1 and noting that RCP 6.0 lies between B1 and B2. No SRES scenarios result in forcing as low as RCP 2.6, though mitigation scenarios developed from initial SRES trajectories have been applied in a few climate model experiments (e.g. the E1 scenario – Johns et al., 2011).

In addition, five SSPs have been proposed, representing a wide range of possible development pathways (van Vuuren et al., 2013). An inverse approach is applied, whereby the SSPs are constructed in terms of outcomes most relevant to IAV and mitigation analysis, depicted as challenges to mitigation and adaptation (Chapter 20, Figure 20-3). Narrative storylines for the SSPs have been outlined and preliminary quantifications of the socio-economic variables are underway (O'Neill et al., 2013). Priority has been given to a set of *basic* SSPs with the minimum detail and comprehensiveness needed to provide inputs to IAV and integrated assessment models, primarily at global or large regional scales. Building on the basic SSPs, a second stage will construct *extended* SSPs, designed for finer-scale regional and sectoral applications (O'Neill *et al*., 2013).

An overall scenario architecture has been designed for integrating RCPs and SSPs (Ebi et al., 2013; van Vuuren et al., 2013), for considering mitigation and adaptation policies using Shared Policy Assumptions (SPAs – Kriegler et al., 2013) and for providing relevant socio-economic information at the scales required for IAV analysis (van Ruijven et al., 2013). Additional information on these scenarios can be found in chapter 1 of this report (section 1.1.3) and elsewhere in the assessment (Blanco et al., 2014.; Collins et al., 2014a.; Kunreuther et al., 2014). However, due to the time lags that still exist between the generation of RCP-based climate change projections in CMIP5 (the Coupled Model Intercomparison Project – Taylor *et al*., 2012) and the development of SSPs, few of the IAV studies assessed in this report actively use these scenarios. Instead, most of the scenario-related studies in the assessed literature still rely on the SRES.

_____ END BOX 21-1 HERE _____

21.2.3. Introduction to Methods and Information

There has been significant confusion and debate about the definitions of key terms (Janssen and Ostrom, 2006), such as vulnerability (Adger, 2006), adaptation (Stafford Smith *et al.,* 2011), adaptive capacity (Smit and Wandel, 2006) and resilience (Klein et al., 2003). One explanation is that the terms are not independent concepts, but defined by each other, thus making it impossible to remove the confusion around the definitions (Hinkel, 2011). The differences in the definitions relate to the different entry points for looking at climate change risk (IPCC, 2012).

Table 21-3 shows two ways to think about vulnerability, demonstrating that different objectives (e.g., improving well-being and livelihoods or reducing climate change impacts) lead to different sets of questions being asked. This results in the selection of different methods to arrive at the answers. The two approaches portrayed in the middle and right hand columns of Table 21-3 have also been characterised in terms of top-down (middle column) and bottom-up (right column) perspectives, with the former identifying physical vulnerability and the latter social vulnerability (Dessai and Hulme, 2004). In the middle column, the climate change impacts are the starting point for the analysis, revealing that people and/or ecosystems are vulnerable to climate change. This approach commonly applies global-scale scenario information and seeks to refine this to the region of interest through downscaling procedures. For the approach illustrated on the right, the development context is the starting point (i.e., social vulnerability), commonly focusing on local scales, on top of which climate change occurs. The task is then to identify what changes are needed in the broader-scale development pathways in order to reduce vulnerability to climate change. Another difference is a contrast in time-frames, where a climate change focused approach tends to look to the future to see how to adjust to expected changes, whereas a vulnerability focused approach is centred on addressing the drivers of current vulnerability. A similar approach is described by McGray *et al.* (2009).

[INSERT TABLE 21-3 HERE
Table 21-3: Two possible entry points for thinking about vulnerability to climate change (illustrative and adapted from Füssel 2007).]

The information assessed in this chapter stems from different entry points, framings and conceptual frameworks for thinking about risk. They merge social and natural science perspectives with transdisciplinary ones. There is no single "best" conceptual model: the approaches change as scientific thinking evolves. The IPCC itself is an example of this: IPCC SREX (IPCC, 2012) presented an approach that has been adjusted and adapted in Chapter 19 of this volume. Chapter 2 describes other conceptual models for decision making in the context of risk. While this diversity in approaches enriches our understanding of climate change, it can also create difficulties in comparisons. For instance, findings that are described as vulnerabilities in some studies may be classified as impacts in others; lack of adaptive capacity in one setting might be described as social vulnerability in another.

21.3. Synthesis of Key Regional Issues

This section presents information on vulnerabilities and impacts, adaptation, and climate science in a regional context. To illustrate how these different elements play out in actual decision-making contexts, Table 21-4 presents examples drawn from the regional and thematic chapters, which illustrate how information about vulnerability and exposure, and climate science at different scales, inform adaptation (implemented in policy and practice as part of a wider decision-making context). These show that decision-making is informed by a combination of different types of information. However, this section is organized by the three constituent elements: vulnerabilities and impacts; adaptation; and climate science.

[INSERT TABLE 21-4 HERE
Table 21-4: Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.]

The following two sub-sections offer a brief synopsis of the approaches being reported in the different regional chapters on impacts and vulnerability studies (21.3.1) and adaptation studies (21.3.2), aiming to particularly highlight similarities and differences among regions. Table 21-5 serves as a rough template for organising this discussion which is limited to the literature that has been assessed by the regional chapters. It is organized according to the broad research approach applied, distinguishing impacts and vulnerability approaches from adaptation approaches; and according to scales of application ranging from global to local.

[INSERT TABLE 21-5 HERE
Table 21-5: Dimensions of assessments of impacts and vulnerability and of adaptation drawn upon to serve different target fields (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to the original studies and to the chapters in which they are cited. Aspects of some of the studies in this table are also alluded to in Section 21.5.]

Section 21.3.3 then provides an analysis of advances in understanding of the physical climate system for the different regions covered in chapters 22-30, introducing new regional information to complement the large-scale and process-oriented findings presented by Working Group I. Understanding the reliability of this information is of crucial importance. In the context of IAV studies it is relevant to a very wide range of scales and it comes with a similarly wide range of reliabilities. Using a similar classification of spatial scales to that presented in Table 21-5, Table 21-6 provides a summary assessment of the reliability of information on two basic climate variables of relevance, surface temperature and precipitation. It is drawn from the extensive assessment and supporting literature from the IPCC SREX (IPCC, 2012) and the AR5 WG1 reports. Some discussion of relevant methodologies and related issues and results are also presented in section 21.5.

[INSERT TABLE 21-6 HERE
Table 21-6: Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to Very Low (VL).]

Table 21-6 shows there are significant variations in reliability with finer scales information generally less reliable given the need for a greater density of observations and/or for models to maintain accuracy at high resolutions. The reliability of information on past climate depends on the availability and quality of observations which is higher for temperature than precipitation as observations of temperature are easier to make and generally more representative of surrounding areas than is the case for precipitation. Future climate change reliability depends on the performance of the models used for the projections in simulating the processes that lead to these changes. Again, information on temperature is generally more reliable due to the models' demonstrated ability to simulate the relevant processes when reproducing past changes. The significant geographical variations, in the case of the observations, result from issues with availability and/or quality of data in many regions, especially for precipitation. For future climate change, data availability is less of an issue with the advent of large ensembles of climate model projections but quality is a significant problem in some regions where the models perform poorly and there is little confidence that processes driving the projected changes are accurately captured. A framework for summary information on model projections of future climate change placed this in the context of observed changes is presented in Box 21-2.

_____ START BOX 21-2 HERE _____

Box 21-2. Summary Regional Climate Projection Information

Summary figures on observed and projected changes in temperature and precipitation are presented in the following regional chapters. These provide some context to the risks associated with climate change vulnerability and impacts and the decision-making on adaptations being planned and implemented in response to these risks. Figure 21-2 provides an example for Africa. The information is identical to that displayed in Box CC-RC.

[INSERT FIGURE 21-2 HERE
Figure 21-2: Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Observed temperature trends from 1901-2012 determined by linear regression. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression. [WGI AR5 Figure SPM.2] For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See alsoAnnex I of WGI AR5. [Boxes 21-3 and CC-RC]]

These figures provide a very broad overview of the projected regional climate changes but in dealing with only annual averages they are not able to convey any information about projected changes on seasonal timescales or shorter, such as for extremes. In addition, they are derived solely from the CMIP5 general circulation models (GCMs) and do not display any information derived from CMIP3 data which are widely used in many of the studies assessed within the AR5 WG2 report. To provide additional context two additional sets of figures are presented here and in Box 21-4 that display temperature and precipitation changes at the seasonal and daily timescales respectively.

Figure 21-3 displays projected seasonal and annual changes averaged over the regions defined in the IPCC SREX report, "Managing the risks of extreme events and disasters to advance climate change adaptation" (IPCC 2012), for Central and South America for the four RCP scenarios and three of the SRES scenarios. The temperature and precipitation changes for the period 2071-2100 compared to a baseline of 1961-1990 are plotted for the four standard three months seasons with the changes from each CMIP3 or CMIP5 represented by a symbol. Symbols showing the CMIP3 model projections are all grey but differ in shape depending on the driving SRES concentrations scenario and those showing the CMIP5 projections differ in colour depending on the driving RCP emissions/concentrations scenario (see figure legend for details and Box 21-1 for more information on the SRES and RCP scenarios). The thirty year periods were chosen for consistency with the figures displayed in Box 21-4 (Figures 21-7 and 21-8) showing changes in daily temperatures and precipitation. Figures presenting similar information for the SREX regions contained in the other inhabited continents are presented in supplementary figures SM21-1 to SM21-7.

[INSERT FIGURE 21-3 HERE
Figure 21-3: Regional average change in seasonal and annual mean temperature and precipitation over five sub-regions covering South and Central America for the period 2071-2100 relative to 1961-90 in GCM projections from 35 CMIP5 ensemble under four RCP scenarios (van Vuuren et al., 2011) compared with GCM projections from 22 CMIP3 ensemble under three SRES scenarios (IPCC, 2000); see Table 21-1 for details of the relationship between the SRES and RCP scenarios. Regional averages are based on SREX region definitions (see Figure 21-3). Temperature changes are given in ºC and precipitation changes in mm/day with axes scaled relative to the maximum changes projected across the range of models. The models which generated the data displayed are listed in supplementary material Table SM21-3.]

_____ END BOX 21-2 HERE _____

21.3.1. Vulnerabilities and Impacts

21.3.1.1. Observed Impacts

The evidence linking observed impacts on biological, physical and (increasingly) human systems to recent and ongoing regional climate changes has become more compelling since the AR4 (see chapter 18). One reason for this is the improved reporting of published studies from hitherto under-represented regions of the world, especially in the tropics (Rosenzweig and Neofotis, 2013). That said, the disparity is still large between the copious evidence being presented from Europe and North America, as well as good quality data emerging from Australasia, polar regions, many ocean areas and some parts of Asia and South America, compared to the much sparser coverage of studies from Africa, large parts of Asia, central and South America and many small islands. On the other hand, as the time series of well-calibrated satellite observations become longer in duration, and hence statistically more robust, these are increasingly providing a near global coverage of changes in surface characteristics such as vegetation, hydrology, and snow and ice conditions that can usefully complement or substitute for surface observations (see Table 21-4 and chapter 18 for examples). Changes in climate variables other than temperature, such as precipitation. evapotranspiration and CO_2 concentration, are also being related to observed impacts in a growing number of studies (Rosenzweig and Neofotis, 2013; and see examples from Australia in chapter 25, Table 25-3 and south eastern South America in chapter 27, Figure 27-7).

Other regional differences in observed changes worth pointing out include trends in relative sea level, which is rising on average globally (Church *et al*., 2014), but displays large regional variations in magnitude, or even sign, due to a combination of influences ranging from El Niño/La Nina cycles to local tectonic activity (Nicholls et al., 2013), making general conclusions about ongoing and future risks of sea level change very difficult to draw across diverse regional groupings such as small islands (see chapter 29). There are also regional variations in another ongoing effect of rising CO_2 concentration – ocean acidification, with a greater pH decrease at high latitudes consistent with the generally lower buffer capacities of the high latitude oceans compared to lower latitudes (Rhein et al., 2014, section 3.8.2). Calcifying organisms are expected to show responses to these trends in future, but key uncertainties remain at organismal to ecosystem levels (chapter 30, Box CC-OA).

21.3.1.2. Future Impacts and Vulnerability

21.3.1.2.1. Impact models

The long-term monitoring of environmental variables, as well as serving a critical role in the detection and attribution of observed impacts, also provides basic calibration material used for the development and testing of impact models. These include process-based or statistical models used to simulate the biophysical impacts of climate on outcomes such as crop yield, forest productivity, river runoff, coastal inundation or human mortality and morbidity (see chapters 2-7; 11). They also encompass various types of economic models that can be applied to evaluate the costs incurred by biophysical impacts (see, for example, chapters 10 and 17). There are also integrated assessment models (IAMs), Earth System Models, and other more loosely linked integrated model frameworks that represent multiple systems and processes (e.g. energy, emissions, climate, land use change, biophysical impacts, economic effects, global trade) and the various interactions and feedbacks between them. For examples of these, see chapter 17, section 17.6.3 and Flato *et al.* (2014).

21.3.1.2.2. Vulnerability mapping

A second approach to projecting potential future impacts is to construct vulnerability maps. These usually combine information on three components: exposure to a hazard (commonly defined by the magnitude of climate change, sensitivity to that hazard), the magnitude of response for a given level of climate change, and adaptive capacity (describing the social and economic means to withstand the impacts of climate change (IPCC, 2001)). Key indicators are selected to represent each of the three components, which are sometimes combined into a single index of vulnerability. Indicators are usually measured quantities taken from statistical sources (e.g. income, population), or have been modelled separately (e.g. key climate variables). Vulnerability indices have received close scrutiny in several recent reviews (Füssel, 2010; Hinkel, 2011; Malone and Engle, 2011; Preston *et al.*, 2011; Kienberger et al., 2012), and a number of global studies have been critiqued by Füssel (2010).

A variant of vulnerability mapping is risk mapping (e.g., Tran et al., 2009; Ogden et al., 2008). This commonly identifies a single indicator of hazard (e.g. a level of flood expected with a given return period), which can be mapped accurately to define those regions at risk from such an event (e.g. in a flood plain). Combined with information on changing return periods of such events under a changing climate would enable some estimate of altered risk to be determined.

21.3.1.2.3. Experiments

A final approach for gaining insights on potential future impacts, concerns physical experiments designed to simulate future altered environments of climate (e.g. temperature, humidity and moisture), and atmospheric composition (e.g. CO_2, surface ozone and sulphur dioxide concentrations). These are typically conducted to study responses of crop plants, trees and natural vegetation, using open top chambers, greenhouses or free air gas release systems (e.g., Craufurd *et al.*, 2013), or responses of aquatic organisms such as plankton, macrophytes or fish, using experimental water enclosures known as mesocosms (e.g., Sommer et al., 2007; Lassen et al., 2010).

21.3.1.2.4. Scale issues

Impact models operate at a range of spatial and temporal resolutions, and while their outputs are sometimes presented as fine resolution maps, key model findings are rarely produced at the finest resolution of the simulations (i.e. they are commonly aggregated to political or topographic units of interest to the target audience, e.g. watershed, municipality, national or even global). Aggregation of data to coarse-scale units is also essential for allowing comparison of outputs from models operating at different resolutions, but it also means that sometimes quite useful detail may be overlooked when model outputs are presented at the scale of the coarsest common denominator. Conversely, if outputs from impact models are required as inputs to other models, the outputs may need to be harmonized to a finer grid than the original data. In such cases, downscaling methods are commonly applied. This was the case, for example, when providing spatially explicit projections of future land use from different IAMs (Hurtt et al., 2011) for climate modellers to apply in the CMIP5 process (Collins et al., 2014a). It is also a common procedure used in matching climate model outputs to impact models designed to be applied locally (e.g. over a river basin or an urban area – see section 21.3.3.2).

Even if the same metrics are being used to compare aggregate model results (e.g. developed versus developing country income under a given future scenario) estimates may have been obtained using completely different types of models operating at different resolutions. Moreover, many models that have a large-scale coverage (e.g. continental or global) may nonetheless simulate processes at a relatively fine spatial resolution, offering a potentially useful source of spatially explicit information that is unfamiliar to analysts working in specific regions, who may defer to models more commonly applied at the regional scale. Examples include comparison of hydrological models with a global and regional scope (Todd *et al.*, 2011) and bioclimatic models of vascular plant distributions with a European and local scope (Trivedi *et al.*, 2008). Vulnerability mapping exercises can also be undermined by the inappropriate merging of indicator datasets that resolve information to a different level of precision (e.g. Tzanopoulos *et al.*, 2013). There is scope for considerably enhanced cross-scale model intercomparison work in the future, and projects such as AgMIP (Rosenzweig *et al.*, 2013) and ISI-MIP (Schiermeier, 2012, – see section 21.5) have provision for just such exercises.

21.3.2. Adaptation

This section draws on material from the regional chapters (22-30) as well as the examples described in Table 21-4. Material from chapters 14-17 is also considered. See also Table 16.4 for a synthesis from the perspective of adaptation constrains and limits.

21.3.2.1. Similarities and Differences in Regions

As described in the regional chapters, a large portion of adaptation knowledge is based on conclusions drawn from case studies in specific locations, the conceptual findings are typically being applied globally (chapters 14-17).). It is this empirical knowledge on adaptation that guides understandings in the different regions. This is especially the case for developing regions. Thus, regional approaches to adaptation vary in their degree of generality. One of the most striking differences between regions in terms of adaptation is the extent to which it has been studied and implemented. Australia and Europe have invested heavily in research on adaptation since the AR4, and the result is a rich body of literature published by local scientists. The ability to advance in adaptation knowledge may be related to the amount and quality of reliable climate information, the lack of which has been identified as a constraint to developing adaptation measures in Africa (22.4.2). Many case studies, especially of community-based adaptation, stem from Asia, Africa, Central and South America and Small Islands but the majority of this work has been undertaken and authored by international non-governmental organisations, as well as by other non-local researchers. In Africa, most planned adaptation work is considered to be pilot, and seen as part of learning about adaptation, although there has been significant progress since the AR4 (22.4.4.2).

Most regional chapters report lags in policy work on adaptation (see also 16.5.2). While most European countries have adaptation strategies, few have been implemented (23.1.2). Lack of implementation of plans is also the case for Africa (22.4). In North (26.8.4.1.2*)* and Central and South America (27.5.3.2), adaptation plans are in place for some cities. In Australasia, there are few adaptation plans (25.4.2). In the Arctic, they are in their infancy (28.4). At the same time, civil society and local communities have the opportunity to play a role in decision making about adaptation in Europe and Asia (23.7.2, 24.4.6.5). In Africa, social learning and collective action are used to promote adaptation (22.4.5.3). Adaptation is observed as mostly autonomous (spontaneous) in Africa, although socio-ecological changes are creating constraints for autonomous adaptation (22.4.5.4). There is a disconnect in most parts of Africa between policy and planning levels, and the majority of work is still autonomous and unsupported (22.4.1). In the case of UNFCCC-supported activities, such as National Adaptation Programmes of Action, few projects from the African (22.4.4.2) least developed countries have been funded, thus limiting the effectiveness of these investments. Several chapters (Africa, Europe, North America, Central and South America and Small Islands) explicitly point out that climate change is only one of multiple factors that affect societies and ecosystems and drives vulnerability or challenges adaptation (22.4.2, 23.10.1, 26.8.3.1, 27.3.1.2, 29.6.3*)*. For example, North America reports that for water resources, most adaptation actions are ‘no-regrets’, meaning that they have benefits beyond just adaptation to climate change (26.3.4). In Australasia, the limited role of socio-economic information in vulnerability assessments restricts confidence regarding the conclusions about future vulnerability and adaptive capacity (25.3.2).

Some chapters (Polar Regions, North America, Australasia) emphasise the challenges faced by indigenous peoples and communities in dealing with climate change (28.4.1, 26.8.2.2, 25.8.2). Although they are described as having some degree of adaptive capacity to deal with climate variability, shifts in lifestyles combined with a loss of traditional knowledge leave many groups more vulnerable to climate change (28.2.4.2). Also, traditional responses have been found to be maladaptive because they are unable to adjust to the rate of change, or the broader context in which the change is taking place, as seen in the Arctic (28.4.1). In response to changing environmental conditions, people are taking on maladaptive behaviour – for instance, by going further to hunt because of changed fish-stocks and thus exposing themselves to greater risk, or changing to different species and depleting stocks (28.4.1). Limits to traditional approaches for responding to changing conditions have also been observed in several Small Island States (29.8).

Most populated regions have experience with adaptation strategies in agriculture, where exposure to the impacts of climate variability over centuries provides a starting point for making adjustments to new changes in climate. Water and land use management strategies stand out in the literature in common across all of the main continental regions.

The link between adaptation and development is explicit in Africa, where livelihood diversification has been key to reducing vulnerability (22.4.5.2). At the same time, there is evidence that many short-term development initiatives have been responsible for increasing vulnerability (22.4.4.2). Other chapters mention constraints or barriers to adaptation in their regions. For example, the low priority accorded to adaptation in parts of Asia, compared to more pressing issues of employment and education, is attributed in part to a lack of awareness of the potential impacts of climate change and the need to adapt, a feature common to many regions (22.5.4). All developing regions cite insufficient financial resources for implementing adaptation as a significant limitation.

21.3.2.2. Adaptation Examples in Multiple Regions

Across regions, similar responses to climate variability and change can be noted. Heat waves are an interesting example (Table 21-4), as early warning systems are gaining use for helping people reduce exposure to heat waves. At the global scale, the length and frequency of warm spells, including heat waves, has increased since 1950 (*medium confidence*), and over most land areas on a regional scale, more frequent and/or longer heat waves or warm spells are *likely* by 2016-2035 and *very likely* by 2081-2100 (IPCC, 2014d). Warning systems are now planned and implemented in Europe, the US, Canada, Asia and Australia.

Use of mangroves to reduce flood risks and protect coastal areas from storm surges is a measure promoted in Asia, Africa, the Pacific and South America (Table 21-4). Often, mangroves have been cut down to provide coastal access, so there is a need to restore and rehabilitate them. This is an example that is considered low-regrets because it brings multiple benefits to communities besides protecting them from storm surges, such as providing food security and enhancing ecosystem services. Mangrove forests also store carbon, offering synergies with mitigation.

In several African countries, as well as in India, index-based insurance for agriculture has been used to address food insecurity and loss of crops resulting from more hot and fewer cold nights, an increase in heavy precipitation events and longer warm spells (Table 21-4). A predetermined weather threshold typically associated with high loss triggers an insurance pay-out. The mechanism shares risk across communities and can help encourage adaptive responses and foster risk awareness and risk reduction. However, limited availability of accurate weather data mean that establishing which weather conditions causes losses can be challenging. Furthermore, if there are losses but not enough to trigger payout, farmers may lose trust in the mechanism.

21.3.2.3. Adaptation Examples in Single Regions

Although conditions are distinct in each region and location, practical lessons can often be drawn from looking at examples of adaptation in different locations. Experience with similar approaches in different regions offers additional lessons that can be useful when deciding whether an approach is appropriate.

Community-based adaptation is happening and being planned in many developing regions, especially in locations that are particularly poor. In small islands, where a significant increase in the occurrence of future sea-level extremes by 2050 and 2100 is anticipated, traditional technologies and skills may still be relevant for adapting (Table 21-4). In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. These actions provide more than just the immediate benefits; they empower people to feel in control of their situations.

In Europe, several governments have made ambitious efforts to address risks of inland and coastal flooding due to higher precipitation and sea level rise during the coming century (Table 21-4). Efforts include a multitude of options. One of the key ingredients is strong political leadership or government champions. In the Netherlands, government recommendations include ‘soft’ measures preserving land from development to accommodate increased river inundation; raising the level of lakes to ensure continuous freshwater supply; restoring natural estuary and tidal regimes; maintaining coastal protection through beach nourishment; and ensuring necessary political-administrative, legal, and financial resources. The British government has also developed extensive adaptation plans to adjust and improve flood defenses and restrict development in flood risk areas in order to protect London from future storm surges and river flooding. They undertook a multi-stage process, engaging stakeholders and using multi-criteria analysis. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions.

In Australia, farmers and industries are responding to experienced and expected changes in temperature, rainfall, and water availability by relocating parts of their operations, such as for rice, wine, or peanuts, or changing land use completely (Table 21-4). In South Australia, for instance, there has been some switching from grazing to cropping. The response is transformational adaptation, and can have positive or negative implications for communities in both origin and destination regions. This type of adaptation requires a greater level of commitment, access to more resources and greater integration across decision-making levels because it spans regions, livelihoods and economic sectors.

21.3.3. Climate System

This section places the regional chapters in a broader context of regional climate information, particularly regarding cross regional aspects, but does not provide a detailed region-by-region assessment. Boxes 21-2 and 21-4 introduce examples of regional information for continental/sub-continental regions but other regional definitions are often relevant (see Box 21-3). The focus in this section is on the summary of new and emerging knowledge since the AR4 relevant to vulnerability, impacts and adaptation research, with emphasis on material deriving from dynamical and statistical downscaling work which is often of greater relevance for VIA applications than the coarser resolution global climate model data. In a regional context, the AR5 WG1 Chapter 14 (Regional Phenomena) is particularly relevant for the projections and evaluation of confidence in models’ ability to simulate temperature, precipitation and phenomena, together with an assessed implication for the general level of confidence in projections for 2080-2099 of regional temperature and precipitation (See WG1, Ch 14, Table 14.2).

_____ START BOX 21-3 HERE _____

Box 21-3. Developing Regional Climate Information Relevant to Political and Economic Regions

In many world regions, countries form political and/or economic groupings that coordinate activities to further the interests of the constituent nations and their peoples. For example, the Intergovernmental Authority on Development (IGAD) of the countries of the Greater Horn of Africa recognizes that the region is prone to extreme climate events such as droughts and floods that have severe negative impacts on key socio-economic sectors in all its countries. In response it has set up the IGAD Climate Prediction and Applications Centre (ICPAC). ICPAC provides and supports application of early warning and related climate information for the management of climate-related risks (for more details see http://www.icpac.net/). In addition it coordinates the development and dissemination of seasonal climate forecasts for the IGAD countries as part of a WMO-sponsored Regional Climate Outlook Forum process (Ogallo et al., 2008) which perform the same function in many regions. A more recent WMO initiative, the Global Framework for Climate Services (Hewitt et al., 2012), aims to build on these and other global, regional and national activities and institutions to develop climate information services for all nations.

As socio-economic factors are important contributors to both the vulnerability and adaptability of human and natural systems, it clearly makes sense to summarise and assess available climate and climate change information for these regions, as this will be relevant to policy decisions taken within these groupings on their responses to climate change. For example, Figure 22-2 in Chapter 22 illustrates the presentation of observed and projected climate changes of two summary statistics for 5 political/economic regions covering much of Africa. It conveys several important pieces of information: the models are able to reproduce the observed trends in temperature; they simulate significantly lower temperatures without the anthropogenic forcings and significantly higher future temperatures under typical emissions paths; for most regions the models project that future variations in the annual average will be similar to those simulated for the past. However, for a more comprehensive understanding additional information needs to be included on other important aspects of climate, e.g. extremes (see Box 21-4).

_____ END BOX 21-3 HERE _____

21.3.3.1. Global context

21.3.3.1.1. Observed changes

Temperature and precipitation

New estimates of global surface air temperatures give a warming of about 0.89 ºC (0.69 ºC – 1.08 ºC) for the period of 1901-2012 and about 0.72 ºC (0.49 ºC – 0.79 ºC) for the period 1951-2012 (WGI Chapter 2, Section 2.4.3). Positive annual temperature trends are found over most land areas, particularly since 1981. Over the period 1981-2012, relatively large trends have occurred over areas of Europe, the Sahara and middle East, central and northern Asia, north-eastern North America (WGI Chapter 2, Section 2.4.3).

For precipitation, the Northern Hemisphere mid to high latitudes show a *likely* increasing trend (*medium confidence* prior to 1950, *high confidence* afterwards) (WGI Chapter 2, Section 2.5.1). Observed precipitation trends show a high degree of spatial and temporal variability, with both positive and negative values (WGI Chapter 2, Section 2.5). The human influence on warming since the middle of the 20th century is *likely* over every continental region, except Antarctica (WGI Chapter 10, Section 10.3.1), while the attribution of changes in hydrological variables is *less confident* (WGI Chapter 10, Section 10.3.2).

Cryosphere

New data have become available since the AR4 to evaluate changes in the cryosphere (WGI Chapter 4, Section 4.1) showing that the retreat of annual Arctic sea ice extent has continued, at a *very likely* rate of 3.5-4.1% *per* decade during the period 1979-2012. The perennial sea ice extent (sea ice area at summer minimum) decreased at a rate of 11.5 ± 2.1% *per* decade (*very likely*) over the same period 1979-2012 (WGI Chapter 4, Section 4.2.2). The thickness, concentration and volume of arctic ice have also decreased. Conversely, the total annual extent of Antarctic ice has increased slightly (*very likely* 1.2-1.8% *per* decade between 1979 and 2011), with strong regional differences (WGI Chapter 4, Section 4.2.3).

Almost all glaciers worldwide have continued to shrink since the AR4, with varying rates across regions (WG1 Chapter 4, Sections 4.3.1, 4.3.3). In particular, during the last decade most ice loss has been observed from glaciers in Alaska, the Canadian Arctic, the Southern Andes, the Asian mountains and the periphery of the Greenland Ice Sheet. Several hundred glaciers globally have completely disappeared in the last 30 years (WG1 Chapter 4, 4.3.3).

Because of better techniques and more data, confidence has increased in the measurements of Greenland and Antarctica ice sheets. These indicate that parts of the Antarctic and Greenland ice sheets have been losing mass over the last two decades (*high confidence)*, mostly due to changes in ice flow in Antarctica, and a mix of changes in ice flow and increases in snow/ice melt in Greenland. Ice shelves in the Antarctic Peninsula are continuing a long-term trend of thinning and partial collapse started some decades ago (WGI Chapter 4, Sections 4.4.2, 4.4.3, 4.4.5).

21.3.3.1.2. Near-term and long-term climate projections

The uncertainty in near term CMIP5 projections is dominated by internal variability of the climate system (see Glossary entry on Climate Variability), initial ocean conditions and inter-model response, particularly at smaller spatial and temporal scales (Hawkins and Sutton 2009, 2011). In the medium and long term, emission profiles may affect the climate response. Global warming of 0.3-0.7ºC is *likely* for the period of 2016-2035 compared to 1986-2005 based on the CMIP5 multi model ensemble, and spatial patterns of near term warming are generally consistent with the AR4 (WGI Chapter 11, Section 11.3.6). For precipitation (2016-2035 vs. 1986-2005), zonal mean precipitation will *very likely* increase in high and some of the mid-latitudes, and will *more likely than not* decrease in the subtropics (WGI Chapter 11, Section 11.3.2). Results from multi-decadal near term prediction experiments (up to 2035) with initialized ocean state show that there is some evidence of predictability of yearly to decadal temperature averages both globally and for some geographical regions (WGI Chapter 11, Section 11.2.3).

Moving to long term projections (up to 2100), analyses of the CMIP5 ensemble have shown that, in general, the mean temperature and precipitation regional change patterns are similar to those found for CMIP3, with a pattern correlation between CMIP5 and CMIP3 ensemble mean late 21st century change greater than 0.9 for temperature and greater than 0.8 for precipitation (WGI Chapter 12, Section 12.4). Given the increased comprehensiveness and higher resolution of the CMIP5 models this adds an element of robustness to the projected regional change patterns.

Some of the main characteristics of the projected late 21st century regional temperature and precipitation changes derived from the CMIP5 ensemble can be broadly summarized as follows (from WGI Chapter 12 and the WGI Atlas) with further details provided in Box 21-2 and accompanying supplementary material.

Temperature

Regions that exhibit relatively high projected temperature changes (often greater than the global mean by 50% or more) are high latitude Northern Hemisphere land areas and the Arctic, especially in December-January-February, and Central North America, portions of the Amazon, the Mediterranean, and Central Asia in June-July-August (Figure 21-4).

[INSERT FIGURE 21-4 HERE
Figure 21-4: CMIP5 ensemble median ratio of local:global average temperature change in the period 2071-2100 relative to 1961-90 under the RCP8.5 emissions/concentrations scenario. The values are displayed on a common 2.5ºx3.75º grid onto which each models' data were regridded and they were calculated as follows: 1) for each model the local change was calculated between 1961 and 1990 at each grid cell, and is divided by the global average change in that model projection over the same period; 2) the median ratio value across all models at each grid cell is identified and shown. Data used are from the 35 CMIP5 models for which monthly projections were available under RCP8.5 which are listed in supplementary Table 21-3. Overplotted polygons indicate the SREX regions (IPCC, 2012) used to define the sub-regions used to summarise information in Chapters 21 and some of the subsequent regional chapters.]

Precipitation

Changes in precipitation are regionally highly variable, with different areas projected to experience positive or negative changes (Box 21-2). By the end of the century in the RCP8.5 scenario, the high latitudes will *very likely* experience greater amounts of precipitation, some mid-latitude arid and semi-arid regions will *likely* experience drying, while some moist mid-latitude regions will *likely* experience increased precipitation (WG1 Chapter 12, Section 12.4.5).

Studies have also attempted to obtain regional information based on pattern scaling techniques in which regional temperature and precipitation changes are derived as a function of global temperature change (e.g. Giorgi 2008; Watterson 2008; Watterson and Whetton 2011; Watterson 2011 Ishizaki et al. 2012, 2013a, 2013b). Figure 21-5 from Harris et al. (2013) provides an example of Probability Density Functions (PDFs) of temperature and precipitation change over sub-continental scale regions obtained using a Bayesian method complemented by pattern scaling and performance-based model weighting.

[INSERT FIGURE 21-5 HERE
Figure 21-5: Evolution of the 5%, 17%, 33%, 50%, 66%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (upper panel) and annual precipitation (lower panel) for the Giorgi-Francisco (2000) regions and the globe with the SRES A1B forcing scenario combining results from a perturbed physics ensemble and the CMIP3 ensemble. Twenty year means relative to the 1961-1990 baseline are plotted in decadal steps using a common y-axis scale. The 5%, 50% and 95% percentile values for the period 2080-2099 are displayed for each region. (From Harris et al. 2012).]

21.3.3.2. Dynamically and Statistically Downscaled Climate Projections

Dynamical and statistical downscaling techniques have been increasingly applied to produce regional climate change projections, often as part of multi-model intercomparison projects (Görgen et al, 2010). A large number of RCM-based climate projections for the European region were produced as part of the European projects PRUDENCE (Christensen et al. 2007; Deque et al. 2007) and ENSEMBLES (Hewitt 2005; Deque and Somot 2010). High resolution projections (grid interval of ~12 km) were also produced as part of Euro-CORDEX (Jacob et al 2013). All these studies provide a generally consistent picture of seasonally and latitudinally varying patterns of change, which Giorgi and Coppola (2007) summarized with the term “European Climate Change Oscillation (ECO)”. The ECO consists of a dipole pattern of precipitation change, with decreased precipitation to the south (Mediterranean) and increased to the north (Northern Europe) following a latitudinal/seasonal oscillation. As a result, the Mediterranean region is projected to be much drier and hotter than today in the warm seasons (Giorgi and Lionello 2008), and central/northern Europe much warmer and wetter in the cold seasons (Kjellstrom and Ruosteenoja, 2007). An increase of interannual variability of precipitation and summer temperature is also projected throughout Europe, with a decrease in winter temperature variability over Northern Europe (Schar et al. 2004; Giorgi and Coppola 2007; Lenderink et al. 2007). This leads to broader seasonal anomaly distributions and a higher frequency and intensity of extreme hot and dry summers (e.g. Schar et al. 2004; Seneviratne et al. 2006; Beniston et al. 2007; Coppola and Giorgi 2010), for which a substantial contribution is given by land-atmosphere feedbacks (Seneviratne et al. 2006; Fischer et al. 2007; Seneviratne et al. 2010; Hirschi et al. 2011; Jaeger and Seneviratne 2011). The broad patterns of change in regional model simulations generally follow those of the driving global models (Christensen and Christensen 2007; Deque et al. 2007; Zanis et al. 2009), however fine scale differences related to local topographical, land use and coastline features are produced (e.g. Gao et al. 2006; Coppola and Giorgi 2010; Tolika et al. 2012).

As part of the ENSEMBLES and AMMA projects, multiple RCMs were run for the period 1990-2050 (A1B scenario) over domains encompassing the West Africa region with lateral boundary conditions from different GCMs. The RCM-simulated West Africa monsoon showed a wide range of response in the projections, even when the models were driven by the same GCMs (Paeth et al. 2011) (Figure 21-6). Although at least some of the response patterns may be within the natural variability, this result suggests that for Africa, and probably more generally the tropical regions, local processes and how they are represented in models play a key factor in determining the precipitation change signal, leading to a relatively high uncertainty (Engelbrecht et al. 2009; Haensler et al. 2011; Mariotti et al. 2011; Diallo et al. 2012). Statistical downscaling techniques have also been applied to the Africa region (Hewitson and Crane 2006; Lumsden et al. 2009; Paeth and Diederich 2010; Goergen et al., 2010; Benestad 2011). In this regard, methodological developments since the AR4 have been limited (see, for example reviews in Brown et al. 2008; Paeth et al. 2011) and activities have focused more on the applications (e.g. Mukheibir 2007; Gerbaux et al. 2009) for regional specific activities in the context of IAV work.

[INSERT FIGURE 21-6 HERE
Figure 21-6: Linear changes (i.e. changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001-2050 period from 10 individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land cover changes (see Paeth et al. 2011 for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 95% level are marked by black dots. From Paeth et al. (2011).]

Several RCM and time-slice high resolution GCM experiments have been conducted or analyzed for the South America continent (Nunez et al. 2009; Menendez et al. 2010; Sorensson et al. 2010; Marengo et al. 2009, 2010; Cabre et al. 2010; Kitoh et al. 2011). Overall, these studies revealed varied patterns of temperature and precipitation change, depending on the global and regional models used, however a consistent change found in many of these studies was an increase in both precipitation intensity and extremes, especially in areas where mean precipitation was projected to also increase. The Central American region has emerged as a prominent climate change hot-spot since the AR4, especially in terms of a consistent decrease of precipitation projected by most models, particularly in June-July (Rauscher et al 2008, 2011). Regional model studies focusing specifically on Central America projections are however still too sparse to provide robust conclusions (e.g. Campbell et al. 2010).

Since the AR4 there has been considerable attention to producing higher resolution climate change projections over North America based on RCMs and high resolution global time slices (e.g. Salathe et al. 2008, 2010; Dominguez et al. 2010; Subin et al. 2011), in particular as part of the North American Regional Climate Change Assessment Program (NARCCAP – Mearns et al. 2009; 2012; 2013). Results indicate variations (and thus uncertainty) in future climate based on the different RCMs, even when driven by the same GCM in certain subdomains (De Elia and Cote 2010; Mearns et al., 2013; Bukovsky et al. 2013). However, in the NARCCAP suite of simulations there were also some important commonalities in the climate changes produced by the RCMs. For example, they produced larger and more consistent decreases in precipitation throughout the Great Plains in summer than did the driving GCMs or the full suite of CMIP3 GCM simulations as well as larger increases in precipitation in the northern part of the domain in winter. In the realm of statistical downscaling and spatial disaggregation, considerable efforts have been devoted to applying different statistical models for the entire US and parts of Canada (e.g., Maurer et al. 2007; Hayhoe et al. 2010; Schoof et al., 2010).

Numerous high resolution RCM projections have been carried out over the East Asia continent. While some of these find increases in monsoon precipitation over South Asia in agreement with the driving GCMs (Kumar et al. 2013) others also produce results that are not in line with those from GCMs. For example, both Ashfaq et al. (2009) and Gao et al. (2011) found in high resolution RCM experiments (20 and 25 km grid spacing, respectively) decreases in monsoon precipitation over areas of India and China in which the driving GCMs projected an increase in monsoon rain. Other high resolution (20 km grid spacing) projections include a series of double nested RCM scenario runs for the Korea peninsula (Im et al. 2007a; 2008a,b; 2010; 2011; Im and Ahn, 2011) indicating a complex fine scale structure of the climate change signal in response to local topographical forcing. Finally, very high resolution simulations were also performed. Using a 5-km mesh non-hydrostatic RCM nested within a 20-km mesh AGCM, Kitoh et al. (2009) and Kanada et al. (2012) projected a significant increase in intense daily precipitation around western Japan during the late Baiu season.

Finally, a range of RCM, variable resolution and statistical downscaling 21st century projections have been conducted over the Australian continent or some of its sub-regions (Nunez and Mc Gregor 2007; Watterson et al.

2008; Song et al. 2008, Timbal et al. 2008; Yin et al. 2010, Grose et al 2012a,b; Bennett et al 2012), showing that a local fine scale modulation of the large scale climate signal occurs in response to topographical and coastal forcings.

21.3.3.3. Projected Changes in Hydroclimatic Regimes, Major Modes of Variability, and Regional Circulations

By modifying the Earth's energy and water budgets, climate change may possibly lead to significant changes in hydroclimatic regimes and major modes of climate variability (Trenberth et al. 2003). For example, Giorgi et al. (2011) defined an index of hydroclimatic intensity (HY-INT) incorporating a combined measure of precipitation intensity and mean dry spell length. Based on an analysis of observations, global and regional climate model simulations, they found that a ubiquitous global and regional increase in HY-INT was a strong hydroclimatic signature in model projections consistent with observations for the late decades of the 20th century. This suggests that global warming may lead to a hydroclimatic regime shift towards more intense and less frequent precipitation events, which would increase the risk of both flood and drought associated with global warming.

ENSO is a regional mode of variability that substantially affects human and natural systems (Mc Phaden et al. 2006). Although model projections indicate that ENSO remains a major mode of tropical variability in the future, there is little evidence to indicate changes forced by GHG warming which are outside the natural modulation of ENSO occurrences (WGI Chapter 14, Sections 14.4, 14.8).

The North Atlantic Oscillation (NAO) is a major mode of variability for the northern Hemisphere mid-latitude climate. Model projections indicate that the NAO phase is *likely* to become slightly more positive (WGI Chapter 14 ES) due to GHG forcing, but the NAO will be dominated by its large natural fluctuations. Model projections indicate that the Southern Annular Mode (SAM), a major mode of variability for the southern hemisphere, is *likely* going to weaken as ozone concentrations recover through the mid-21st century (WGI Chapter 14, Sections 14.5, 14.8).

Regional circulations, such as the monsoon, are expected to change. The global monsoon precipitation, aggregated over all monsoon systems, is *likely* to strengthen in the 21st century with increases in its area and intensity, while the monsoon circulation weakens. Different regional monsoon systems, however, exhibit different responses to GHG forcing in the 21st century (WGI Chapter 14, Section 14.2.1).

21.3.3.4. Projected Changes in Extreme Climate Events

CMIP5 projections confirm results from the CMIP3; a decrease in the frequency of cold days and nights, an increase in the frequency of warm days and nights, an increase in the duration of heat waves and an increase in the frequency and intensity of high precipitation events, both in the near term and far future (IPCC (2012), 3.3.2, 3.4.4; WGI Chapter 12, 12.4.5). Increases in intensity of precipitation (and thus risk of flood) and summer drought occurrence over some mid-continental land areas is a robust signature of global warming, both in observations for recent decades and in model projections (Trenberth 2011; WG1 Chapter 12, 12.4.5). For tropical cyclones there is still little confidence in past trends and near term projections (Seneviratne et al 2012). Globally, tropical cyclone frequency is projected to either not change or decrease and, overall, wind speed and precipitation is *likely* to increase though basin scale specific conclusions are still unclear (Knutson et al. 2010). A summary of observed and projections extremes along with some statistics on CMIP5 projections of changes in daily temperature and precipitation extremes over the main continents and the SREX regions (Figure 21-4) are introduced in Box 21-4 and accompanying supplementary material.

_____ START BOX 21-4 HERE _____

Box 21-4. Synthesis of Projected Changes in Extremes Related to Temperature and Precipitation

The IPCC report, "Managing the risks of extreme events and disasters to advance climate change adaptation" (IPCC 2012), or SREX for short, provides an in depth assessment of observed and projected changes in climate extremes.

Due to the relevance of this material for assessing risks associated with climate change vulnerability and impacts and responses to these risks, summary information is presented here both drawing from and building on the material in the SREX report, including additional analyses of CMIP5 data (only CMIP3 data were used in SREX).

Summaries of SREX findings relevant to three continents Latin America (Cameron et al., 2012), Asia and Africa (available from http://cdkn.org/srex/) have been developed using material from SREX Chapter 3. A synthesis of this material for all SREX regions, along with additional material from WG1 AR5, is presented in Table 21-7. This demonstrates that in many areas of the world there is higher confidence in future changes in extreme events than there is in past trends, often due to a lack of evidence on observed changes.

[INSERT TABLE 21-7 HERE
Table 21-7: An assessment of observed and projected future changes in temperature and precipitation extremes over 26 sub-continental regions as defined in the SREX report (IPCC 2012; see also Figure 21-4 and Table SM21.2). Confidence levels are indicated by colour coding of the symbols. Likelihood terms are given only for high confidence statements and are specified in the text. Observed trends in temperature and precipitation extremes, including dryness, are generally calculated from 1950, using the period 1961-1990 as a baseline (see Box 3-1 of IPCC (2012a)). The future changes are derived from global and regional climate model projections of the climate of 2071-2100 compared with 1961-1990 or 2080-2100 compared with 1980-2000. Table entries are summaries of information in Tables 3-2 and 3-3 of IPCC (2012a) supplemented with or superseded by material from Chapters 2 (section 2.6 and Table 2-13) and 14 (section 14.4) of the IPCC AR5 WG1 report and Table 25-1 of the IPCC WG2 report. The source(s) of information for each entry are indicated by the superscripts a (Table 3-2 of IPCC, 2012a), b (Table 3-3 of IPCC, 2012a), c (Chapter 2 (section 2.6 and Table 2-13) IPCC AR5 WG1 report), d (Chapter 14 (section 14.4) of the IPCC AR5 WG1 report) and e (Table 25-1 of the IPCC WG2 report).]

In the SREX report, the only coordinated global multi-model ensemble information available was from the CMIP3. In order to provide information consistent with the projections assessed elsewhere in WG1 and 2, changes in daily temperature and precipitation projected by the CMIP5 models are presented here for two example indices, the 90th percentiles of the daily maximum temperature and daily precipitation amounts on wet days. Changes in these indices were calculated over 30 year periods (1961-1990 for the baseline and two future periods, 2041-2070 and 2071-2100) and the analysis was focused on the less extreme daily events to reduce problems with the number needed to be sampled to generate robust statistics (Kendon et. al, 2008). Projected changes were calculated for RCPs 4.5 and 8.5 and the results are displayed as a map for a given continental region and also regional averages over the SREX regions within that continent. Two examples are provided, for temperature changes over N America (Figure 21-7) and precipitation changes over Asia (Figure 21-8). A full set can be found in supplementary Figures SM21-8 to SM21-19.

[INSERT FIGURE 21-7 HERE
Figure 21-7: The frequency of 'warm days' (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961-1990) projected for the 2071-2100 period by 26 CMIP5 GCMs for North America. Map: Ensemble median frequency of 'warm days' during 2071-2100 under RCP8.5. Graphs: Box-and-whisker plots indicate the range of regionally-averaged 'hot-day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5 across the 26 CMIP5 models for each SREX sub-regions in North America. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘warm days’ of 10% is represented on the graphs by the dashed line. A full list of CMIP5 models for which data is shown here can be found in supplementary material Table SM21-4.]

[INSERT FIGURE 21-8 HERE
Figure 21-8: The frequency of 'very wet days' (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961-1990 with wet days defined as days with 1mm of precipitation or more) projected for the 2071-2100 period by 26 CMIP5 GCMs for Asia. Map: Ensemble median frequency of 'very wet days' during 2071-2100 under RCP8.5. Graphs: Box-and-whisker plots indicate the range of regionally-averaged 'very wet day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5 across the 26 CMIP5 models for each SREX sub-regions in Asia Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘Very wet days’ of 10% is represented on the graphs by the dashed line. A full

list of CMIP5 models for which data is shown here can be found in supplementary material Table SM21-4. (Note the WMO Expert Team on Climate Change Detection Indices defines “very wet days” threshold as the 95%-ile daily precipitation event.]

_____ END BOX 21-4 HERE _____

21.3.3.5. Projected Changes in Sea Level

Projections of regional sea level changes, both based on the CMIP3 and CMIP5 models, indicate a large regional variability of sea level rise (even more than 100% of the global mean sea level rise) in response to different regional processes (WGI Chapter 13, Section 13.6.5). However, by the end of the 21st century it is *very likely* that over about 95% of the oceans will undergo sea level rise, with about 70% of coastlines experiencing a sea level rise within 20% of the global value and most regions experiencing sea level fall being located near current and former glaciers and ice sheets (WGI Chapter 13, Section 13.6.5). Some preliminary analysis of the CMIP5 ensembles indicates areas of maximum steric sea level rise in the Northern Atlantic, the northwestern Pacific off the East Asia coasts, the eastern coastal oceanic regions of the Bay of Bengal and the western coastal regions of the Arabian Sea (WGI Chapter 13, Section 13.6.5).

21.3.3.6. Projected Changes in Air Quality

Since the AR4 more studies have become available addressing the issue of the effects of both climate and emission changes on air quality. Most of these studies focused on the continental United States and Europe, and utilized both global and regional climate and air quality models run in off-line or coupled mode. Regional modeling studies over the United States or some of its sub-regions include, for example, those of Hogrefe et al. (2004), Knowlton et al. (2004), Steiner et al. (2006), Dawson et al. (2006), Lin et al. (2008), Zhang et al. (2008), Weaver et al. (2009), while examples of global modeling studies include Murazaki and Hess (2006), Stevenson et al. (2006), Shindell et al. (2006), Doherty et al. (2006). Weaver et al. (2009) provide a synthesis of simulated effects of climate change on ozone concentrations in the U.S. using an ensemble of regional and global climate and air quality models, indicating a predominant increase in near-surface ozone concentrations, particularly in the Eastern U.S. (Figure 21-9) mostly tied to higher temperatures and corresponding biogenic emissions. An even greater increase was found in the frequency and intensity of extreme ozone concentration events, which are the most dangerous for human health. Examples of regional studies of air quality changes in response to climate change over Europe include Langner et al. (2005), Forkel and Knocke (2006) , Szopa and Hauglustaine (2007), and Meleux et al. (2007), Kruger et al (2008), Engardt et al. (2009), Carvalho et al. (2010), Andersson and Engardt (2010), Athanassiadou et al. (2010), Katragkou et al. (2010, 2011), Zanis et al. (2011), Huszar et al. (2011), Juda-Rezler et al. (2012). All these studies indicated the potential of large increases in near surface summer ozone concentrations especially in Central and Southern Europe due to much warmer and drier projected summer seasons.

[INSERT FIGURE 21-9 HERE
Figure 21-9 Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2050s minus 1990s) MDA8 summer ozone concentrations across (left-hand panels) all seven experiments (five regional and 2 global) and for comparison purposes (right hand panels), not including the WSU experiment (which simulated July only conditions). The different experiments use different pollutant emission and SRES GHG emission scenarios. The pollutant emissions are the same in the present and future simulations (from Weaver et al., 2009).]

21.4. Cross-Regional Phenomena

Thus far, this chapter has covered climate change-related issues that have a regional expression in one part of the world or another. In principle, these issues can be studied and described, *in situ*, in the regions in which they occur. However, there is a separate class of issues that transcends regional boundaries and demands a different treatment. In order to understand such cross-regional phenomena, knowledge is required of critical but geographically remote associations and of dynamic cross-boundary flows. The following sections consider some examples of these phenomena, focusing on trade and financial flows and migration. Though these issues are treated in more detail in Part A of this report, they are restated here in Part B to stress the importance of a global perspective in appreciating climate change challenges and potential solutions at the regional scale.

21.4.1. Trade and Financial Flows

Global trade and international financial transactions are the motors of modern global economic activity. Their role as key instruments for implementing mitigation and adaptation policies is explored in detail in chapters 14-17 and in the Working Group III report – Stavins et al., 2014; Gupta et al., 2014). They are also inextricably linked to climate change (WTO-UNEP, 2009) through a number of other interrelated pathways that are expanded here: (i) as a direct or indirect cause of anthropogenic emissions (e.g., Peters et al., 2011), (ii) as contributory factors for regional vulnerability to the impacts of climate change (e.g. Leichenko and O'Brien, 2008), and (iii) through their sensitivity to climate trends and extreme climate events (e.g., Nelson et al., 2009a; Headey, 2011).

21.4.1.1. International Trade and Emissions

The contemporary world is highly dependent on trading relationships between countries in the import and export of raw materials, food and fibre commodities and manufactured goods. Bulk transport of these products, whether by air, sea or over land, is now a significant contributor to emissions of greenhouse gases and aerosols (Stavins et al., 2014). Furthermore, the relocation of manufacturing has transferred net emissions via international trade from developed to developing countries (see Figure 21-10), and most developed countries have increased their consumption-based emissions faster than their domestic (territorial) emissions (Peters *et al.*, 2011). This regional transfer of emissions is commonly referred to in climate policy negotiations as "carbon leakage" (Barker *et al.*, 2007), though only a very small portion of this can be attributed to climate policy ("strong carbon leakage"), a substantial majority being due to the effect of non-climate policies on international trade ("weak carbon leakage" – Peters, 2010). A particular example of strong carbon leakage concerns the conversion of land use from the production of food to bioenergy crops. These crops sequester carbon otherwise extracted from the ground as fossil fuels, but in the process displace demand for food production to land in other regions, often inducing land clearance and hence an increase in emissions (Searchinger *et al.*, 2008), though the empirical basis for this latter assertion is disputed (see Kline and Dale, 2008).

[INSERT FIGURE 21-10 HERE
Figure 21-10: Growth rates from 1990-2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macrovariables, all indexed to 1990 (Peters et al., 2011). Annex B and non-Annex B Parties to the UNFCCC are listed in the supplementary material.]

21.4.1.2. Trade and Financial Flows as Factors Influencing Vulnerability

The increasingly international nature of trade and financial flows (commonly referred to as globalisation), while offering potential benefits for economic development and competitiveness in developing countries, also presents high exposure to climate-related risks for some of the populations already most vulnerable to climate change (Leichenko and O'Brien, 2008). Examples of these risks, explored further in Chapters 7-9, 12, 13 and 19 of Part A, include:

- Severe impacts of food price spikes in many developing countries (including food riots and increased incidence of child malnutrition) such as occurred in 2008 following shortfalls in staple cereals, due to a coincidence of regional weather extremes (e.g. drought) in producer countries, the reallocation of food crops by some major exporters for use as biofuels (an outcome of climate policy – see previous section) and market speculation (Ziervogel and Ericksen, 2010). Prices subsequently fell back as the world economy went into recession, but spiked again in early 2011 for many of the same reasons (Trostle *et al.*,

2011), with some commentators predicting a period of rising and volatile prices due to increasing demand and competition from biofuels (Godfray *et al.*, 2010).
- A growing dependence of the rural poor on supplementary income from seasonal urban employment by family members and/or on international financial remittances from migrant workers (Davies *et al.*, 2009). These workers are commonly the first to lose their jobs in times of economic recession, which automatically decreases the resilience of recipient communities in the event of adverse climate conditions.On the other hand, schemes to provide more effective communication with the diaspora in times of severe weather and other extreme events can provide rapid access to resources to aid recovery and reduce vulnerability (Downing, 2012).
- Some aspects of international disaster relief, especially the provision of emergency food aid over protracted periods, has been cited as an impediment to enhancing adaptive capacity to cope with climate-related hazards in many developing countries (Schipper and Pelling, 2006). Here, international intervention, while well-intentioned to relieve short-term stress, may actually be counter-productive in regard to the building of long-term resilience.

21.4.1.3. Sensitivity of International Trade to Climate

Climate trends and extreme climate events can have significant implications for regional resource exploitation and international trade flows. The clearest example of an anticipated, potentially major impact of climate change concerns the opening of Arctic shipping routes as well as exploitation of mineral resources in the exclusive economic zones (EEZs) of Canada, Greenland/Denmark, Norway, Russia and the USA (Figure 21-11, and see chapter 28, section 28.3.4). For instance, the CCSM4 climate and sea ice model has been used to provide projections under RCP4.5, RCP6.0 and RCP8.5 forcing (see Box 21-1) of future accessibility for shipping to the sea ice hazard zone of the Arctic marine environment defined by the International Maritime Organization (Stephenson et al., 2013 – Figure 21-11 (central map). Results suggest that moderately ice-strengthened ships (Polar Class 6), which are estimated under baseline (1980-1999) conditions to be able to access annually about 36 % of the IMO zone, would increase this access to 45-48 % by 2011-2030, 58-69% by 2046-2065 and 68-93% by 2080-2099, with almost complete accessibility projected for summer (90-98% in July-October) by the end of the century (Stephenson *et al.*, 2013). The robustness of those findings was confirmed using seven sea ice models in an analysis of optimal sea routes in peak season (September) for 2050-2069 under RCP 4.5 and RCP8.5 forcing (Smith and Stephenson, 2013). All studies imply increased access to the three major cross Arctic routes: the Northwest Passage, Northern Sea Route (which is part of the Northeast Passage), and Trans-Polar Route (Figure 21-11), which could represent significant distance savings for trans-continental shipping currently using routes via the Panama and Suez Canals (Stephenson *et al.*, 2011). Indeed, in 2009 two ice-hardened cargo vessels – the Beluga Fraternity and Beluga Foresight – became the first to successfully traverse the Northeast Passage from South Korea to the Netherlands, a reduction of 5,500 km and 10 days compared to their traditional 20,000 km route via the Suez Canal, translating into an estimated saving of some $300,000 per ship, including the cost of standby icebreaker assistance (Smith, 2009; Det Norsk Veritas, 2010). A projection using an earlier version of the CCSM sea ice model under the SRES A1B scenario, but offering similar results (with forcing by mid-century lying just below RCP8.5 – chapter 1, Figure 1-5a), is presented in Figure 21-11 (peripheral maps), which also portrays winter transportation routes on frozen ground. These routes are heavily relied upon for supplying remote communities and for activities such as forestry and, in contrast to the shipping routes, are projected to decline in many regions.

[INSERT FIGURE 21-11 HERE
Figure 21-11: Central map: Marine exclusive environmental zones (EEZs – dashed lines) of Canada, Greenland/Denmark, Norway, Russia, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the IMO Guidelines Boundary for Arctic shipping (thick black border). After Stephenson et al. (2013). Peripheral monthly maps: Projected change in accessibility of maritime and land-based transportation by mid-century (2045-2059 relative to 2000-2014) using the Arctic Transport Accessibility Model and CCSM3 climate and sea ice estimates assuming an SRES A1B scenario. Dark blue areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).]

A second illustration of how the risk of adverse climate changes may have contributed to anticipatory adaptive actions affecting countries in other regions of the world and potentially influencing commodity markets, relates to the purchase or renting of large tracts of productive land in parts of Africa, Latin America, Central Asia and Southeast Asia by countries in Europe, Africa, the Gulf and South and East Asia (De Schutter, 2009; Cotula *et al.*, 2011; Zoomers, 2011). While there is clearly a profit motive in many of these purchases (i.e., cheap and fertile land and the opportunity to cultivate high value food or biofuel crops), there is also a concern that domestic agricultural production in some countries will be unable to keep pace with rapid growth in domestic demand and changing dietary preferences, especially in agricultural regions affected by frequent shortfalls due to droughts, floods and cyclones (Cotula *et al.*, 2011), or threatened by sea-level rise (Zoomers, 2011). Land acquisition on such a large scale raises a number of ethical issues relating to local access to food and the appropriate and sustainable management of the land (Deininger and Byerlee, 2012). These issues have led the UN Special Rapporteur on the right to food to recommend a list of eleven principles for ensuring informed participation of local communities, adequate benefit sharing and the respect of human rights (De Schutter, 2009). This issue is elaborated with respect to livelihoods and poverty in chapter 13, section 13.4.3.4, and land dispossession is categorised a key risk in chapter 19, section 19.6.2.

Extreme climate phenomena that may be harbingers of similar and more frequent events in a warmer world, already exact devastating consequences in some regions that extend well beyond country boundaries. A recent event that disrupted international trade and commodity flows was the severe 2010/2011 flooding in eastern Australia (Giles, 2011; Queensland Floods Commission of Inquiry, 2012; and see chapter 25, Box 25-8), which combined with damaging cyclones in Queensland and Western Australia curtailed numerous mining operations and damaged transportation networks, leading to declines in both thermal and metallurgical coal exports (by 31% and 19%, respectively, relative to the previous quarter – ABARES, 2011) with a sharp rise in their monthly price between November 2010 and January 2011 (Index Mundi, 2012). The severe weather was the primary factor contributing to a fall in Australian GDP of 1.2% during January-March 2011 compared with a rise of 0.7% in the preceding three-month period (Australian Bureau of Statistics, 2011). Other examples of how extreme climate events can affect international trade are reported by Oh and Reuveny (2010) and Handmer et al. (2012).

21.4.2. Human Migration

There has been considerable debate in recent years around the postulate that anthropogenic climate change and environmental degradation could lead to mass migration (Perch-Nielsen *et al.*, 2008; Feng *et al.*, 2010; Warner, 2010; Black *et al.*, 2011; Government Office for Science, 2011; Assan and Rosenfeld, 2012). The issue is treated at length in Chapters 9, 12 and 19 of Part A, so only a few aspects are touched on here, to highlight the growing significance of migration in all regions of the world. Four possible pathways through which climate change could affect migration are suggested by Martin (2009):

1) Intensification of natural disasters
2) Increased warming and drought that affects agricultural production and access to clean water
3) Sea-level rise, which makes coastal areas and some island states increasingly uninhabitable
4) Competition over natural resources, leading to conflict and displacement of inhabitants.

Abundant historical evidence exists to suggest that changes in climatic conditions have been a contributory factor in migration, including large population displacements in the wake of severe events such as Hurricane Katrina in New Orleans, Louisiana in 2005 (Cutter *et al.*, 2012), Hurricane Mitch in Central America in 1998 and the northern Ethiopian famines of the 1980s (McLeman and Smit, 2006). Other examples are provided in Chapter 12, Table 12-3. However, the evidence is not clear cut (Black, 2001), with counter examples also available of migration being limited due to economic hardship (e.g. during the Sahel drought of the mid-1980s in Mali – Findley, 1994).

The spatial dimension of climate-related migration is most commonly internal to nations (e.g. from affected regions to safer zones – Naik, 2009). In this context it is also worth pointing out that internal migration for other (predominantly economic) reasons may actually expose populations to increased climate risk. For instance, there are large cities in developing countries in low elevation coastal zones that are vulnerable to sea-level rise. Increased migration to these cities could exacerbate the problems with the migrants themselves being especially vulnerable (Nordås and Gleditsch, 2007; UNFPA, 2007).

Migration can also be international, though this is less common in response to extreme weather events, and where it does happen it usually occurs along well established routes. For example, emigration following Hurricane Mitch tripled from Honduras and increased from Nicaragua by 40%, mainly to the southern States of the US (already a traditional destination for migrants), and was aided by a relaxation of temporary residency requirements by the United States (Naik, 2009).

The causal chains and links between climate change and migration are complex and can be difficult to demonstrate (e.g., Perch-Nielsen et al., 2008; Piguet, 2010; Tänzler et al., 2010; ADB, 2012; Oliver-Smith, 2012; Chapter 12, section 12.4; Chapter 9, section 9.3.3.3.1; Chapter 19, section 19.4.2.1), though useful insights can be gained from studying past abandonment of settlements (McLeman, 2011). Thus projecting future climate-related migration remains a challenging research topic (Feng et al., 2010). There are also psychological, symbolic, cultural and emotional aspects to place attachment, which are well documented from other non-climate causes of forced migration, and are also applicable to cases of managed coastal retreat due to sea-level rise (e.g., Agyeman *et al.*, 2009).

Forced migration appears to be an emerging issue requiring more scrutiny by governments in organising development co-operation, and to be factored into international policy making as well as international refugee policies. For example, it has been suggested that the National Adaptation Plans of Action (NAPAs) under the UNFCCC, by ignoring transboundary issues (such as water scarcity), and propounding nationally-orientated adaptation actions (e.g. upstream river management, to the detriment of downstream users in neighbouring countries), could potentially be a trigger for conflict, with its inevitable human consequences. Currently there is no category in the United Nations High Commission for Refugees classification system for environmental refugees, but it is possible that this group of refugees will increase in the future and their needs and rights will need to be taken into consideration (Brown, 2008). The Nansen Initiative, put forward jointly by Norway and Switzerland at a 2011 ministerial meeting, pledges "to cooperate with interested states and relevant actors, including UNHCR, to obtain a better understanding of cross-border movements provoked by new factors such as climate change, identify best practices and develop a consensus on how best to protect and assist those affected ", and may eventually result in a soft law or policy framework (Kolmannskog, 2012). However, migration should not always be regarded as a problem; in those circumstances where it contributes to adaptation (e.g. through remittances) it can be part of the solution (Laczko and Aghazarm, 2009).

21.4.3. Migration of Natural Ecosystems

One of the more obvious consequences of climate change is the displacement of biogeographical zones and the natural migration of species (see Chapters 4, 6 and 19). General warming of the climate can be expected to result in migration of ecosystems towards higher latitudes and upward into higher elevations (Chapter 4, section 4.3.2.5) or downward to cooler depths in marine environments (Chapter 6, section 6.3.2.1). Species shifts are already occurring in response to recent climate changes in many parts of the world (Rosenzweig et al., 2008), with average poleward shifts in species' range boundaries of 6 km per decade being reported (Parmesan et al., 2011).

Study of the estimated shifts of climatic zones alone can provide insights into the types of climatic regimes to anticipate under projected future anthropogenic climate change. By grouping different combinations and levels of climatic variables it is possible not only to track the shifts in the zones in which they occur, but also to identify newly emerging combinations of conditions not found at the present day as well as combinations that may not survive global climate change (known respectively as novel and disappearing climates – Williams *et al.*, 2007; and see Chapter 19, section 19.5.1). These analyses can help define what types of climatic niches may be available in the future and where they will be located. Such a spatial analogue approach can delimit those regions that might currently or potentially (in the future) be susceptible to invasion by undesirable aquatic (e.g., EPA, 2008) or terrestrial (e.g., Mainka and Howard, 2010) alien species or alternatively might be candidates for targetting translocation (assisted colonisation) of species endangered in their native habitats (e.g., Brooker et al., 2011;

Thomas, 2011). However, there are many questions about the viability of such actions, including genetic implications (e.g., Weeks et al., 2011), inadvertent transport of pests or pathogens with the introduced stock (e.g., Brooker et al., 2011) and risk of invasiveness (e.g., Mueller and Hellmann, 2008).

The ability of species to migrate with climate change must next be judged, in the first instance, against the rate at which the climatic zones shift over space (e.g. Loarie et al., 2009; Burrows et al., 2011; Diffenbaugh and Field, 2013; Chapter 4, section 4.3.2.5). For projecting potential future species shifts, this is the most straightforward part of the calculation. In contrast, the ecological capacity of species to migrate is a highly complex function of factors, including their ability to:

- Reproduce, propagate or disperse
- Compete for resources
- Adapt to different soils, terrain, water quality and daylength
- Overcome physical barriers (e.g. mountains, water/land obstacles)
- Contend with obstacles imposed by human activity (e.g. land use, pollution or dams).

Conservation policy under a changing climate is largely a matter of promoting the natural adaptation of ecosystems, if this is even feasible for many species given the rapidity of projected climate change. Studies stress the risks of potential mismatching in responses of co-dependent species to climate change (e.g., Schweiger *et al.*, 2012) as well as the importance of maintaining species diversity as insurance for the provision of basic ecosystem services (e.g., Traill et al., 2010; Isbell et al., 2011). Four priorities have been identified for conservation stakeholders to apply to climate change planning and adaptation (Heller and Zavaleta, 2009): (i) regional institutional coordination for reserve planning and management and to improve landscape connectivity; (ii) a broadening of spatial and temporal perspectives in management activities and practice, and actions to enhance system resilience; (iii) mainstreaming of climate change into all conservation planning and actions; and (iv) holistic treatment of multiple threats and global change drivers, also accounting for human communities and cultures. The regional aspects of conservation planning transcend political boundaries, again arguing for a regional (rather than exclusively national) approach to adaptation policy. This issue is elaborated in Chapters 4 (section 4.4.2) and 19 (section 19.4.2.3).

21.5. Analysis and Reliability of Approaches to Regional Impacts, Adaptation, and Vulnerability Studies

Assessing climate vulnerability or options for adapting to climate impacts in human and natural systems requires an understanding of all factors influencing the system and how change may be effected within the system or applied to one or more of the external influencing factors. This will require, in general, a wide range of climate and non-climate information and methods to apply this to enhance the adaptive capacity of the system. There are both areas of commonality across and differences between regions in the information and methods and these are explored in this section. It initially focuses on advances in methods to study vulnerability and adaptive capacity and to assess impacts (studies of practical adaptation and the processes of adaptation decision-making are treated in detail in Chapters 14-17 and so not addressed here). This is followed by assessments of new information on, and thinking related to: (a) baseline and recent trends in factors needed to assess vulnerability and define impacts baselines; and (b) future scenarios used to assess impacts, changes in vulnerability and adaptive capacity; and then assessment of the credibility of the various types of information presented.

21.5.1. Analyses of Vulnerability and Adaptive Capacity

Multiple approaches exist for assessing vulnerability and for exploring adaptive capacity (Schipper et al 2010, UNFCCC 2008). The choice of method is influenced by objectives and starting point (see Table 21-3) as well as the type of information available. Qualitative assessments usually draw on different methods and inputs from quantitative assessments. Qualitative information cannot always be translated to quantitative information, or *vice versa*, yet both approaches can sometimes be used to answer the same questions. Indicators, indices and mapping are the most common ways to aggregate the resulting vulnerability and adaptive capacity information to compare across regions (section 21.5.1.1) or to identify "hotspots" (section 21.5.1.2). .

21.5.1.1. Indicators and Indices

Several attempts have been made to develop vulnerability indicators and indices (Birkmann 2011; Chen et al. 2011; Barr et al 2010; Cardona, 2007; Luers et al 2003; Lawrence *et al.*, 2003, Villa and McLeod, 2002, Downing *et al.* 2001, Atkins *et al.*, 2000; Moss *et al.* 2001). Representation on a map or through an index is a common way to depict global vulnerability information and requires quantification of selected variables in order to measure them against a selected baseline, even though quantification of some qualitative information may not be possible (Hinkel, 2011; Edwards et al, 2007; Luers et al 2003). Vulnerability is differentiated according to factors such as gender, age, livelihood or access to social networks, among many other factors (Cardona et al 2012; Wisner et al 2005), which may not be represented accurately through some indicators. One approach used to create regional comparisons is to use indices, which are composites of several indicators thought to contribute to vulnerability, each normalised and sometimes weighted so they can be combined (Rygel et al 2006, Adger et al 2004). The approach has been critiqued extensively because the weights assigned the indicators depends on expert opinion which can result in different regions appearing more or less vulnerable, as Füssel (2010) found in reviewing global vulnerability maps based on different indices.

Vulnerability indices developed to date have failed to reflect the dynamic nature of component indicator variables. This is illustrated by the (in)ability to characterise how the selected indicators contribute to determining vulnerability over time. Importantly, the relative importance of the indicator may change from season-to-season (e.g. access to irrigation water) or may gradually or rapidly become obsolete. Hinkel's (2011) review of literature on vulnerability indicators suggests that vulnerability has been confused as a proxy for unsustainable or insufficient development so that simple measurements are seen as sufficient to tell a story about vulnerability. Hinkel (2011) suggests that the simplification of information to create vulnerability indicators is what limits their utility.

Indicator systems have also been developed to improve understanding of adaptive capacity. These are used both to measure adaptive capacity and identify entry points for enhancing it (Adaptation Sub-Committee, 2011; Lioubimtseva and Henebry, 2009; Swanson et al., 2007; Adger and Vincent, 2005; Eriksen and Kelly, 2007). For example, the Global Adaptation Index, developed by the Global Adaptation Alliance (GAIN, n.d.) uses a national approach to assess vulnerability to climate change and other global challenges and compare this with a country's "Readiness to improve resilience" (GAIN, n.d.) to assist public and private sectors to prioritise financial investments in adaptation activities.

21.5.1.2. Hotspots

A special case of the use of indicators concerns the identification of hotspots, a term original used in the context of biodiversity, where a "biodiversity hotspot" is a biologically diverse region typically under threat from human activity, climate change or other drivers (Myers, 1988). The term typically relates to a geographical location, which emerges as a concern when multiple layers of information are compiled to define it. In climate change analysis, hotspots are used to indicate locations that stand out in terms of impacts, vulnerability or adaptive capacity (or all three). Examples of hotspot mapping include how climate change can influence disease risk (de Wet et al., 2001), extinctions of endemic species (Malcolm et al., 2006), and disaster risk (Dilley, 2006). Hotspots analysis is used to serve various purposes, such as setting priorities for policy action, identifying focal regions for further research (de Sherbinin, 2013; Dilley, 2006, Ericksen et al., 2011, see www.climatehotmap.org), or, increasingly, helping distinguish priority locations for funding. Examples of the latter purpose include guiding the allocation of global resources to pre-empt, or combat, disease emergence (Jones et al 2008) or funding for disaster risk management (Arnold et al 2005). Because identifying hotspots raises important methodological issues about the limitation of using indicators to integrate quantitative impacts with qualitative dimensions of vulnerability, their use to compare regions leads to a subjective ranking of locations as having priority for climate change investment. This can be controversial and considered politically-motivated (Klein 2009).

Certain locations are considered hotspots because of their regional or global importance. These can be defined by population size and growth rate, contributions to regional or global economies, productive significance (e.g., food production) as well as by disaster frequency and magnitude, and projected climate change impacts. The choice of variables may result in different locations being identified as hotspots (Füssel, 2009). For example, the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change Agriculture and Food Security (CCAFS) mapped hotspots of food insecurity and climate change in the tropics (Ericksen et al, 2011) using stunted growth as a proxy for food security, but other variables could also have been selected. Scale matters in representing hotspots and they will look different on a global scale than on a finer scale (Arnold et al., 2006).

The rationale for identifying such hotspots is that they may gradually evolve into locations of conflict or disaster, where a combination of factors lead to the degradation of resources and social fabric. Climate change hotspots have been defined as locations where impacts of climate change are "well pronounced and well documented" (UCS 2011). A climate change hotspot can describe (a) a region for which potential climate change impacts on the environment or different activity sectors can be particularly pronounced or (b) a region whose climate is especially responsive to global change (Giorgi 2006). An example of the former is given by Fraser et al (2013), combining hydrological modelling with quantitatively modelled adaptive capacity (defined as the inverse of sensitivity to drought) to identify vulnerability hotspots for wheat and maize. Examples of the latter are given by Giorgi (2006), Diffenbaugh et al. (2008), Giorgi and Bi (2009), Xu et al. (2009), Diffenbaugh and Scherer (2011) and Diffenbaugh and Giorgi (2012) who used different regional climate change indices, including changes in mean and interannual variability of temperature and precipitation and metrics of seasonal extremes, to identify the Mediterranean Basin, Central America, Central and West Africa, the Northern high latitude regions, the Amazon, the southwestern United States, Southeast Asia and the Tibetan Plateau as prominent hot-spots.

21.5.2. Impacts Analyses

In recent years, there has been increased scrutiny of the methods and tools applied in impact assessment, especially quantitative models that are used to project the biophysical and socio-economic impacts of future climate change (see chapter 2, 2.3.2.1), but also encompassing qualitative methods, including studies of indigenous knowledge (Galloway McLean, 2010, and see chapter 12, 12.3.3). In an advance from previous assessments, different types of impact models are now being applied for the first time in many regions of the world. This is largely due to burgeoning international development support for climate change vulnerability and adaptation studies (Fankhauser, 2010). It is also related to a surge of interest in regional economic assessments in the wake of the Stern review (Stern, 2007) as well as to the evolution of climate models into Earth system models that incorporate a more realistic representation of land surface processes (Flato et al., 2014) and their increased application to study hydrological (chapter 3, 3.4.1), ecophysiological (chapter 4, 4.3.3) and cryospheric (Vaughan et al., 2014) impacts.

Potential impacts have been simulated for single as well as multiple sectors, at spatial scales ranging from site or household to global, and over a range of temporal scales and time horizons (Table 21-5). A majority of impact studies still follow the conventional approach where future impacts are modelled based on a set of assumptions (scenarios) about future climate and socioeconomic conditions (see 21.2.3, left hand side of Table 21-3),. However, an increasing number are being undertaken that follow a "socio-institutional" approach to adaptation planning (Downing, 2012), right hand side of Table 21-3, which emphasises the importance of adaptive flexibility and climate resilience given the often intractable, "deep" uncertainties implicit in many projections of future change (e.g., Donley *et al.*, 2012; Garrett *et al.*, 2013; Gersonius *et al.*, 2013).

Impact modelling studies also commonly treat aspects of adaptation, either explicitly as modelled options or implicitly as built-in autonomous responses (Dickinson, 2007; White *et al.*, 2011). Furthermore, as an anthropogenic signature is attributed to ongoing climate changes in many regions (Bindoff et al., 2014), and with growing evidence that these changes are having impacts on natural and human systems in many more regions than reported in the AR4 (chapter 18, Rosenzweig and Neofotis, 2013), it is now possible in some regions and sectors to test impact models' projections against observed impacts of recent climate change (e.g. Araújo *et al.*, 2005; Barnett *et al.*, 2008; Lobell *et al.*, 2011). This is also an essential element in the attribution of observed impacts (Chapter 18, 18.3, 18.4, 18.5).

Uncertainties in and Reliability of Impacts Analyses

Literature on uncertainty in impacts analyses has focused mainly on the uncertainties in impacts that result from the uncertainties in future climate (Mearns et al., 2001; Carter et al., 2007), and this literature continues to grow since AR4, particularly in the realm of agriculture and water resources (e.g., Wetterhall et al., 20011; Ferrise et al., 2011; Ficklin et al., 2012; Littell et al., 2011, Osborne et al., 2013), but also in other areas such as flood risk (Ward et al., 2013). Furthermore, research has advanced to establish which future climate uncertainties are most important to the resultant uncertainties about crop yields (e.g., Lobell and Burke, 2008) and to apply future resource uncertainties to adaptation studies (Howden et al., 2007). Use of multiple global or regional model scenarios is now found in many more studies (e.g. Gosling et al., 2011; Bae et al., 2011; Arnell, 2011; Olsson et al., 2011) and the use of probabilistic quantification of climate uncertainties has produced estimates of probabilities of changes in future resources such as agriculture and water (e.g., Watterson and Whetton, 2011; Tebaldi and Lobell, 2008). Some studies have developed probability distributions of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009). Nobrega et al. (2011) apply 6 different GCMs and 4 different SRES emissions scenarios to study the impacts of climate change on water resources in the Rio Grande Basin in Brazil and found that choice of GCM was the major source of uncertainty in terms of river discharge.

With an ever-increasing number of impacts' projections appearing in the literature and the unprecedented rate and magnitude of climate change projected for many regions, some authors have begun to question both the robustness of the impacts models being applied (e.g., Heikkinen *et al.*, 2006; Fitzpatrick and Hargrove, 2009; Watkiss, 2011a) as well as the methods used to represent key uncertainties in impacts' projections (e.g., Arnell, 2011; Rötter *et al.*, 2011; White *et al.*, 2011). This is being addressed through several prominent international research efforts, Agricultural Model Intercomparison and Improvement Project, involving crop and economic models at different scales (AgMIP – Rosenzweig *et al.*, 2013), the Carbon Cycle Model Intercomparison Project (C^4MIP – Friedlingstein *et al.*, 2006; Sitch *et al.*, 2008; Arora *et al.*, 2013) and the Water Model Intercomparison Project (WaterMIP – Haddeland *et al.*, 2011). Modelling groups from these projects are also participating in the Inter-Sectoral Impact Model Intercomparison Project, initially focusing on intercomparing global impact models for agriculture, ecosystems, water resources, health and coasts under RCP- and SSP-based scenarios (see Box 21-1) with regional models being considered in a second phase of work (ISI-MIP – Schiermeier, 2012). AgMIP results for 27wheat models run at contrasting sites worldwide indicate that projections of yield to the mid-21st century are more sensitive to crop model differences than to global climate model scenario differences (Asseng et al., 2013; Carter, 2013). WaterMIP's analysis of runoff and evapotranspiration from five global hydrologic and six land surface models indicate substantial differences in the models' estimates in these key parameters (Haddelenad et al., 2011). Finally, as in climate modelling, researchers are now applying multiple impact model and perturbed parameter ensemble approaches to future projections (e.g., Araújo and New, 2007; Jiang *et al.*, 2007; Palosuo *et al.*, 2011), usually in combination with ensemble climate projections treated discretely (e.g., New *et al.*, 2007; Graux *et al.*, 2013; Tao and Zhang, 2013) or probabilistically (e.g., Luo *et al.*, 2007; Fronzek *et al.*, 2009, 2011; Børgesen and Olesen, 2011; Ferrise *et al.*, 2011; Wetterhall *et al.*, 2011).

These new impact MIPs, and similar initiatives, have the common purpose of mobilising the research community to address some long-recognised but pervasive problems encountered in impact modelling. A sample of recent papers illustrate the variety of issues being highlighted, e.g. forest model typology and comparison (Medlyn *et al.*, 2011), crop pest and disease modelling and evaluation (Sutherst *et al.*, 2011; Garrett *et al.*, 2013), modelling responses to extreme weather events (Lobell *et al.*, 2010; Asseng *et al.*, 2013), field experimentation for model calibration and testing (Long *et al.*, 2006; Craufurd *et al.*, 2013) and data quality considerations for model input and calibration (Lobell, 2013). Greater attention is also being paid to methods of economic evaluation of the costs of impacts and adaptation at scales ranging from global (e.g., UNFCCC, 2007; Nelson *et al.*, 2009b; Parry *et al.*, 2009; Fankhauser, 2010; Füssel, 2010; Patt *et al.*, 2010), through regional (e.g., EEA, 2007; World Bank, 2010; Ciscar *et al.*, 2011; Watkiss, 2011b), to national (SEI, 2009; GCAP, 2011) and local level (e.g., Perrels *et al.*, 2010).

21.5.3. Development and Application of Baseline and Scenario Information

21.5.3.1. Baseline Information: Context, Current Status, and Recent Advances

This section deals with defining baseline information for assessing climate change impacts, adaptation and vulnerability The baseline refers to a reference state or behaviour of a system, e.g. current biodiversity of an ecosystem, or a reference state of factors (e.g. agricultural activity, climate) which influence that system (see Glossary entry). For example, the UNFCCC defines the pre-industrial baseline climate, prior to atmospheric composition changes from its baseline pre-industrial state, as a reference for measuring global average temperature rises. A baseline may be used to characterise average conditions and/or variability during a reference period, or may allude to a single point in time, such as a reference year. It may provide information on physical factors such as climate, sea level or atmospheric composition, or on a range of non-climate factors, such as technological, land -use or socio-economic conditions. In many cases a baseline needs to capture much of system's variability to enable assessment of its vulnerability or to test whether significant changes have taken place. Thus the information used to establish this baseline must account for the variability of the factors influencing the system. In the case of climate factors often this requires 30 years of data (e.g. Jones et al., 1997) and sometimes substantially more (e.g. Kendon et al., 2008). Also temporal and spatial properties of systems will influence the information required. Many depend on high resolution information, for example urban drainage systems (high spatial scales) or temperature sensitive organisms (sub-daily time-scales). This section assesses methods to derive relevant climatic and non-climatic information and its reliability.

21.5.3.1.1. Climate baselines and their credibility

Observed weather data are generally used as climate baselines, e.g. with an impacts model to form a relevant impacts baseline, though downscaled climate model data are now being used as well. For example Bell et al. (2012) use dynamically and statistically downscaled hourly rainfall data with a 1km river flow model to generate realistic high resolution baseline river flows. These were then compared with future river flows derived used corresponding downscaled future climate projections to generate projected impacts representing realistic responses to the imposed climate perturbations. This use of high resolution data was important to ensure that changes in climate variability the system was sensitive to were taken into account (see also Hawkins et al., 2013). Underscoring the importance of including the full spectrum of climate variability when assessing climate impacts, Kay and Jones (2012) showed a greater range of projected changes in UK river flows resulted when using high time-resolution (daily rather than monthly) climate data.

Thus to develop the baseline of a climate-sensitive system it is important to have a good description of the baseline climate, thus including information on its variability on timescales of days to decades. This has motivated significant efforts to enhance the quality, length and homogeneity of, and make available, observed climate records (also important for monitoring, detecting and attributing observed climate change – Hartmann et al., 2014; Rhein et al., 2014; Vaughan et al., 2014; Masson-Delmotte et al., 2014; Bindoff et al., 2014). This has included generating new datasets such as APHRODITE (a gridded rain-gauge based dataset for Asia, Yatagai, et al., 2012), coordinated analyses of regional climate indices and extremes by CLIVAR's ETCCDI (see e.g. Zhang et al., 2011) and data rescue work typified by the ACRE initiative (Allan et al., 2011) resulting in analysis and digitization of many daily or sub-daily weather records from all over the world. Also, estimates of uncertainty in the observations are either being directly calculated, e.g. for the HadCRUT4 near-surface temperature record (Morice et al., 2012), or can be generated from multiple datasets, e.g. for precipitation using datasets such as GPCC (Rudolf et al., 2011), TRMM (Huffman et al., 2010) and APHRODITE, Yatagi et al.; 2012.

Significant progress has also been made in developing improved and new global reanalyses. These use climate models constrained by long time-series of observations from across the globe to reconstruct the temporal evolution of weather patterns during the period of the observations. An important new development has been the use of digitized surface pressure data from ACRE by the 20th Century Reanalysis (20CR) project (Compo et al., 2011) covering 1871 to the present day. 20CR provides the basis for estimating historical climate variability from the sub-daily to the multi-decadal timescale (Figure 21-12) at any location. It can be used directly, or via downscaling, to develop estimates of the baseline sensitivity of a system to climate and addressing related issues such as establishing links between historical climate events and their impacts. Other advances in reanalyses (http://reanalyses.org) have focused on developing higher quality reconstructions for the recent past. They include a new European Centre for Medium Range Weather Forecasts Reanalyses (ERA) dataset, ERA-Interim (Dee et al., 2011) and the NASA Modern Era Reanalysis for Research and Applications (MERRA – Rienecker et al., 2011), 1979-present, the NCEP Climate Forecast System Reanalysis (CFSR), 1979-Jan 2010 (Saha et al., 2010) and regional reanalyses such as the North American Regional Reanalysis (NARR) (Mesinger et al., 2006) and EURO4M (http://www.euro4m.eu/).

[INSERT FIGURE 21-12 HERE
Figure 21-12: Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann etal. (2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis and model sources: statistical reconstructions of the PWC, the PNA and the NAO, see Brönnimann et al. (2009) for details, (all cyan); 20CR (pink); NCEP–NCAR reanalyses (NNR; dark blue); ERA-40 (green); ERA-Interim (orange). The black line and grey shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed seas-surface temperatures and sea-ice from the HadISST dataset (Rayner et al. 2003), see Brönnimann etal. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea-surface temperature and sea-ice alone and demonstrate that the reanalyses have significantly higher skill in reproduces these modes of variability.]

In many regions high temporal and spatial resolution baseline climate information is not available (e.g. Washington et al. 2006, World Weather Watch 2005). Recent reanalyses may provide globally complete and temporally detailed reconstructions of the climate of the recent past but generally lack the spatial resolution or have significant biases (Thorne and Vose, 2010; Dee et al., 2011; Cerezo-Mota et al., 2011). Downscaling the reanalyses can be used with available observations to estimate the error in the resulting reconstructions which can often be significant (Duryan et al., 2010; Mearns et al., 2012). Advances in this area are expected through the WCRP-sponsored Coordinated Regional Downscaling Experiment (CORDEX) project (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html; Giorgi et al., 2009) which includes downscaling ERA-Interim over all land and enclosed sea areas (e.g. Nikulin et al. 2012).

21.5.3.1.2. Non-climatic baselines and their credibility

Climate-sensitive systems can be influenced by many non-climatic factors, so information on the baseline state of these factors is also commonly required (Carter et al., 2001; Carter et al., 2007). Examples of physical non-climatic factors include availability of irrigation systems, effectiveness of disease prevention or flood protection. Examples of socio-economic factors include levels of social, educational and economic development, political/governance background and available technology. Significant work has been undertaken to collect and make this information available. Local and national governments and international agencies (e.g. UN agencies, World Bank) have been collecting data (http://data.worldbank.org/data-catalog) on the human-related factors for many decades and similarly information on technological developments is widely available. Often these factors are evolving quickly and the baseline is taken as the reference state at a particular point in time rather than aggregated over a longer period. In the case of the physical factors, information on many of these have been refined and updated as they are critical inputs to deriving the climate forcings in the Representative Concentration Pathways (RCPs, van Vuuren et al., 2011) used in CMIP5 (Taylor et al., 2012). This includes updated information on land-use change (Hurtt et al., 2011), atmospheric composition (Meinshausen et al., 2011) and aerosols (Grainer et al., 2011, Lamarque et al., 2011).

The importance of establishing an appropriate physical baseline is illustrated in a study of potential climate change impacts on flow in the River Thames in the UK over a 126 year period. No long-term trend is seen in annual maximum flows despite increases in temperature and a major change in the seasonal partitioning of rainfall, winter rainfall becoming larger than summer (Marsh 2004). An investigation of the physical environment found that it had been significantly modified as part of river management activities with increases in channel capacity of 30% over 70 years leading to fewer floods. Thus establishing a baseline for river channel capacity explained the current reduced vulnerability of the Thames to flooding. In a study of the potential for crop adaptation (Challinor et al., 2009), the relevant non-climatic factor identified was technological. Detailed field studies demonstrated that the current germplasm included varieties with a wide range of tolerance to higher temperatures (Badigannavar et al., 2002). This established an agricultural technology baseline, current crop properties, which demonstrated the potential to reduce vulnerability in the system to compensate for the projected climate change impact.

21.5.3.2. Development of Projections and Scenarios

Since the AR4 there have been several new developments in the realm of scenarios and projections: 1) a new approach to the construction of global scenarios for use in climate change analysis, initiated with the development of representative concentration pathways (RCPs) (see Box 21.1 for a full description); 2) the development and application of a greater number of higher resolution climate scenarios (21.3.3.2); and 3) further use of multiple scenario elements as opposed to use of climate change scenarios only and greater focus on multiple stressors.

21.5.3.2.1. Application of high-resolution future climate information

There are now many examples of the generation and application of high resolution climate scenarios for assessing impacts and adaptation planning. These provide information at resolutions relevant for many impacts and adaptation studies but also, particularly with regard to dynamical downscaling, account for higher resolution forcings, such as complex topography (e.g., Salathé et al., 2010) or more detailed land-atmosphere feedbacks such as in West Africa (Taylor et al. 2011). In an analysis of climate impacts including possible adaptations in the Pacific North West of North America (Miles et al., 2010) application of two dynamically downscaled scenarios was particularly useful for the assessment of effects of climate change on storm water infrastructure (Rosenberg et al., 2010). More widely in North America results from NARCCAP have been used to assess impacts of climate change on available wind energy (Pryor and Barthelmie, 2011), road safety (Hambly et al., 2012), hydrology (Burger et al., 2011; Shrestha et al., 2011), forest drought (Williams et al., 2012), and human health (Li et al., 2012).

Several European-led projects have generated and applied high resolution climate scenarios to investigate the impacts of climate change over Europe for agriculture, river flooding, human health, and tourism (Christensen et al. 2012) and on energy demand, forest fire risk, wind storms damage, crop yields and water resources (Morse et al., 2009). The UK developed new UK Climate Projections in 2009 (UKCP09) combining the CMIP3, a perturbed physics GCM and a regional climate model ensemble to develop probabilities of changes in temperature and precipitation at a 25 km resolution (Murphy et al., 2009) to determine probabilities of different impacts of climate change and possible adaptations. In general, with all of this work a range of different techniques have been used with little assessment or guidance on the relative merits of each.

21.5.3.2.2. Use of multiple scenario elements and focus on multiple stressors

Many more impacts and adaptation studies now use multiple scenario elements, and focus on multiple stressors as opposed to climate change scenarios and effects alone (e.g., 3.3.2, 4.2.4, and 7.1.2). Good examples of use of multiple scenario elements involve studies of climate change and human health considering additional factors such as urban heat island (e.g., Knowlton et al., 2008; Rosenzweig et al., 2009), population increase and expanded urban areas (McCarthy et al., 2010) and population and socio-economic conditions (Watkiss and Hunt, 2012). As these studies are often undertaken at small scales, local scale information on relevant factors may be inconsistent with larger scale scenario elements used in quantifying other stressors. In recognition of this, efforts have been or are being made to downscale the large-scale scenario elements, e.g. the SRES scenarios were downscaled for Europe (van Vuuren and O'Neill, 2006) and economic activity information has been downscaled to 0.5 degree grids in some regions (Gaffin et al., 2004; Grübler et al., 2007; van Vuuren et al., 2010) However, this information is far from comprehensive and has not yet been examined carefully in the impacts and vulnerability literature (van Ruijven et al., 2013).

Typical non-climate stressors include changes in population, migration, land use, economic factors, technological development, social capital, air pollution, and governance structures. They can have independent, synergistic, or antagonistic effects and their importance varies regionally. Land-use and socio-economic changes are stressors of equal importance to climate change for some studies in Latin America (27.2.2.1), numerous changes in addition to climate strongly affect ocean ecosystem health (6.6.1) and in Asia rapid urbanization, industrialization and economic development are identified as major stressors expected to be compounded by climate change in (24.4-7). Most multiple stressor studies are regional or local in scope. For example Ziervogel and Taylor (2008) examined two different villages in South Africa and found that a suite of stressors are present such as high unemployment, health status (e.g., increased concern about AIDs), and access to education with climate change concerns present only in the context of other impacts such as availability of water. In a study on the Great Lakes region, additional stressors included land use change, population increase, and point source pollution (Danz et al., 2007). Mawdesly et al. (2009) considered wildlife management and biodiversity conservation and noted that reducing pressure from other stressors can maximize flexibility for adaptation to climate change. This increased focus on multiple stressors obviously increases the need for a much wider range of data and wider range of projections for the wide range of stressors, across multiple spatial scales.

21.5.3.3. Credibility of Projections and Scenarios

21.5.3.3.1. Credibility of regional climate projections

Obtaining robust regional projections of climate change (i.e. at least a clear indication of the direction of change), requires combining projections with detailed analysis and understanding of the drivers of the changes. The most successful example of this is the application of the attribution of observed global and regional temperature changes using global models incorporating known natural and anthropogenic climate forcing factors (Flato et al., 2014, section 10.3). The ability of GCMs to reproduce the observed variations in temperature, the quantification of the influence of the different forcings factors and how well these influences are captured in the models provide confidence that models capture correctly the physical processes driving the changes. This can also provide confidence in projections of precipitation when physically linked to changes in temperature (Rowell and Jones, 2006; Kendon et al. 2010). It is important, especially with precipitation where regional change may appear to differ in direction from one model to another, to distinguish when changes are significant (Tebaldi et al. 2011, Collins et al., 2014b, Box 12.1). Significant future projections of opposite direction are found with neither possibility able to be excluded on the basis of our physical understanding of the drivers of these changes. For example, McSweeney et al. (2012) found that in an ensemble of GCM projections over south-east Asia, all models simulated the important monsoon processes and rainfall well but projected both positive and negative changes in monsoon precipitation and significantly different patterns of change.

Model trends or projections may also be inconsistent with trends in available observations and in these cases, their projections are less credible. For example, the magnitude of the significant drying trend seen in the Sahel from the 1960s to the 1990s is not captured by models driven by observed sea-surface temperatures (SSTs) (e.g. Held et al. 2005) despite statistical analysis demonstrating the role of SSTs in driving Sahel rainfall variability. Thus our understanding of the system and its drivers, and their representation in the models, is incomplete, which complicates the interpretation of future projected changes in this region (e.g. Biasutti et al., 2008, Druyan, 2010). It implies that other processes are important and so research is required to identify these and ensure they are correctly represented in the models, without which projections of rainfall changes over this region cannot be considered reliable.

21.5.3.3.1. Credibility regarding socioeconomic scenario elements

Cash et al. (2003) distinguish three criteria for linking scientific knowledge to policy action; credibility (scientific adequacy of a policy-relevant study), salience (relevance of a study’s findings to the needs of decision-makers), and legitimacy (the perception that the study is respectful of divergent values and beliefs). Studies examining the performance of scenarios in climate change research across all three of these criteria are rare, but a general conclusion has been that much less attention is paid to salience and legitimacy (Hulme and Dessai 2008, Garb et al.

2008, Girod et al. 2009). Recognising this a new framework for global scenarios has been developed (Box 21-1), providing researchers greater freedom than hitherto for customizing information provided by global scenarios. These innovations may pose challenges for scientific credibility, and it is unclear how difficult it will be to bring independently developed climate and socioeconomic projections together as scenarios in an internally consistent manner, especially when some of these may include fine-scale regional detail (O'Neill and Schweizer, 2011; O'Neill et al., 2013).

Due to the common practice for scenario development of using narrative descriptions of alternative futures as the inspiration for socioeconomic simulations (the Story and Simulation approach – Alcamo 2008) it has been suggested that the exclusion of some details in socioeconomic scenario studies can affect the internal consistency and therefore the overall credibility of a study (e.g. Lloyd and Schweizer, 2013; Schweizer and Kriegler, 2012). Storylines can offer a point of entry for multi-scalar scenario analyses (Rounsevell and Metzger, 2010), and such sub-global scenario studies have been on the rise (Kok et al. 2011, Preston et al. 2011, Sietz et al. 2011, van Ruijven et al., 2013).

Environmental scenario exercises crossing geographical scales suggests that linkages between scenarios at different scales can be hard or soft (Zurek and Henrichs 2007), where downscaling (van Vuuren et al. 2010) would be an example of a hard linkage while other similarities between scenarios would be soft linkages. How to apply flexible interpretations of scientific adequacy and maintain scenario credibility is relatively unexplored, and there is thus a need for studies to document best practices in this respect.

21.6. Knowledge Gaps and Research Needs

Understanding of the regional nature of climate change, its impacts, regional and cross-regional vulnerabilities, and options for adaptation is still at a rudimentary level. There are both fundamental and methodological research issues in the physical sciences concerned with the projection of regional changes in the climate system and the potential impacts of those changes on various resource sectors and natural systems. Of equal importance, there are also fundamental gaps in our understanding of the determinants of vulnerability and adaptive capacity, thus presenting methodological challenges for projecting how societal vulnerability might evolve as the climate system changes. While development of new scenarios is a part of the underlying research agenda, they will inevitably be limited without further progress in our knowledge of the determinants of vulnerability.

Table 21-8 summarizes major research gaps in the physical, ecological, and social sciences that impede the scientific communities' progress in understanding the regional context of climate changes, their consequences, and societies' responses.

[INSERT TABLE 21-8 HERE]
Table 21-8: Leading knowledge gaps and related research needs.]

Frequently Asked Questions

FAQ 21.1: How does this report stand alongside previous assessments for informing regional adaptation?
[to be inserted in Section 21.3]
The five major Working Group II Assessment Reports produced since 1990 all share a common focus that addresses the environmental and socioeconomic implications of climate change. In a general sense, the earlier assessments are still valid, but the assessments have become much more complete over time, evolving from making very simple, general statements about sectoral impacts, through greater concern with regions regarding observed and projected impacts and associated vulnerabilities, through to an enhanced emphasis on sustainability and equity, with a deeper examination of adaptation options. Finally, in the current report there is a much improved appreciation of the context for regional adaptation and a more explicit treatment of the challenges of decision-making within a risk management framework.

Obviously one can learn about the latest understanding of regional impacts, vulnerability and adaptation in the context of climate change by looking at the most recent report. This builds on the information presented in previous reports by reporting developments in key topics. New and emergent findings are given prominence, as these may present fresh challenges for decision-makers. Differences with the previous reports are also highlighted – whether reinforcing, contradicting or offering new perspectives on earlier findings – as these too may have a bearing on past and present decisions. Following its introduction in the Third Assessment Report (TAR), uncertainty language has been available to convey the level of confidence in key conclusions, thus offering an opportunity for calibrated comparison across successive reports. Regional aspects have been addressed in dedicated chapters for major world regions, first defined following the Second Assessment and used with minor variations in the three subsequent assessments. These comprise the continental regions of Africa, Europe, Asia, Australasia, North America, Central and South America, Polar Regions and Small Islands , with a new chapter on The Oceans added for the present assessment.

FAQ 21.2: Do local and regional impacts of climate change affect other parts of the world?
[to be inserted in Section 21.3.1]
Local and regional impacts of climate change, both adverse and beneficial, may indeed have significant ramifications in other parts of the world. Climate change is a global phenomenon, but often expresses itself in local and regional shocks and trends impacting vulnerable systems and communities. These impacts often materialize in the same place as the shock or trend, but also much farther afield, sometimes in completely different parts of the world. Regional interdependencies include both the global physical climate system as well as economic, social and political systems that are becoming increasingly globalised.

In the physical climate system, some geophysical impacts can have large-scale repercussions well beyond the regions in which they occur. A well-known example of this is the melting of land-based ice, which is contributing to sea-level rise (and adding to the effects of thermal expansion of the oceans), with implications for low-lying areas far beyond the polar and mountain regions where the melting is taking place.

Other local impacts can have wider socio-economic and geopolitical consequences. For instance, extreme weather events in one region may impact production of commodities that are traded internationally, contributing to shortages of supply and hence increased prices to consumers, influencing financial markets and disrupting food security worldwide, with social unrest a possible outcome of food shortages. Another example, in response to longer-term trends is the potential prospect of large-scale migration due to climate change. While hotly contested, this link is already seen in the context of natural disasters, and could become an issue of increasing importance to national and international policy makers. A third example is the shrinkage of Arctic sea ice, opening Arctic shipping routes as well as providing access to valuable mineral resources in the exclusive economic zones of countries bordering the Arctic, with all the associated risks and opportunities. Other examples involving both risks and opportunities include changes of investment flows to regions where future climate change impacts may be beneficial for productivity

Finally, some impacts that are entirely local and may have little or no direct effect outside the regions in which they occur still threaten values of global significance, and thus trigger international concern. Examples include humanitarian relief in response to local disasters or conservation of locally threatened and globally valued biodiversity.

FAQ 21.3: What regional information should I take into account for climate risk management for the 20 year time horizon? *[to be inserted in Section 21.3.2]*
The fundamental information required for climate risk management is to understand the climate events that put the system being studied at risk and what is the likelihood of these arising. The starting point for assembling this information is a good knowledge of the climate of the recent past including any trends in aspects of these events (e.g. their frequency or intensity). It is also be important to consider that many aspects of the climate are changing, to understand how the future projected changes may influence the characteristics of these events and that these changes will, in general, be regionally variable. However, it should be noted that over the coming 20 years the magnitude of projected changes may not be sufficient to have a large influence the frequency and intensity of these events. Finally, it is also essential to understand which other factors influence the vulnerability of the system. These may be important determinants in managing the risks and also if they are changing at faster rates than the climate then changes in the latter become a secondary issue.

For managing climate risks over a 20-year time horizon it is essential to identify the climate variables which the system at risk is vulnerable to. It could be a simple event such as extreme precipitation or a tropical cyclone or a more complex sequence of a late onset of the monsoon coupled with prolonged dry spells within the rainy season.

The current vulnerability of the system can then be estimated from historical climate data on these variables including any information on trends in the variables. These historical data would give a good estimate of the vulnerability assuming the record was long enough to provide a large sample of the relevant climate variables and that the reasons for any trends, e.g. clearly resulting from climate change, were understood. It should be noted that in many regions sufficiently long historical records of the relevant climate variables are often not available.

It is also important to recognize that many aspect of the climate of the next 20 years will be different from the past. Temperatures are continuing to rise with consequent increases in evaporation and atmospheric humidity and reductions in snow amount and snow season length in many regions. Average precipitation is changing in many regions with both increases and decreases and there is a general tendency for increases in extreme precipitation observed over land areas. There is a general consensus amongst climate projections that further increases in heavy precipitation will be seen as the climate continues to warm and more regions will see significant increases or decreases in average precipitation. In all cases the models project a range of changes for all these variables which are generally different for different regions.

Many of these changes may often be relatively small compared to their natural variations but it is the influence of these changes on the specific climate variables which the system is at risk from that is important. Thus information needs to be derived from the projected climate changes on how the characteristics of these variables, e.g. the likelihood of their occurrence or magnitude, will change over the coming 20 years. These projected future characteristics in some cases may be indistinguishable from those historically observed but in other cases some or all models will project significant changes. In the latter situation, the effect of the projected climate changes will then result in a range of changes in either the frequency or magnitude of the climate event, or both. The climate risk management strategy would then need to adapt to accounting for either a greater range or changed magnitude of risk. This implies that in these cases a careful analysis of the implications of projected changes for the specific temporal and spatial characteristic of the climate variables relevant to the system at risk is required.

FAQ 21.4: Is the highest resolution climate projection the best to use for performing impacts assessments?
[to be inserted in Section 21.5.3.3]
A common perception is that higher resolution (i.e., more spatial detail) equates to more useable and robust information. Unfortunately data does not equal information, and more high resolution data does not necessarily translate to more or better information. Hence, while high resolution global climate models (GCMs) and many downscaling methods can provide high resolution data, and add value in, for example, regions of complex topography, it is not a given that there will be more value in the final climate change message. This partially depends upon how the higher resolution data were obtained. For example, simple approaches such as spatial interpolation or adding climate changes from GCMs to observed data fields do increase the spatial resolution but add no new information on high resolution climate change. Nonetheless, these data sets are useful for running impacts models. Many impacts settings are somewhat tuned to a certain resolution, such as the nested size categorizations of hydrologic basins down to watershed size, commonly used in hydrologic modeling. Using dynamical or statistical downscaling methods will add a new high resolution component, providing extra confidence that sub-GCM scale processes are being represented more accurately. However, , there are new errors associated with the additional method applied which need to be considered. More importantly, if downscaling is applied to only one or two GCMs then the resulting high resolution scenarios will not span the full range of projected changes that a large GCM ensemble would indicate are plausible futures. Spanning that full range is important in being able to properly sample the uncertainty of the climate as it applies in an impacts context. Thus for many applications, such as understanding the full envelope of possible impacts resulting from our current best estimates of regional climate change, lower resolution data may be more informative. At the end of the day, no one data set is best, and it is through the integration of multiple sources of information that robust understanding of change is developed. What is important in many climate change impacts contexts is appropriately sampling the full range of known uncertainties, regardless of spatial resolution. It is through the integration of multiple sources of information that robust understanding of change is developed.

Cross-Chapter Box

Box CC-RC. Regional Climate Summary Figures

[Noah Diffenbaugh (USA), Dáithí Stone (Canada / South Africa / USA), Peter Thorne (USA / Norway / UK), Filippo Giorgi (Italy), Bruce Hewitson (South Africa), Richard Jones (UK), Geert Jan van Oldenborgh (Netherlands)]

Information about the likelihood of regional climate change, assessed by WGI, is foundational for the Working Group II assessment of climate-related risks. To help communicate this assessment, the regional chapters of WGII present a coordinated set of regional climate figures, which summarize observed and projected change in annual average temperature and precipitation during the near-term and the longer-term for RCP2.6 and RCP8.5. These WGII regional climate summary figures use the same temperature and precipitation fields that are assessed in WGI Chapter 2 and WGI Chapter 12, with spatial boundaries, uncertainty metrics, and data classes tuned to support the WGII assessment of climate-related risks and options for risk management. Additional details on regional climate and regional climate processes can be found in WGI Chapter 14 and WGI Annex 1.

The WGII maps of observed annual temperature and precipitation use the same source data, calculations of data sufficiency, and calculations of trend significance as WGI Chapter 2 and WGI Figures SPM.1 and SPM.2. (A full description of the observational data selection and significance testing can be found in WGI Box 2.2.) Observed trends are determined by linear regression over the 1901-2012 period of MLOST for annual temperature, and over the 1951-2010 period of GPCC for annual precipitation. Data points on the maps are classified into three categories, reflecting the categories used in WGI Figures SPM.1 and SPM.2:

1) Solid colors indicate areas where (i) sufficient data exist to permit a robust estimate of the trend (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period), and (ii) the trend is significant at the 10% level (after accounting for autocorrelation effects on significance testing).
2) Diagonal lines indicate areas where sufficient data exist to permit a robust estimate of the trend, but the trend is not significant at the 10% level.
3) White indicates areas where there are not sufficient data to permit a robust estimate of the trend.

The WGII maps of projected annual temperature and precipitation are based on the climate model simulations from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012), which also form the basis for the figures presented in WGI (including WGI Chapter 12, Chapter 14, and Annex I). The CMIP5 archive includes output from atmosphere-ocean general circulation models (AOGCMs), AOGCMs with coupled vegetation and/or carbon cycle components, and AOGCMs with coupled atmospheric chemistry components. The number of models from which output is available, and the number of realizations of each model, varies between the different CMIP5 experiments.

The WGII regional climate maps use the same source data as WGI Chapter 12 (e.g., Box 12.1 Figure 1), including the WGI multi-model mean values; the WGI individual model values; the WGI measure of baseline ("internal") variability; and the WGI time periods for the reference (1986-2005), mid-21st-century (2046-2065), and late-21st-century (2081-2100) periods. The full description of the selection of models, the selection of realizations, the definition of internal variability, and the interpolation to a common grid can be found in WGI Chapter 12 and Annex 1.

In contrast to Phase 3 of the Coupled Model Intercomparison Project (CMIP3) (Meehl et al., 2007), which used the IPCC SRES emission scenarios (IPCC, 2000), CMIP5 uses the Representative Concentration Pathways (RCPs) (van Vuuren et al., 2011) to characterize possible trajectories of climate forcing over the 21st century. The WGII regional climate projection maps include RCP2.6 and RCP8.5, which represent the high and low end of the RCP range at the end of the 21st century. Projected changes in global mean temperature are similar across the RCPs over the next few decades (Figure RC-1; WGI Fig. 12.5). During this near-term era of committed climate change, risks will evolve as socioeconomic trends interact with the changing climate. In addition, societal responses, particularly adaptations, will influence near-term outcomes. In the second half of the 21st century and beyond, the magnitude of global temperature increase diverges across the RCPs (Figure RC-1; WGI Fig. 12.5). For this longer-term era of climate options, near-term and ongoing mitigation and adaptation, as well as development pathways, will determine the risks of climate change. The benefits of mitigation and adaptation thereby occur over different timeframes, and present-day choices thus affect the risks of climate change throughout the 21st century.

[INSERT FIGURE RC-1 HERE
Figure RC-1: Observed and projected changes in global annual average temperature. Values are expressed relative to 1986-2005. Black lines show the GISTEMP, NCDC-MLOST, and HadCRUT4.2 estimates from observational measurements. Colored shading denotes the ±1.64 standard deviation range based on simulations from 32 models for RCP2.6 (blue) and 39 models for RCP8.5 (red). Blue and red lines denote the scenario mean for RCP2.6 and RCP8.5, respectively.]

The projection maps plot differences in annual average temperature and precipitation between the future and reference periods (Figure RC-2 and Figure RC-3), categorized into four classes. The classes are constructed based on the IPCC uncertainty guidance, providing a quantitative basis for assigning likelihood (Mastrandrea et al., 2010), with "likely" defined as 66-100% and "very likely" defined as 90-100%.

The classifications in the WGII regional climate projection figures are based on two aspects of likelihood (e.g., WGI Box 12.1 and Knutti et al. (2010)). The first is the likelihood that projected changes exceed differences arising from internal climate variability (e.g., Tebaldi et al. (2011)). The second is agreement among models on the sign of change (e.g., Christensen et al. (2007) and IPCC (2012)).

The four classifications of projected change depicted in the WGII regional climate maps are:

1) Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. These criteria (and the areas that fall into this category) are identical to the highest-confidence category in WGI Box 12.1. This category supersedes other categories in the WGII regional climate maps.
2) Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability, and >66% of models agree on sign of change.
3) Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change.
4) Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability. It should be noted that areas that fall in this category for the annual average could still exhibit significant change at seasonal, monthly and/or daily timescales.

[INSERT FIGURE RC-2 HERE
Figure RC-2: Observed and projected changes in annual average temperature. (A) Observed temperature trends from 1901-2012 are determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.1 and 2.21. The range of grid-point values is -0.53 to +2.50°C over period. (B) CMIP5 multi-model mean projections of annual average temperature changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, relative to 1986-2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability (although there may be significant change at shorter timescales such as seasons, months, or days). Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: +0.19 to +4.08˚C for mid-21st century of RCP2.6; +0.06 to +3.85˚C for late-21st century of RCP2.6; +0.70 to +7.04˚C for mid-21st century of RCP8.5; and +1.38 to +11.71°C for late-21st century of RCP8.5.]

[INSERT FIGURE RC-3 HERE
Figure RC-3: Observed and projected changes in annual average precipitation. (A) Observed precipitation trends from 1951-2010 are determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.2. The range of grid-point values is -185 to +111 mm/year/decade. (B) CMIP5 multi-model mean projections of annual average precipitation changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, relative to 1986-2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability (although there may be significant change at shorter timescales such as seasons, months, or days). Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: -10 to +24% for mid-21st century of RCP2.6; -9 to +22% for late-21st century of RCP2.6; -19 to +57% for mid-21st century of RCP8.5; and -34 to +112% for late-21st century of RCP8.5.]

Box CC-RC References

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Table 21-1: Dimensions of the institutions and actors involved in climate change decision-making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decison-making domains are illustrative. Modified and extended from Mickwitz (2009).

Coherent policies and decision-making

Multi-level organisation and governance

Level: / Domain:	Economy	Energy	Food/fibre	Technology	Environment	...
Global	IMF/WB WTO MDGs NGOs	IEA NGOs	FAO WTO CLOS (fisheries) NGOs	WIPO NGOs	UNFCCC CBD Montreal Protocol NGOs	
Trans-national	MFIs/MDBs BFIs OECD/EU CLOS (transport)	OPEC Electric grid operators Oil/gas distributor	AFTA COMESA MERCOSUR EU CAP/CFP	Multi-nationals R&D EU Innovation Union	CLRTAP MRC LVBC EU Directives	
National	Ministry/Gov. Dept./Agency Banks Taxation	Ministry/Gov. Dept./Agency Energy provider Energy regulator	Ministry/Gov. Dept./Agency Tariffs, Quotas, Regulations	Ministry/Gov. Dept./Agency Education/R&D/ Innovation	Ministry/Gov. Dept./Agency Environmental law	
Sub-national	State/Province/ County/City Taxation	State/Province/ County/City Public/private energy provider	State/Province/ County/City Extension service Land use planning	State/Province/ County/City Incentives, Science parks	State/Province/ County/City Protected areas Regional offices	
Local	Micro-finance, Co-operative, Employer, Voter, Consumer	Renewables Producer, Voter, Consumer	Farmer, Forester, Fisher, Landowner, Voter, Consumer	Entrepreneur, Invester, Voter, Consumer	Environmentalist, Landowner, Voter, Consumer	

Acronyms: IMF – International Monetary Fund; WB – World Bank; WTO – World Trade Organization; MDGs – Millennium Development Goals, NGO – Non-governmental Organization; MDBs – Multilateral Development Banks; MFIs Multilateral Financial Institutions; BFIs – Bilateral Finance Institutions; ECD – Organisation for Economic Co-operation and Development; EU – European Union; CLOS – United Nations Convention on the Law of the Sea; IEA – International Energy Agency; OPEC – Organization of the Petroleum Exporting Countries; FAO – Food and Agriculture Organization of the United Nations; AFTA – Association of Southeast Asian Nations (ASEAN) Free Trade Area; COMESA – Common Market for Eastern and Southern Africa; MERCOSUR – Mercado Común del Sur (Southern Common Market); CAP/CFP – Common Agricultural Policy/Common Fisheries Policy; WIPO – World Intellectual Property Organization, UNFCCC – United Nations Framework Convention on Climate Change; CBD – Convention on Biological Diversity; CLRTAP – Convention on Long-range Transboundary Air Pollution (Europe, N. America, C. Asia); MRC – Mekong River Commission For Sustainable Development; Lake Victoria Basin Commission.

Table 21-2: Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SR). Major assessments are subdivided by the three Working Group reports, each described by generic titles.

IPCC report [references]	**Year**	**Treatment of regions**
First Assessment Report (FAR) [1, 2, 3]	1990	*Climate*: Climate projections for 2030 in 5 sub-continental regions; Observations averaged for northern/southern hemisphere, by selected regions and by 20° latitude x 60° longitude grid boxes
		Impacts: Agriculture by continent (7 regions); Ecosystem impacts for 4 biomes; water resources for case study regions; Oceans and Coastal Zones treated separately
		Responses: Emissions scenarios by 5 economic groupings; Energy and Industry by 9 regions; Coastal Zone and Wetlands by 20 world regions
Supplements to FAR [4, 5]	1992	*Climate*: IS92 emissions scenarios by 7 world regions
		Impacts: Agriculture by continent (6 regions); Ocean Ecology by 3 latitude zones; Questionnaire to governments on current activities on impacts by 6 WMO regions
SR: *Climate Change 1994* [6]	1994	Evaluation of IS92 emissions scenarios by 4 world regions: OECD, USSR/E. Europe, China/Centrally Planned Asia and Other.
Second Assessment Report (SAR) [7, 8, 9]	1995	*Climate*: Gridded proportional circle maps for observed climate trends (5° latitude/ longitude); climate projections for 7 sub-continental regions
		Impacts, Adaptations, Mitigation: Energy production statistics by 10 world regions; Forests, Wood Production and Management by three zones: Tropical, Temperate, Boreal; separate chapters by physiographic types: Deserts, Mountain Regions, Wetlands, Cryosphere, Oceans, and Coastal Zones and small islands; country case studies, Agriculture by 8 continental-scale regions; Energy supply by 8 world regions
		Economic and Social Dimensions: Social Costs and Response Options by 6 economic regions
SR: *Regional Impacts* [10]	1998	10 continental-scale regions: Africa, Arctic and Antarctic, Australasia, Europe, Latin America, Middle East and Arid Asia, North America, Small Island States, Temperate Asia, Tropical Asia. Subdivisions applied in some regions; Vegetation shifts mapped by 9 biomes; Baseline (1990) Socio-Economic data provided by country and for all regions except polar.
SR: *Land-Use Change and Forestry* [11]	1998	9 Biomes; 15 land-use categories; National and Regional case studies.
SR: *Aviation* [12]	1999	Observed and projected emissions by 22 regional air routes; Inventories by 5 economic regions
SR: *Technology Transfer* [13]	2000	Country case studies; Indicators of technology transfer by 6-7 economic regions
SR: *Emissions Scenarios* [14]	2000	4 SRES world regions defined in common across integrated assessment models; 11 sub-regions; Driving Factors by 6 continental regions
Third Assessment Report (TAR) [15, 16, 17]	2001	*Climate*: gridded observations of Climate trends; 20 example Glaciers; 9 Biomes for Carbon Cycle; Circulation Regimes for model evaluation; 23 "Giorgi" regions for regional climate projections
		Impacts, adaptation and vulnerability: Example projections from 32 "modified-Giorgi" regions; Basins by continent; 5 Coastal types; Urban/Rural Settlements; Insurance by economic regions; 8 continental-scale regions equivalent to 1998 Special report but with single chapter for Asia; Subdivisions used for each region (Africa, Asia and Latin America by climate zones; North America by 6 core regions and 3 border regions)
		Mitigation: Country examples; Developed (Annex I) and Developing (non-Annex I); Various economic regions; Policies, Measures and Instruments by 4 blocs: OECD, Economies in Transition, China and Centrally Planned Asia, and Rest of the World.
SR: *Ozone Layer* [18]	2005	Various economic regions/countries depending on sources and uses of chemicals;
SR: *Carbon Capture and Storage* [19]	2005	CO_2 sources by 9 economic regions; potential storage facilities: by geological formation, by oil/gas wells, by ocean depth,; costs, by 4 economic groupings

Fourth Assessment Report (AR4) [20, 21, 22]	2007	*Climate*: Land-use types for surface forcing of climate; Observations by 19 "Giorgi" regions; Modes of variability for Model Evaluation; Attribution of climate change by 22 "Giorgi-type" regions and by 6 ocean regions; Climate statistics for 30 "Giorgi-type" regions; PDFs of projections for 26 regions; summary graphs for 8 continental regions
		Impacts, adaptation and vulnerability: Studies reporting observed impacts by 7 IPCC regions; comparison of TAR and AR4 climate projections for 32 Giorgi regions; Ecosystems by 11 biomes; Agriculture by latitudinal zone; Examples of Coastal mega-Deltas; Industry and settlement by continetal region; 8 continental regions, as in TAR, but Small Islands not Small Island States; Sub-regional summary maps for each region, using physiographic, biogeographic or geographic definitions; Example vulnerability maps at sub-national scale and globally by country.
		Mitigation: 17 global economic regions for GDP; Energy supply by continent, by economic regions, by 3 UNFCCC groupings; Trends in CO_2 emissions (and projections) , waste and carbon balance by economic regions.
SR*: Renewable Energy Sources and Climate Change Mitigation* [23]	2012	Global maps showing potential resources for renewable energy: land suitability for bioenergy production, global irradiance for solar, geoethermal, hydropower, ocean waves/tidal range, wind); Various economic/continental regions: installed capacity (realised vs. potential), types of technologies, investment cost, cost effectiveness, various scenario-based projections; Country comparisons of deployment and uptake of technologies, share of energy market.
SR*: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [24]	2012	Trends in observed (tables) and projected (maps and tables) climate extremes (Tmax, Tmin, heat waves, heavy precipitation and dryness) by 26 sub-continental regions covering most land areas of the globe; Attribution studies of return periods of extreme temperatures for 15 "Giorgi-type" regions; Gridded global maps of projected extremes of temperature, precipitation, windspeed, dry spells and soil moisture anomalies; Continental-scale estimates of projected changes in impacts of extremes (floods, cyclones, coastal inundation) as well as frequencies of observed climate extremes and their estimated costs); Distinctions drawn between local, country and international/global actors with respect to risk management and its financing.
Fifth Assessment Report (AR5) [25, 26, 27]	2014	*Climate*: Gridded global maps of observed changes in climate; Cryosphere observations from 19 glacierized regions and 3 Arctic permafrost zones; Paleoclimatic reconstructions for 7 continental regions; CO_2 fluxes for 11 land and 10 ocean regions; Observed aerosol concentrations for 6 continental regions and projections for 9 regions; Detection and attribution of changes in mean and extreme climate for 7 continental and 8 ocean regions; Climate model evaluation and multi-model projections of extremes for 26 sub-continental regions; Maps and time series of seasonal and annual multi-model simulated climate changes for 19 sub-continental regions and global over 1900-2100.
		Impacts, adaptation and vulnerability – Part A Global and sectoral aspects: Gridded global maps of water resources, species distributions, ocean productivity; Global map of 51 ocean biomes; Detection and attribution of observed impacts, key risks and vulnerabilities and adaptation synthesis by IPCC regions. *Part B Regional aspects:* Nine continental-scale regions, eight as in AR4 plus the ocean; Sub-regions in Africa (5), Europe (5), Asia (6), Central and South America (5 or 7); Polar (2); Small Islands (4), Oceans (7); Other disaggregation by gridded maps or countries.
		Mitigation: Economic statistics by development (3 or 5 categories) or by income; 5 country groupings (plus international transport) for emission-related scenario analysis (RCP5: OECD 1990 countries, Reforming Economies, Latin America and Caribbean, Middle East and Africa, Asia) with further disaggregation to 10 regions (RCP10) for regional development; Land use regions for forest (13) and agriculture (11); Most other analyses by example countries.

1. IPCC (1990c); 2. IPCC (1990a); 3. IPCC (1990b); 4. IPCC (1992b); 5. IPCC (1992a); 6. IPCC (1994) 7. IPCC (1996c); 8. IPCC (1996b); 9. IPCC (1996a); 10. IPCC (1998b); 11. IPCC (1998a); 12. IPCC (1999); 13. IPCC(2000a), 14. IPCC (2000b); 15. IPCC (2001c); 16. IPCC (2001a); 17. IPCC (2001b); 18. IPCC/TEAP (2005); 19. IPCC (2005); 20. IPCC (2007c); 21. IPCC (2007a); 22. IPCC (2007b); 23. IPCC (2012b); 24. IPCC (2012a); 25. IPCC (2014b); 26. This assessment; 27. IPCC (2014a).

Table 21-3: Two possible entry points for thinking about vulnerability to climate change (illustrative and adapted from Füssel 2007).

Context	**Climate change impacts perspective**	**Vulnerability perspective**
Root problem	Climate change	Social vulnerability
Policy context	Climate change mitigation, compensation, technical adaptation	Social adaptation, sustainable development
Illustrative policy question	What are the benefits of climate change mitigation?	How can the vulnerability of societies to climatic hazards be reduced?
Illustrative research question	What are the expected net impacts of climate change in different regions?	Why are some groups more affected by climatic hazards than others?
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to current climate variability
Starting point of analysis	Scenarios of future climate change	Current vulnerability to climatic variabilty
Analytical function	Descriptive, positivist	Explanatory, normative
Main discipline	Natural science	Social science
Meaning of ‘vulnerability’	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors
Vulnerability approach	Integrated, risk-hazard	Political economy
Reference	IPCC (2001a)	Adger (1999)

Table 21-4: Illustrative examples of adaptation experience, as well as approaches to reduce vulnerability and enhance resilience. Adaptation actions can be influenced by climate variability, extremes, and change, and by exposure and vulnerability at the scale of risk management. Many examples and case studies demonstrate complexity at the level of communities or specific regions within a country. It is at this spatial scale that complex interactions between vulnerabilities, inequalities, and climate change come to the fore. At the same time, place-based examples illustrate how larger-level drivers and stressors shape differential risks and livelihood trajectories, often mediated by institutions.

Early warning systems for heat
EXPOSURE AND VULNERABILITY: Factors affecting exposure and vulnerability include age, pre-existing health status, level of outdoor activity, socioeconomic factors including poverty and social isolation, access to and use of cooling, physiological and behavioral adaptation of the population, urban heat island effects, and urban infrastructure. [8.2.3-4, 11.3.3-4, 11.4.1, 11.7, 13.2.1, 19.3.2, 23.5.1, 25.3, 25.8.1, SREX Table SPM.1]
CLIMATE INFORMATION AT THE GLOBAL SCALE: **Observed:** *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] **Projected:** *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 12.4.3]
CLIMATE INFORMATION AT THE REGIONAL SCALE: **Observed:** *Likely* that heat wave frequency has increased since 1950 in large parts of Europe, Asia, and Australia. [WGI AR5 2.6.1] *Medium confidence* in overall increase in heat waves and warm spells in North America since 1960. Insufficient evidence for assessment or spatially varying trends in heat waves or warm spells for South America and most of Africa. [SREX Table 3-2; WGI AR5 2.6.1] **Projected:** *Likely* that, by the end of the 21st century under RCP8.5 in most land regions, a current 20-year high temperature event will at least double its frequency and in many regions occur every two years or annually, while a current 20-year low temperature event will become exceedingly rare. [WGI AR5 12.4.3] *Very likely* more frequent and/or longer heat waves or warm spells over most land areas. [WGI AR5 12.4.3]
DESCRIPTION: Heat-health early warning systems are instruments to prevent negative health impacts during heat waves. Weather forecasts are used to predict situations associated with increased mortality or morbidity. Components of effective heatwave and health warning systems include identifying weather situations that adversely affect human health, monitoring weather forecasts, communicating heatwave and prevention responses, targeting notifications to vulnerable populations, and evaluating and revising the system to increase effectiveness in a changing climate. Warning systems for heat waves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia. [11.7.3, 24.4.6, 25.8.1, 26.6, Box 25-6]
BROADER CONTEXT: •Heat health warning systems can be combined with other elements of a health protection plan, for example building capacity to support communities most at risk, supporting and funding health services, and distributing public health information. •In Africa, Asia, and elsewhere, early warning systems have been used to provide warning of and reduce a variety of risks, related to famine and food insecurity; flooding and other weather-related hazards; exposure to air pollution from fire; and vector-borne and food-borne disease outbreaks. [7.5.1, 11.7,15.4.2, 22.4.5, 24.4.6, 25.8.1, 26.6.3, Box 25-6]
Mangrove restoration to reduce flood risks and protect shorelines from storm surge
EXPOSURE AND VULNERABILITY : Loss of mangroves increases exposure of coastlines to storm surge, coastal erosion, saline intrusion, and tropical cyclones. Exposed infrastructure, livelihoods, and people are vulnerable to associated damage. Areas with development in the coastal zone, such as on small islands, can be particularly vulnerable. [5.4.3, 5.5.6, 29.7.2, Box CC-EA]
CLIMATE INFORMATION AT THE GLOBAL SCALE: **Observed:** *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea

level. [WGI AR5 3.7.5]
Low confidence in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3]
Projected: *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2]
In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged.
Likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3]
Projected: *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2]
Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5]
More likely than not substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]

DESCRIPTION:
Mangrove restoration and rehabilitation has occurred in a number of locations (e.g., Vietnam, Djibouti, and Brazil) to reduce coastal flooding risks and protect shorelines from storm surge. Restored mangroves have been shown to attenuate wave height and thus reduce wave damage and erosion. They protect aquaculture industry from storm damage and reduce saltwater intrusion. [2.4.3, 5.5.4, 8.3.3, 22.4.5, 27.3.3]

BROADER CONTEXT:
•Considered a low-regrets option benefiting sustainable development, livelihood improvement, and human well-being through improvements for food security and reduced risks from flooding, saline intrusion, wave damage, and erosion. Restoration and rehabilitation of mangroves, as well as of wetlands or deltas, is ecosystem-based adaptation that enhances ecosystem services.
•Synergies with mitigation given that mangrove forests represent large stores of carbon.
•Well-integrated ecosystem-based adaptation can be more cost effective and sustainable than non-integrated physical engineering approaches.
[5.5, 8.4.2, 14.3.1, 24.6, 29.3.1, 29.7.2, 30.6.1-2, Table 5-4, Box CC-EA]

Community-based adaptation and traditional practices in small island contexts

EXPOSURE AND VULNERABILITY:
With small land area, often low elevation coasts, and concentration of human communities and infrastructure in coastal zones, small islands are particularly vulnerable to rising sea levels and impacts such as inundation, saltwater intrusion, and shoreline change. [29.3.1, 29.3.3, 29.6.1-2, 29.7.2]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5]
Low confidence in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. [WGI AR5 2.6.3]
Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]
Projected: *Very likely* significant increase in the occurrence of future sea level extremes by 2050 and 2100. [WGI AR5 13.7.2]
In the 21st century, *likely* that the global frequency of tropical cyclones will either decrease or remain essentially unchanged.
Likely increase in both global mean tropical cyclone maximum wind speed and rainfall rates. [WGI AR5 14.6]
Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: Change in sea level relative to the land (relative sea level) can be significantly different from the global mean sea level change because of changes in the distribution of water in the ocean and vertical movement of the land. [WGI AR5 3.7.3]
Projected: *Low confidence* in region-specific projections of storminess and associated storm surges. [WGI AR5 13.7.2]
Projections of regional changes in sea level reach values of up to 30% above the global mean value in the Southern Ocean and around North America, and between 10% to 20% above the global mean value in equatorial regions. [WGI AR5 13.6.5]
More likely than not substantial increase in the frequency of the most intense tropical cyclones in the western North Pacific and North Atlantic. [WGI AR5 14.6]

DESCRIPTION:

Traditional technologies and skills can be relevant for climate adaptation in small island contexts. In the Solomon Islands, relevant traditional practices include elevating concrete floors to keep them dry during heavy precipitation events and building low aerodynamic houses with palm leaves as roofing to avoid hazards from flying debris during cyclones, supported by perceptions that traditional construction methods are more resilient to extreme weather. In Fiji after cyclone Ami in 2003, mutual support and risk sharing formed a central pillar for community-based adaptation, with unaffected households fishing to support those with damaged homes. Participatory consultations across stakeholders and sectors within communities and capacity building taking into account traditional practices can be vital to the success of adaptation initiatives in island communities, such as in Fiji or Samoa. [29.6.2]

BROADER CONTEXT:

• Perceptions of self-efficacy and adaptive capacity in addressing climate stress can be important in determining resilience and identifying useful solutions.

•The relevance of community-based adaptation principles to island communities, as a facilitating factor in adaptation planning and implementation, has been highlighted, for example with focus on empowerment and learning-by-doing, while addressing local priorities and building on local knowledge and capacity. Community-based adaptation can include measures that cut across sectors and technological, social, and institutional processes, recognizing that technology by itself is only one component of successful adaptation.

[5.5.4, 29.6.2]

Adaptive approaches to flood defense in Europe

EXPOSURE AND VULNERABILITY :

Increased exposure of persons and property in flood risk areas has contributed to increased damages from flood events over recent decades.

[5.4.3-4, 5.5.5, 23.3.1, Box 5-1]

CLIMATE INFORMATION AT THE GLOBAL SCALE:

Observed: *Likely* increase in the magnitude of extreme high sea level events since 1970, mostly explained by rising mean sea level. [WGI AR5 3.7.5]

Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]

Projected: *Very likely* that the time-mean rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971-2010 for all RCP scenarios. [WGI AR5 13.5.1]

Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:

Observed: *Likely* increase in the frequency or intensity of heavy precipitation in Europe, with some seasonal and/or regional variations. [WGI AR5 2.6.2] Increase in heavy precipitation in winter since the 1950s in some areas of northern Europe (*medium confidence*). Increase in heavy precipitation since the 1950s in some parts of west-central Europe and European Russia, especially in winter (*medium confidence*). [SREX Table 3-2]

Increasing mean sea level with regional variations, except in the Baltic sea where the relative sea level is decreasing due to vertical crustal motion. [5.3.2, 23.2.2]

Projected: Over most of the mid-latitude land-masses, extreme precipitation events will *very likely* be more intense and more frequent in a warmer world. [WGI AR5 12.4.5]

Overall precipitation increase in northern Europe and decrease in southern Europe (*medium confidence*). [23.2.2]

Increased extreme precipitation in northern Europe during all seasons, particularly winter, and in central Europe except in summer (*high confidence*). [23.2.2; SREX Table 3-3]

DESCRIPTION:

Several governments have made ambitious efforts to address flood risk and sea level rise over the coming century. In the Netherlands, government recommendations include “soft” measures preserving land from development to accommodate increased river inundation, maintaining coastal protection through beach nourishment, and ensuring necessary political-administrative, legal, and financial resources. Through a multi-stage process, the British government has also developed extensive adaptation plans to adjust and improve flood defenses in order to protect London from future storm surges and river flooding. Pathways have been analyzed for different adaptation options and decisions, depending on eventual sea level rise, with ongoing monitoring of the drivers of risk informing decisions. [5.5.4, 23.7.1, Box 5-1]

BROADER CONTEXT:

•The Dutch plan is considered a paradigm shift, addressing coastal protection by “working with nature” and providing “room for

river."
•The British plan incorporates iterative, adaptive decisions depending on the eventual sea level rise with numerous and diverse measures possible over the next 50-100 years to reduce risk to acceptable levels.
• In cities in Europe and elsewhere, the importance of strong political leadership or government champions in driving successful adaptation action has been noted.
[5.5.3-4, 8.4.3, 23.7.1-2, 23.7.4, Boxes 5-1 and 26-3]

Index-based insurance for agriculture in Africa

EXPOSURE AND VULNERABILITY:
Susceptibility to food insecurity and depletion of farmers' productive assets following crop failure. Low prevalence of insurance due to absent or poorly developed insurance markets or to amount of premium payments. The most marginalized and resource-poor especially may have limited ability to afford insurance premiums. [10.7.6, 13.3.2, Box 22-1]

CLIMATE INFORMATION AT THE GLOBAL SCALE:
Observed: *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1]
Medium confidence that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1]
Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2]
Low confidence in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2]
Projected: *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 12.4.3]
Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5]
Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]

CLIMATE INFORMATION AT THE REGIONAL SCALE:
Observed: *Medium confidence* in increase in frequency of warm days and decrease in frequency of cold days and nights in southern Africa. [SREX Table 3-2]
Medium confidence in increase in frequency of warm nights in northern and southern Africa. [SREX Table 3-2]
Projected: *Likely* surface drying in southern Africa by the end of this century under RCP8.5 (*high confidence*). [WGI AR5 12.4.5]
Likely increase in warm days and nights and decrease in cold days and nights in all regions of Africa (*high confidence*). Increase in warm days largest in summer and fall (*medium confidence*). [Table SREX 3-3]
Likely more frequent and/or longer heat waves and warm spells in Africa (*high confidence*). [Table SREX 3-3]

DESCRIPTION:
A recently introduced mechanism that has been piloted in a number of rural locations, including in Malawi, Sudan, and Ethiopia, as well as in India. When physical conditions reach a particular predetermined threshold where significant losses are expected to occur--weather conditions such as excessively high or low cumulative rainfall or temperature peaks--the insurance pays out. [9.4.2, 13.3.2, 15.4.4, Box 22-1]

BROADER CONTEXT:
•Index-based weather insurance is considered well-suited to the agricultural sector in developing countries.
•The mechanism allows risk to be shared across communities, with costs spread over time, while overcoming obstacles to traditional agricultural and disaster insurance markets. It can be integrated with other strategies such as micro-finance and social protection programs.
•Risk-based premiums can help encourage adaptive responses and foster risk awareness and risk reduction by providing financial incentives to policyholders to reduce their risk profile.
•Challenges can be associated with limited availability of accurate weather data and difficulties in establishing which weather conditions cause losses. Basis risk (i.e., farmers suffer losses but no payout is triggered based on weather data) can promote distrust. There can also be difficulty in scaling up pilot schemes.
•Insurance for work programs can enable cash-poor farmers to work for insurance premiums by engaging in community-identified disaster risk reduction projects.
[10.7.4-6, 13.3.2, 15.4.4, Table 10-7, Box 22-1, Box 25-7]

Relocation of agricultural industries in Australia
EXPOSURE AND VULNERABILITY : Crops sensitive to changing patterns of temperature, rainfall, and water availability. [7.3, 7.5.2]
CLIMATE INFORMATION AT THE GLOBAL SCALE: **Observed:** *Very likely* decrease in the number of cold days and nights and increase in the number of warm days and nights, on the global scale between 1951 and 2010. [WGI AR5 2.6.1] *Medium confidence* that the length and frequency of warm spells, including heat waves, has increased globally since 1950. [WGI AR5 2.6.1] *Medium confidence* in precipitation change over global land areas since 1950. [WGI AR5 2.5.1] Since 1950 the number of heavy precipitation events over land has *likely* increased in more regions than it has decreased. [WGI AR5 2.6.2] *Low confidence* in a global-scale observed trend in drought or dryness (lack of rainfall). [WGI AR5 2.6.2] **Projected:** *Virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase, for events defined as extremes on both daily and seasonal timescales. [WGI AR5 12.4.3] *Virtually certain* increase in global precipitation as global mean surface temperature increases. [WGI AR5 12.4.1] Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions, and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario. [WGI AR5 12.4.5] Globally, for short-duration precipitation events, *likely* shift to more intense individual storms and fewer weak storms. [WGI AR5 12.4.5]
CLIMATE INFORMATION AT THE REGIONAL SCALE: **Observed:** Cool extremes rarer and hot extremes more frequent and intense over Australia and New Zealand, since 1950 (*high confidence*). [Table 25-1] *Likely* increase in heat wave frequency since 1950 in large parts of Australia. [WGI AR5 2.6.1] Late autumn/winter decreases in precipitation in Southwestern Australia since the 1970s and Southeastern Australia since the mid-1990s, and annual increases in precipitation in Northwestern Australia since the 1950s (*very high confidence*). [Table 25-1] Mixed or insignificant trends in annual daily precipitation extremes, but a tendency to significant increase in annual intensity of heavy precipitation in recent decades for sub-daily events in Australia (*high confidence*). [Table 25-1] **Projected:** Hot days and nights more frequent and cold days and nights less frequent during the 21st century in Australia and New Zealand (*high confidence*). [Table 25-1] Annual decline in precipitation over southwestern Australia (*high confidence*) and elsewhere in southern Australia (*medium confidence*). Reductions strongest in the winter half-year (*high confidence*). [Table 25-1] Increase in most regions in the intensity of rare daily rainfall extremes and in sub-daily extremes (*medium confidence*) in Australia and New Zealand. [Table 25-1] Drought occurrence to increase in Southern Australia (*medium confidence*). [Table 25-1] Snow depth and snow area to decline in Australia (*very high confidence*). [Table 25-1] Freshwater resources projected to decline in far southeastern and far southwest Australia (*high confidence*). [25.5.2]
DESCRIPTION: Industries and individual farmers are relocating parts of their operations, for example for rice, wine, or peanuts in Australia, or are changing land use in situ in response to recent climate change or expectations of future change. For example, there has been some switching from grazing to cropping in South Australia. Adaptive movement of crops has also occurred elsewhere. [7.5.1, 25.7.2, Table 9-7, Box 25-5]
BROADER CONTEXT: •Considered transformational adaptation in response to impacts of climate change. •Positive or negative implications for the wider communities in origin and destination regions. [25.7.2, Box 25-5]

Table 21-5: Dimensions of assessments of impacts and vulnerability and of adaptation drawn upon to serve different target fields (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to the original studies and to the chapters in which they are cited. Aspects of some of the studies in this table are also alluded to in Section 21.5.

Approach/field: **Scale:**	**Impacts/vulnerability**	**Adaptation**	**Target field**
Global	Resource availability[1,2,3] Impact costs[4,5,6,7] Vulnerability/risk mapping[8,9,10] Hotspots analysis[11]	Adaptation costs[4,5,6,7,12]	- Policy negotiations - Development aid - Disaster planning - Capacity building
Continental/ biome	Observed impacts[13,14,15] Future biophysical impacts[16,17] Impact costs[5,16] Vulnerability/risk mapping[18]	Adaptation costs[5] Modelled adaptation[19]	- Capacity building - International law - Policy negotiations - Regional development
National/ state/province	Observed impacts[20,21,22] Future impacts/risks[23,24] Vulnerability assessment[24] Impact costs[25]	Observed adaptation[26] Adaptation assessment[24,27]	- National adaptation plan/strategy - Nat. Communication - Legal requirement - Regulation
Municipality/ basin/patch/ delta/farm	Hazard/risk mapping[28] Pest/disease risk mapping[29] Urban risks/vulnerabilities[30]	Adaptation cost[28] Urban adaptation[30,31]	- Spatial planning - Extension services - Water utilities - Private sector
Site/field/tree/ floodplain/ household	Field experiments[32]	Coping studies[33,34] Economic modelling[35] Agent-based modelling[36]	- Individual actors - Local planners

Notes for Table 21-5

[1] Global terrestrial water balance, in the Water Model Intercomparison Project (Haddeland *et al.*, 2011), see chapter 3
[2] Global dynamic vegetation model intercomparison (Sitch *et al.*, 2008), see chapter 4
[3] Impacts on agriculture, coasts, water resources, ecosystems and health in the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP – Schiermeier, 2012), see chapter 19
[4] UNFCCC study to estimate the aggregate cost of adaptation (UNFCCC, 2007), which is critiqued by Parry (2009) and Fankhauser (2010)
[5] The Economics of Adaptation to Climate Change study (World Bank, 2010)
[6] Chapter 17 provides a thorough evaluation of global modelling studies (see also chapters 14 and 16)
[7] Impacts on agriculture and costs of adaptation (e.g. Nelson *et al.*, 2009), see chapter 7
[8] Can we avoid dangerous climate change? (AVOID) programme and Quantifying and Understanding the Earth System (QUEST) Global-scale impacts of climate change (GSI) project (Arnell *et al.*, 2013), see chapter 19
[9] OECD project on Cities and Climate Change (Hanson *et al.*, 2011), see chapters 5, 23, 24 and 26
[10] For critical reviews of global vulnerability studies, see Füssel (2010) and Preston et al.(2011)
[11] A discussion of hotspots can be found in section 21.5.1.2
[12] Adaptation costs for climate change-related human health impacts (Ebi, 2008), see chapter 17
[13] Satellite monitoring of sea ice over polar regions (Comiso and Nishio, 2008), see also Vaughan *et al*. (2014) and chapters 18 and 28
[14] Satellite monitoring of vegetation growth (e.g., Piao *et al.*, 2011) and phenology (e.g., Heumann *et al.*, 2007), see chapters 4 and 18
[15] Meta-analysis of range shifts in terrestrial organisms (e.g., Chen *et al.*, 2011), see chapters 4 and 18
[16] Physical and economic impacts of future climate change in Europe (Ciscar *et al.*, 2011), see chapter 23
[17] Impacts on crop yields in West Africa (Roudier *et al.*, 2011), see chapter 22
[18] Climate change integrated methodology for cross-sectoral adaptation and vulnerability in Europe (CLIMSAVE) project (Harrison *et al.*, 2012), see chapter 23
[19] Modelling agricultural management under climate change in sub-Saharan Africa (Waha *et al.*, 2013)
[20] Satellite monitoring of lake levels in China (Wang *et al.*, 2013)

[21] Satellite monitoring of rice phenology in India (Singh *et al.*, 2006), see chapter 18
[22] UK Climate Change Risk Assessment (CCRA, 2012), see chapter 23
[23] United States Global Change Research Program second (Karl *et al.*, 2009) and third (in review) national climate change impact assessments, see chapter 26
[24] The Global Environment Facility (GEF)-funded Assessments of Impacts and Adaptations to Climate Change (AIACC) program addressed impacts and vulnerability (Leary *et al.*, 2008b) and adaptation (Leary *et al.*, 2008a) in developing countries, see chapter 27
[25] Economics of Climate Change national studies in Kenya and Tanzania (SEI, 2009; GCAP, 2011), see chapter 22
[26] Sowing dates of various crops in Finland (Kaukoranta and Hakala, 2008), and see chapter 18
[27] Finnish Climate Change Adaptation Research Programme (ISTO) Synthesis Report (Ruuhela, 2012)
[28] Urban flood risk and adaptation cost, Finland (Perrels *et al.*, 2010)
[29] See Garrett (2013) for a specific example of a risk analysis, or Sutherst (2011) for a review – and see chapter 25
[30] New York City coastal adaptation (Rosenzweig *et al.*, 2011), see chapters 8 and 26
[31] Bangkok Assessment Report of Climate Change (BMA/GLF/UNEP, 2009), see chapters 8 and 24
[32] Field, chamber and laboratory plant response experiments (e.g., Long *et al.*, 2006; Hyvönen *et al.*, 2007; Wittig *et al.*, 2009; Craufurd *et al.*, 2013), see chapters 4 and 7
[33] Farming response to irrigation water scarcity in China (Liu *et al.*, 2008) and see chapter 13
[34] Farmers' mechanisms for coping with hurricanes in Jamaica (Campbell and Beckford, 2009) and see chapter 29
[35] Modelling micro-insurance of subsistence farmers for drought losses in Ethiopia (Meze-Hausken *et al.*, 2009), see chapter 14
[36] Simulating adaptive behaviour of farming communities in the Philippines (Acosta-Michlik and Espaldon, 2008), see chapter 24

Table 21-6: Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to Very Low (VL).

Scale	**Temporal**	**Annual**		**Seasonal-Monthly**		**Daily**	
Spatial	**Variable / Era**	**Temp**	**Precip**	**Temp**	**Precip**	**Temp**	**Precip**
Global	Past	VH	H	VH	H	N/A	N/A
	Future change	VH – direction H – amount	H – direction MH – amount	VH – direction H – amount	H – direction MH – amount	N/A	N/A
Regional, Large river basin	Past	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability
	Future change	VH – direction H – amount	H-L depends on capture of processes	VH – direction MH – amount	H-L depends on capture of processes	VH – direction MH – amount	H-L depends on capture of processes
National, State	Past	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability
	Future change	VH – direction MH – amount	H-L depends on capture of processes	VH – direction MH – amount	H-L depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes
City, County	Past	VH-M depends on observation availability	H-VL depends on observation availability	VH-M depends on observation availability	H-VL depends on observation availability	H-ML depends on observation availability	H-VL depends on observation availability
	Future change	H – direction MH – amount	H-VL depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes	H – direction M – amount	M-VL depends on capture of processes
Village, Site/field	Past	VH-ML depends on observation availability	H-VL depends on observation availability	VH-ML depends on observation availability	H-VL depends on observation availability	H-ML depends on observation availability	H-VL depends on observation availability
	Future change	H – direction MH – amount	H-VL depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes	H – direction M – amount	M-VL depends on capture of processes

Table 21-7: An assessment of observed and projected future changes in temperature and precipitation extremes over 26 sub-continental regions as defined in the SREX report (IPCC 2012; see also Figure 21.4 and Table SM21.2). Confidence levels are indicated by colour coding of the symbols. Likelihood terms are given only for high confidence statements and are specified in the text. Observed trends in temperature and precipitation extremes, including dryness, are generally calculated from 1950, using the period 1961-1990 as a baseline (see Box 3.1 chapter 3 of IPCC (2012a)). The future changes are derived from global and regional climate model projections of the climate of 2071-2100 compared with 1961-1990 or 2080-2100 compared with 1980-2000. Table entries are summaries of information in Tables 3.2 and 3.3 of IPCC (2012a) supplemented with or superseded by material from Chapters 2 (section 2.6 and Table 2.13) and 14 (section 14.4) of the IPCC AR5 WG1 report and Table 25-1 of the IPCC WG2 report. The source(s) of information for each entry are indicated by the superscripts a (Table 3.2 of IPCC, 2012a), b (Table 3.3 of IPCC, 2012a), c (Chapter 2 (section 2.6 and Table 2.13) IPCC AR5 WG1 report), d (Chapter 14 (section 14.4) of the IPCC AR5 WG1 report) and e (Table 25-1 of the IPCC WG2 report).

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
West North America WNA, 3	*Very likely* large increases in hot days (large decreases in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* large decreases in cold nights (large increases in warm nights)[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	Increase in warm spell duration[a]	*Likely* more frequent, longer and/or more intense heat waves and warm spells[b]	Spatially varying trends. General increase, decrease in some areas[a]	Increase in 20-year return value of annual maximum daily precipitation and other metrics over northern part of the region (Canada)[b] Less confidence in Southern part of the region, due to inconsistent signal in these other metrics[b]	No or overall slight decrease in dryness[a]	Inconsistent signal[b]
Central North America CNA, 4	Spatially varying trends: small increases in hot days in the north, decreases in the south[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends: Small increase in cold nights (and decreases in warm nights) in south and vice versa in the north[a]	*Very likely* increase in warm nights (decrease in cold nights[b]	Spatially varying trends[a]	*Likely* more frequent, longer and/or more intense heat waves and warm spells[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation[b] Inconsistent signal in other heavy precipitation days metrics[b]	*Likely* decrease[a, c]	Increase in consecutive dry days and soil moisture in southern part of Central North America[b] Inconsistent signal in the rest of the region[b]
East North America ENA, 5	Spatially varying trends. Overall increases in hot days (decreases in cool days), opposite or insignificant signal in a few areas[a]	*Very likely* increase in hot days (decrease in cool days)[b]	Weak and spatially varying trends[a]	*Very likely* increase in warm nights (decrease in cold nights[b]	Spatially varying trends, many areas with increase in duration, some areas with decrease[a]	*Likely* more frequent, longer and/or more intense heat waves and warm spells[b]	*Very likely* increase since 1950[a]	Increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation over northern part of the region[b] No signal or inconsistent signal in these other metrics in the southern part of the region[b]	Slight decrease in dryness since 1950[a]	Inconsistent signal in consecutive dry days, some consistent decrease in soil moisture[b]
Alaska/ Northwest Canada ALA, 1	*Very likely* large increases in warm days (decreases in cold days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* large decreases in cold nights, increases in warm nights[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent, and/or longer heat waves and warm spells[b]	Slight tendency for increase[a] No significant trend in southern Alaska[a]	*Likely* increase in heavy precipitation[b]	Inconsistent trends[a] Increases in dryness in part of the region[a]	Inconsistent signal[b]

Key

Symbols

- Increasing trend or signal
- Decreasing trend or signal
- Both increasing and decreasing trends or signals
- Inconsistent trend or signal or insufficient evidence
- No or only slight change

Level of confidence in findings

- Low confidence
- Medium confidence
- High confidence

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
East Canada, Greenland, Iceland CGI, 2	*Likely* increases in hot days (decreases in cool days) in some areas, decrease in hot days (increase in cool days) in others[a]	*Very likely* increase in warm days (decrease in cold days)[b]	Small increases in unusually cold nights and decreases in warm nights in northeastern Canada[a] Small decrease in cold nights and increase in warm nights in south-eastern/central Canada[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	Some areas with warm spell duration increase, some with decrease[a]	*Likely* more frequent, and/or longer heat waves and warm spells[b]	Increase in a few areas[a]	*Likely* increase in heavy precipitation[b]	Insufficent evidence[a]	Inconsistent signal[b]
Northern Europe NEU, 11	Increase in hot days (decrease in cool days), but generally not significant at the local scale[a]	*Very likely* increase in hot days (decrease in cool days) [but smaller trends than in central and southern Europe][b]	Increase in warm nights (decrease in cold nights) over the whole region, but generally not significant at the local scale[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	Increase in heat waves. Consistent tendency for increase in heat wave duration and intensity, but no significant trend[a]	*Likely* more frequent, longer and/or more intense heat waves/ warm spells, but summer increases smaller than in southern Europe[b] Little change over Scandinavia[b]	Increase in winter in some areas, but often insignificant or inconsistent trends at subregional scale, particularly in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. *Very likely* increases in heavy preciptation intensity and frequency in winter in the north[b]	Spatially varying trends. Overall only slight or no increase in dryness, slight decrease in dryness in part of the region[a]	No major changes in dryness[b]
Central Europe CEU, 12	*Likely* overall increase in hot days (decrease in cool days) since 1950 in most regions. *Very likely* increase in hot days (likely decrease in cool days) in west Central Europe[a] Lower confidence in trends in east Central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Likely* overall increase in warm nights (decrease in cold nights) at the yearly timescale. Some regional and seasonal variations in significance and in a few cases sign of trends. *Very likely* increase in warm nights (decrease in cold nights) in west Central Europe[a] Lower confidence in trends in east Central Europe (due to lack of literature, partial lack of access to observations, overall weaker signals, and change point in trends)[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	Increase in heat waves. Consistent increase in heat wave duration and intensity, but no significant trend. Significant increase in maximum heatwave duration in west Central Europe in summer[a]	*Likely* more frequent, longer and/or more intense heat waves/ warm spells[b]	Increase in part of the region, in particular central Western Europe and European Russia, especially in winter[a] Insignificant or inconsistent trends elsewhere, in particular in summer[a]	*Likely* increase in 20-year return value of annual maximum daily precipitation. Additional metrics support an increase in heavy precipitation in large part of the region over winter[b] Less confidence in summer, due to inconsistent evidence[b]	Spatially varying trends. Increase in dryness in part of the region but some regional variation in dryness trends and dependence of trends on studies considered (index, time period)[a]	Increase in dryness in central Europe and increase in short-term droughts[b]
Southern Europe and Mediterra-nean MED, 13	*Likely* increase in hot days (decrease in cool days) in most of the region. Some regional and temporal variations in the significance of the trends. Likely strongest and most significant trends in Iberian peninsula and southern France[a] Smaller or less significant trends in southeastern Europe and Italy due to change point in trends, strongest increase in hot days since 1976[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease in cold nights) in most of the region. Some regional variations in the significance of the trends.Very likely overall increase in warm nights (decrease in cold nights in S.W. Europe/W. Mediterranean[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	*Likely* increase in most regions[a]	*Likely* more frequent, longer and/or more intense heat waves and warm spells (*likely* largest increases in SW, S and E of the region)[b]	Inconsistent trends across the region and across studies[a]	Inconsistent changes and/or regional variations[b]	Overall increase in dryness, *likely* increase in the Mediterranean[a,c]	Increase in dryness. Consistent increase in area of drought[b,d]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
West Africa WAF, 15	Significant increase in temperature of hottest day and coolest day in some parts[a] Insufficient evidence in other parts[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increasing frequency of warm nights. Decrease in cold nights in western central Africa, Nigeria, and Gambia[a] Insufficient evidence on trends in cold nights in other parts[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Insufficient evidence for most of the region[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Rainfall intensity increased[a]	Slight or no change in heavy precipitation indicators in most areas[b] Low model agreement in northern areas[b]	*Likely* increase but 1970s Sahel drought dominates the trend; greater inter- annual variation in recent years[a,c]	Inconsistent signal[b]
East Africa EAF, 16	Lack of evidence due to lack of literature and spatially non-uniform trends[a] Increases in hot days in Southern tip (decrease in cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Spatially varying trends in most areas[a] Increases in warm nights in Southern tip (decrease in cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Insufficient evidence[a] Increase in warm spell duration in Southern tip of the region[a]	*Likely* Likely more frequent and/or longer heat waves and warm spells[b]	Insufficient evidence[a]	*Likely* increase in heavy precipitation[b]	Spatially varying trends in dryness[a]	Decreasing dryness in large areas[b]
Southern Africa SAF, 17	*Likely* increase in hot days (decrease in cool days)[a,c]	*Likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease in cold nights)[a,c]	*Likely* increase in warm nights (decrease in cold nights)[b]	Increase in warm spell duration[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Increases in more regions than decreases but spatially varying trends[a]	Lack of agreement in signal for region as a whole[b] Some evidence of increase in heavy precipitation in southeast regions[b]	General increase in dryness[a]	Increase in dryness, except eastern part[b,d] Consistent increase in area of drought[b]
Sahara SAH, 14	Lack of literature[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in warm nights[a] Lack of literature on trends in cold nights[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Insufficient evidence[a]	Low agreement[b]	Limited data, spatial variation of the trends[a]	Inconsistent signal of change[b]
Central America and Mexico CAM, 6	Increases in the number of hot days, decreases in the number of cool days[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increases in number of warm nights (decrease in number of cold nights)[a]	*Likely* increase in warm nights (*likely* decrease in cold nights)[b]	Spatially varying trends (increases in some areas, decreases in others)[a]	*Likely* more frequent, longer and/or more intense heat waves/ warm spells in most of the region[b]	Spatially varying trends. Increase in many areas, decrease in a few others[a]	Inconsistent trends[b]	Varying and inconsistent trends[a]	Increase in dryness in Central America and Mexico, with less confidence in trend in extreme South of region[b]
Amazon AMZ, 7	Insufficient evidence to identify trends[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Insufficient evidence to identify trends[a]	*Very likely* increase in warm nights (*likely* decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent and longer heat waves and warm spells[b]	Increases in many areas, decreases in a few[a]	Tendency for increases in heavy precipitation events in some metrics[b]	Decrease in dryness for much of the region. Some opposite trends and inconsistencies[a]	Inconsistent signals[b]
Northeastern Brazil NEB, 8	Increases in the number of hot days[a]	Hot days *likely* to increase (cool days *likely* to decrease)[b]	Increases in the number of warm nights[a]	*Likely* increase in warm nights (*likely* decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent and longer heat waves and warm spells in some studies[b]	Increases in many areas, decreases in a few[a]	Slight or no change[b]	Varying and inconsistent trends[a]	Increase in dryness[b]
Southeast-ern South America SSA, 10	Spatially varying trends (increases in some areas decreases in others)[a]	Hot days *likely* to increase (cool days *likely* decrease)[b]	Increases in number of warm nights (decreases in number of cold nights)[a]	*Very likely* increase in warm nights (*likely* decrease in cold nights)[b]	Spatially varying trends (increases in some areas, decreases in others)[a]	Tendency for more frequent and longer heat waves and warm spells[b]	Increases in northern areas[a] Insufficient evidence in southern areas[a]	Increases in northern areas[b] Insufficient evidence in southern areas[b]	Varying and inconsistent trends[a]	Inconsistent signals[b]
West Coast South America WSA, 9	Spatially varying trends (increases in some areas decreases in others)[a]	Hot days *likely* to increase (cool days *likely* decrease)[b]	Increases in number of warm nights (decreases in number of cold nights)[a]	*Likely* increase in warm nights (*likely* decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent and longer heat waves and warm spells[b]	Increases in many areas, decrease in a few areas[a]	Increases in tropics[b] Low confidence in extratropics[b]	Varying and inconsistent trends[a]	Decrease in consecutive dry days in the tropics, and increase in the extratropics[b] Increase in consecutive dry days and soil moisture in southwest South America[b]

Region/ region code	Trends in daytime temperature extremes (frequency of hot and cool days)		Trends in nighttime temperature extremes (frequency of warm and cold nights)		Trends in heat waves/warm spells		Trends in heavy precipitation (rain, snow)		Trends in dryness and drought	
	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected	Observed	Projected
North Asia NAS, 18	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Spatially varying trends[a]	*Likely* more frequent and/or longer heat waves and warm spells[a]	Increase in some regions, but spatial variation[a]	*Likely* increase in heavy precipitation for most regions[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
Central Asia CAS, 20	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Increase in warm spell duration in a few areas[a] Insufficient evidence in others[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Spatially varying trends[a]	Inconsistent signal in models[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
East Asia EAS, 22	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in warm nights (decrease cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Increase heat wave in China[a] Increase in warm spell duration in northern China, decrease in southern China[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Spatially varying trends[a]	Increase in heavy precipitation across the region[b]	Tendency for increased dryness[a]	Inconsistent signal of change[b]
Southeast Asia SEA, 24	Increase in hot days (decrease cool days) for northern areas[a] Insufficient evidence for Malay Archipelago[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in warm nights (decrease cold nights) for northern areas[a] Insufficient evidence for Malay Archipelago[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent and/or longer heat waves and warm spells over continental areas[b] Low confidence in changes for some areas[b]	Spatially varying trends, partial lack of evidence[a]	Increases in most metrics over most (especially non-continental) regions. One metric shows inconsistent signals of change[b]	Spatially varying trends[a]	Inconsistent signal of change[b]
South Asia SAS, 23	Increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	Increase in warm nights (decrease in cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Insufficient evidence[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Mixed signal in India[a]	More frequent and intense heavy precipitation days over parts of S. Asia. Either no change or some consistent increases in other metrics[b]	Inconsistent signal for different studies and indices[a]	Inconsistent signal of change[b]
West Asia WAS, 19	*Very likely* increase in hot days (decrease in cool days *more likely than not*)[a]	*Likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease in cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Increase in warm spell duration[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Decrease in heavy precipitation events[a]	Inconsistent signal of change[b]	Lack of studies, mixed results[a]	Inconsistent signal of change[b]
Tibetan Plateau TIB, 21	*Likely* increase in hot days (decrease cool days)[a]	*Likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease cold nights)[a]	*Likely* increase in warm nights (decrease in cold nights)[b]	Spatially varying trends[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Insufficient evidence[a]	Increase in heavy precipitation[b]	Insufficient evidence. Tendency to decreased dryness[a]	Inconsistent signal of change[b]
North Australia NAU, 25	*Likely* increase in hot days (decrease in cool days). Weaker trends in northwest[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Likely* increase in warm nights (decrease in cold nights)[a]	*Very likely* increase in warm nights (decrease of cold nights)[b]	Insufficient literature[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Spatially varying trends, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e. current 20 year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e]	Inconsistent signal[b]
South Australia/ New Zealand SAU, 26	*Very likely* increase in hot days (decrease in cool days)[a]	*Very likely* increase in hot days (decrease in cool days)[b]	*Very likely* increase in warm nights (decrease in cold nights)[a]	*Very likely* increase in warm nights (decrease in cold nights)[b]	Increase in warm spells across southern Australia[a]	*Likely* more frequent and/or longer heat waves and warm spells[b]	Spatially varying trends in S Australia, which mostly reflect changes in mean rainfall[e] Spatially varying trends in NZ, which mostly reflect changes in mean rainfall[e]	Increase in most regions in the intensity of extreme (i.e. current 20 year return period) heavy rainfall events[e]	No significant change in drought occurrence over Australia (defined using rainfall anomalies)[e] No trend in drought occurrence over New Zealand (defined using a soil water balance model) since 1972[e]	Increase in drought frequency in southern Australia, and in many regions of New Zealand[e]

Table 21-8: Leading knowledge gaps and related research needs.

	Knowledge Gap	Research need
1	There is no clear understanding of how to integrate the diversity of climate change projections data. The full associated uncertainty is weakly characterized and quantifying how much of an observed or simulated climate change is due to internal variability or external forcings is difficult in many situations. Collectively this results in data products with differing time and space resolution, differing dependencies and assumptions and that can have conflicting messages. At present individual products are plausible and mostly defensible in-so-far as they have physical basis within the assumptions of the method. However, at decision-relevant scales understanding where (or whether) the true outcome will lie within the range of the products collectively is often not possible and thus the products are often not strongly actionable.	Research is needed to distinguish the relative stochastic and deterministic sources of variability and change as a function of scale, variable, and application. The need is to develop further and build on physical understanding of the drivers of climate variability and change and how to represent these realistically within models to understand the source of the spread and any contradictions in the regional projections at scales relevant to users –and then to provide guidance on a likely range of outcomes within which the true response would be expected to lie. Similarly, there is a need is to articulate the real inherent uncertainty within climate projection data and to understand when climate information is useful at the scales of need. This also requires stronger dialogues with users of climate information to inform choices of variables and ways to characterize envelopes of risk and uncertainties.
2.	The growth of multi-model, multi-method, and multi-generational data for climate projections creates confusion for the IAV community. The lack of a clear approach to handling this diversity leads to choosing one or other subset, and where one choice may substantially alter the IAV conclusion compared to a different subset.	Methodological and conceptual advances are needed to facilitate the synthesis of diverse data sets on different scales from methods with different assumptions, and to integrate these into cohesive and defensible understanding of projected regional change.
3	The attributes of regional climate change through which impacts are manifest, such as the intensity, persistence, distribution, recurrence, and frequency of weather events is poorly understood. The information conveyed to the adaptation community is dominated by aggregates in time and space (e.g. SREX regional averages, or time averages), which hide the important attributes underlying these aggregated changes. In part this is a consequence of (1) above.	The research need is to be able to demonstrate how to unpack the regional projections into terms relevant for impacts and adaptation. For example, how is the shape of the distribution of weather events changing (not just the extremes), or how stable are the critical global teleconnection patterns that contribute to the variability of a region?
4	The historical record for many regions, especially those regions most vulnerable to climate change, is poor to the extent that the historical record is at best an estimate with unknown uncertainty. This severely undermines the development of regional change analysis, limits the evaluation of model skill, and presents a weak baseline against which to assess change signals or to develop impacts, adaptation or vulnerability baselines.	The research need is to integrate the multiplicity of historical data as represented by the raw observations processed gridded products (e.g. CRU and GPCP), satellite data, and reanalysis data sets. Involving national scientists with their inherent local knowledge and rescue and digitization of the many national archives still inaccessible to the wider research community would significantly enhance this research activity.
5	Impact model sensitivity studies and inter-comparison exercises are beginning to reveal fundamental flaws and omissions in some impact models in the representation of key processes that are expected to be important under projected climate changes. For example, high temperature constraints, and CO2 and drought effects on agricultural yields are poorly represented in many crop models.	Intensified efforts are needed to refine, test and inter-compare impact models over a wider range of sectors and environments than hitherto. These should be supported, where applicable, by targeted field, chamber and laboratory experiments under controlled atmospheric composition and climate conditions, to improve understanding of key physical, biological and chemical processes operating in changed environments. Such experiments are needed across a range of terrestrial and aquatic biogeographical zones in different regions of the world

6	New global scenarios are under development, based on climate projections for different representative concentration pathways (RCPs) and socio-economic scenarios based on shared socio-economic pathways (SSPs). However, there is currently little or no guidance on how these projections are to be accessed or applied in IAV studies. Moreover, as yet, quantitative SSPs are available only for large regions (basic SSPs), and regional SSPs that are consistent with the global SSPs (extended SSPs) along with scenarios that include mitigation and adaptation policies (shared policy assumptions – SPAs) have not yet been developed.,	Extended SSPs for major sub-continental regions of the world, including variables that define aspects of adaptive capacity and guidance on how to combine RCP-based regional climate projections with regional SSPs and SPAs to form plausible regional scenarios for application in IAV analysis.
7	The determinants and regional variability of vulnerability, exposure and adaptive capacity are not well understood, and methods for projecting changes in them are under-developed. Furthermore, given these lacks of understanding uncertainties of these three elements are poorly characterized and quantified	Case studies and underlying theory of these features of societies, and documentation of the effectiveness of actions taken are needed in conjunction with methods development for projections. More attention placed on determining their uncertainties, in national and regional assessments.

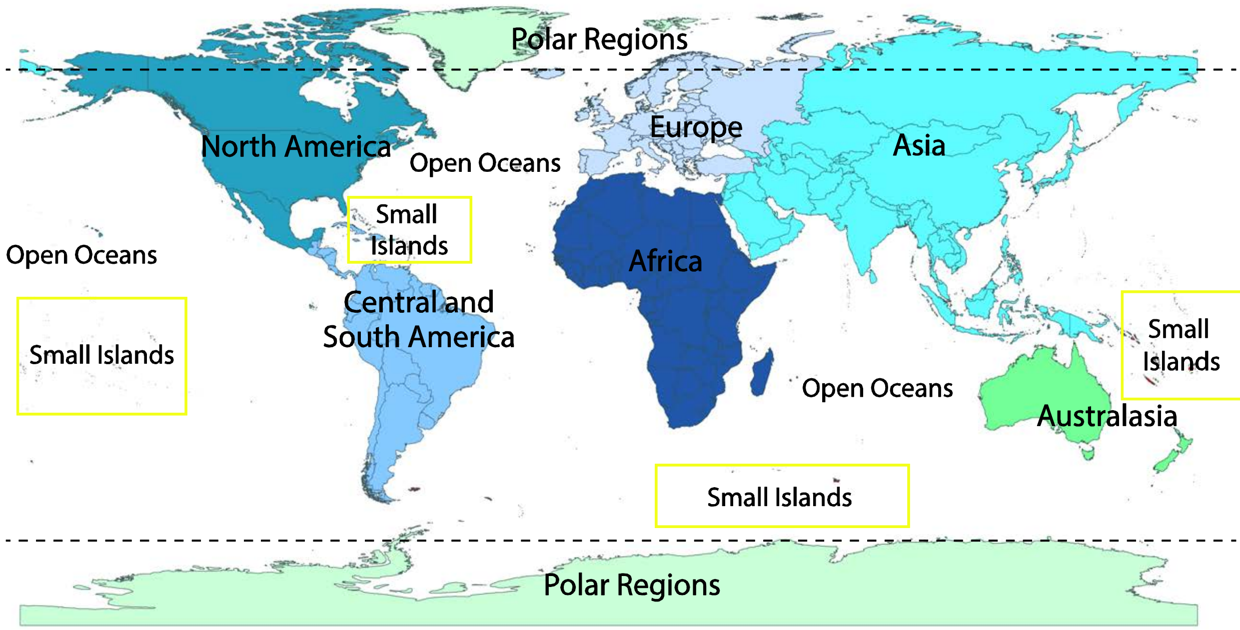

Figure 21-1: Specification of the world regions described in chapters 22-30 of this volume.
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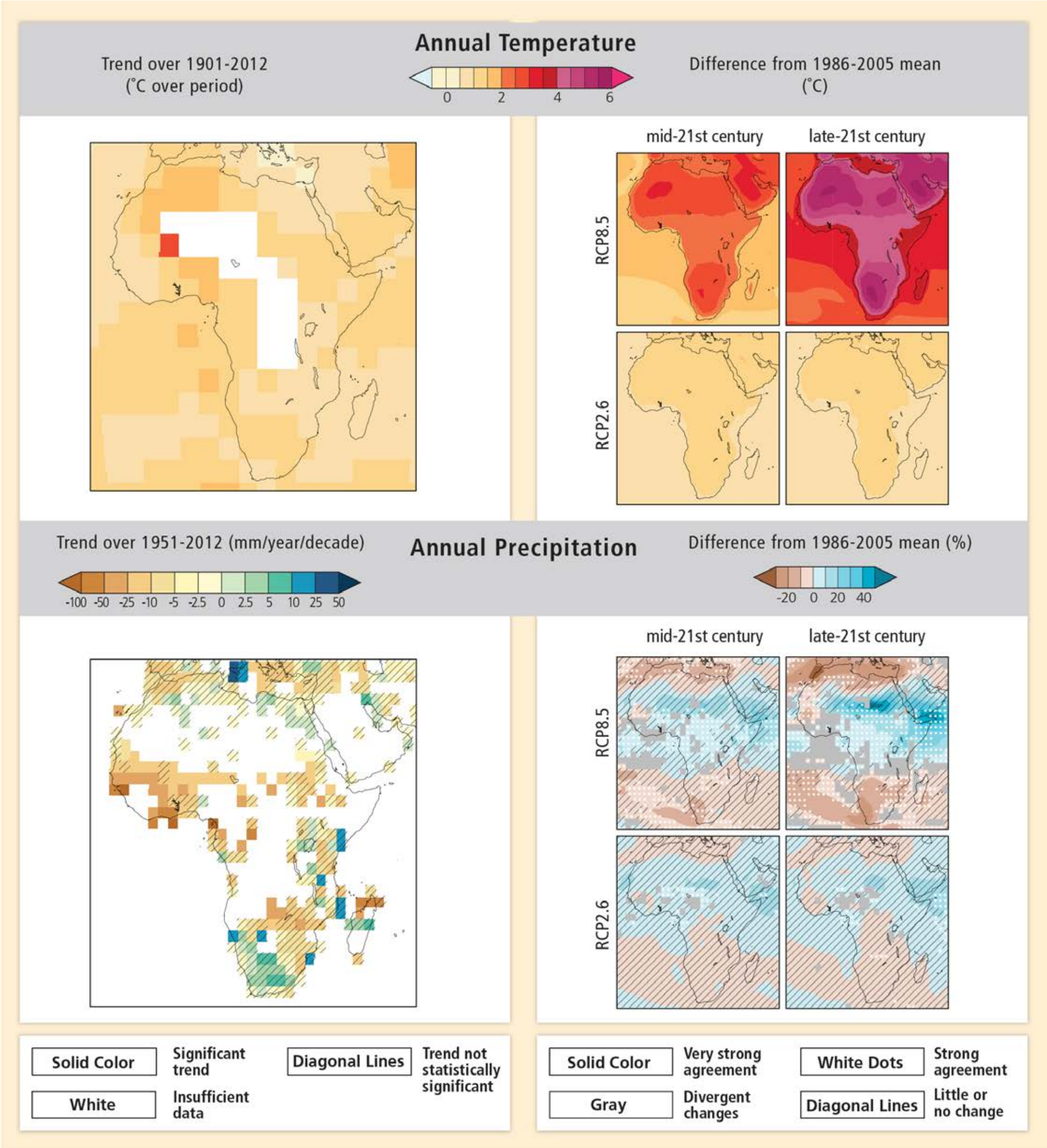

Figure 21-2: Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Observed temperature trends from 1901-2012 determined by linear regression. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression. [WGI AR5 Figure SPM.2] For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See alsoAnnex I of WGI AR5. [Boxes 21-3 and CC-RC]

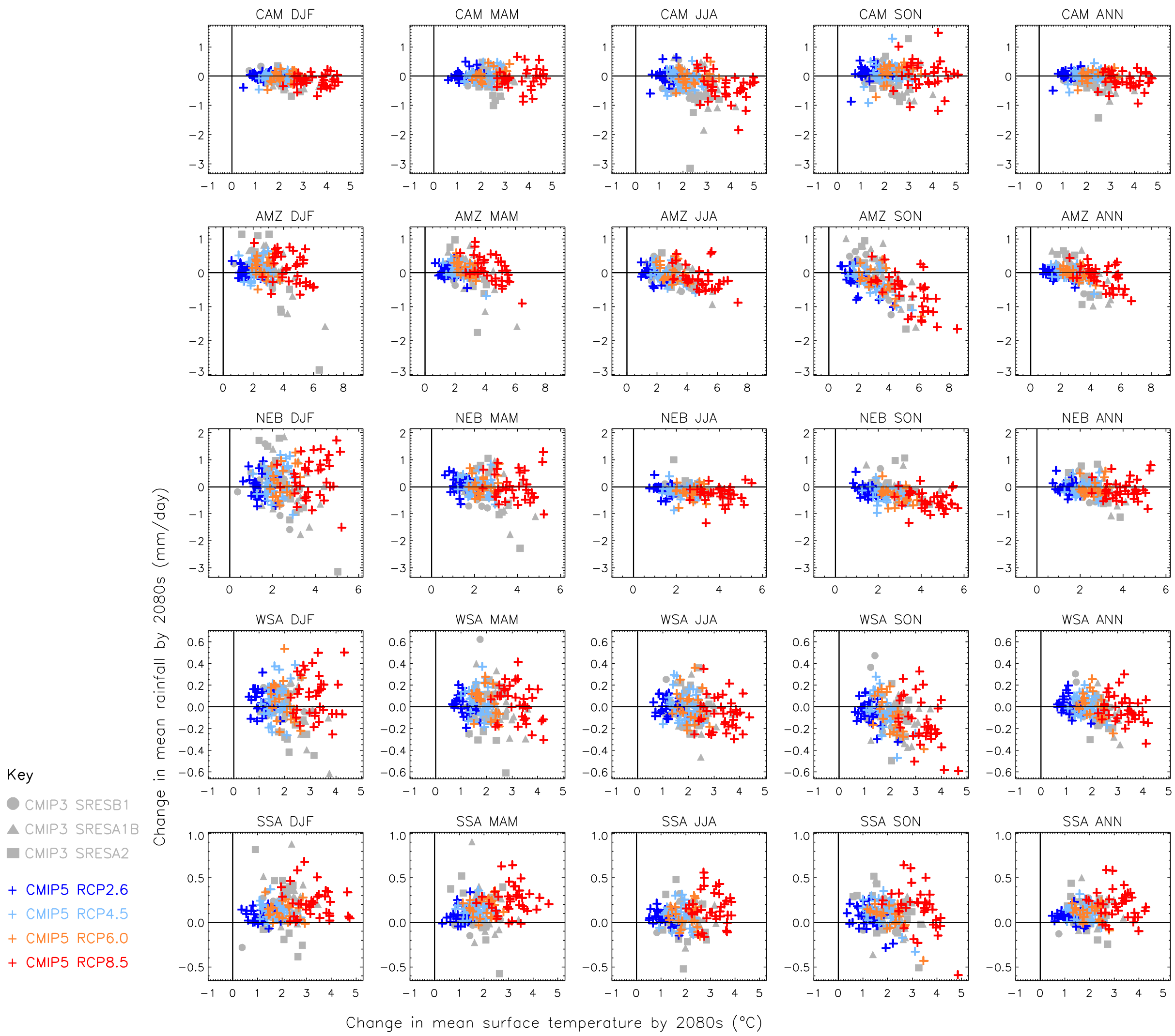

Figure 21-3: Regional average change in seasonal and annual mean temperature and precipitation over five sub-regions covering South and Central America for the period 2071-2100 relative to 1961-90 in GCM projections from 35 CMIP5 ensemble under four RCP scenarios (van Vuuren et al., 2011) compared with GCM projections from 22 CMIP3 ensemble under three SRES scenarios (IPCC, 2000); see Table 21-1 for details of the relationship between the SRES and RCP scenarios. Regional averages are based on SREX region definitions (see Figure 21-3). Temperature changes are given in ºC and precipitation changes in mm/day with axes scaled relative to the maximum changes projected across the range of models. The models which generated the data displayed are listed in supplementary material Table SM21-3.

[Illustration to be redrawn to conform to IPCC publication specifications.]

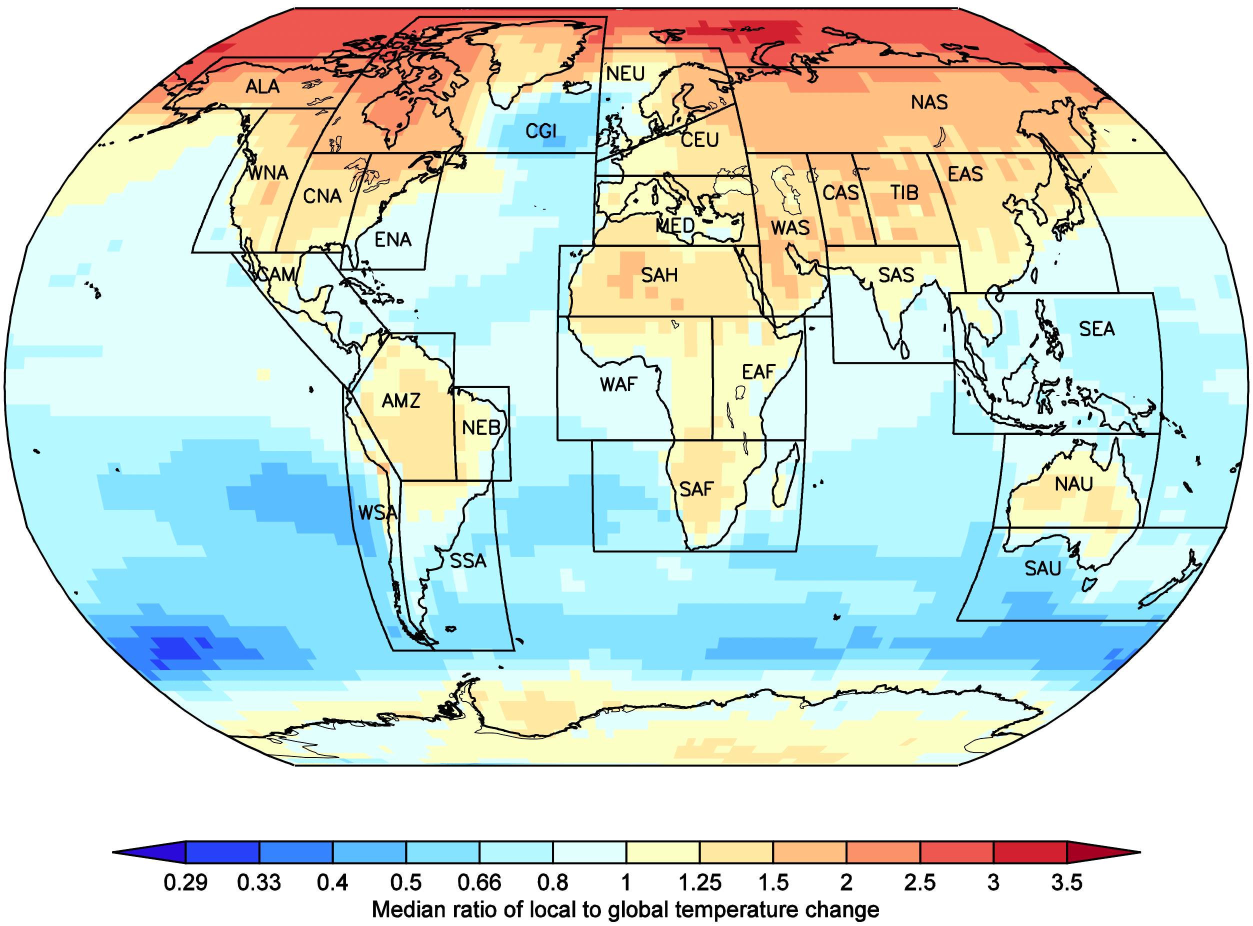

Figure 21-4: CMIP5 ensemble median ratio of local:global average temperature change in the period 2071-2100 relative to 1961-90 under the RCP8.5 emissions/concentrations scenario. The values are displayed on a common 2.5ºx3.75º grid onto which each models' data were regridded and they were calculated as follows: 1) for each model the local change was calculated between 1961 and 1990 at each grid cell, and is divided by the global average change in that model projection over the same period; 2) the median ratio value across all models at each grid cell is identified and shown. Data used are from the 35 CMIP5 models for which monthly projections were available under RCP8.5 which are listed in supplementary Table 21-3. Overplotted polygons indicate the SREX regions (IPCC, 2012) used to define the sub-regions used to summarise information in Chapters 21 and some of the subsequent regional chapters**. [Illustration to be redrawn to conform to IPCC publication specifications.]**

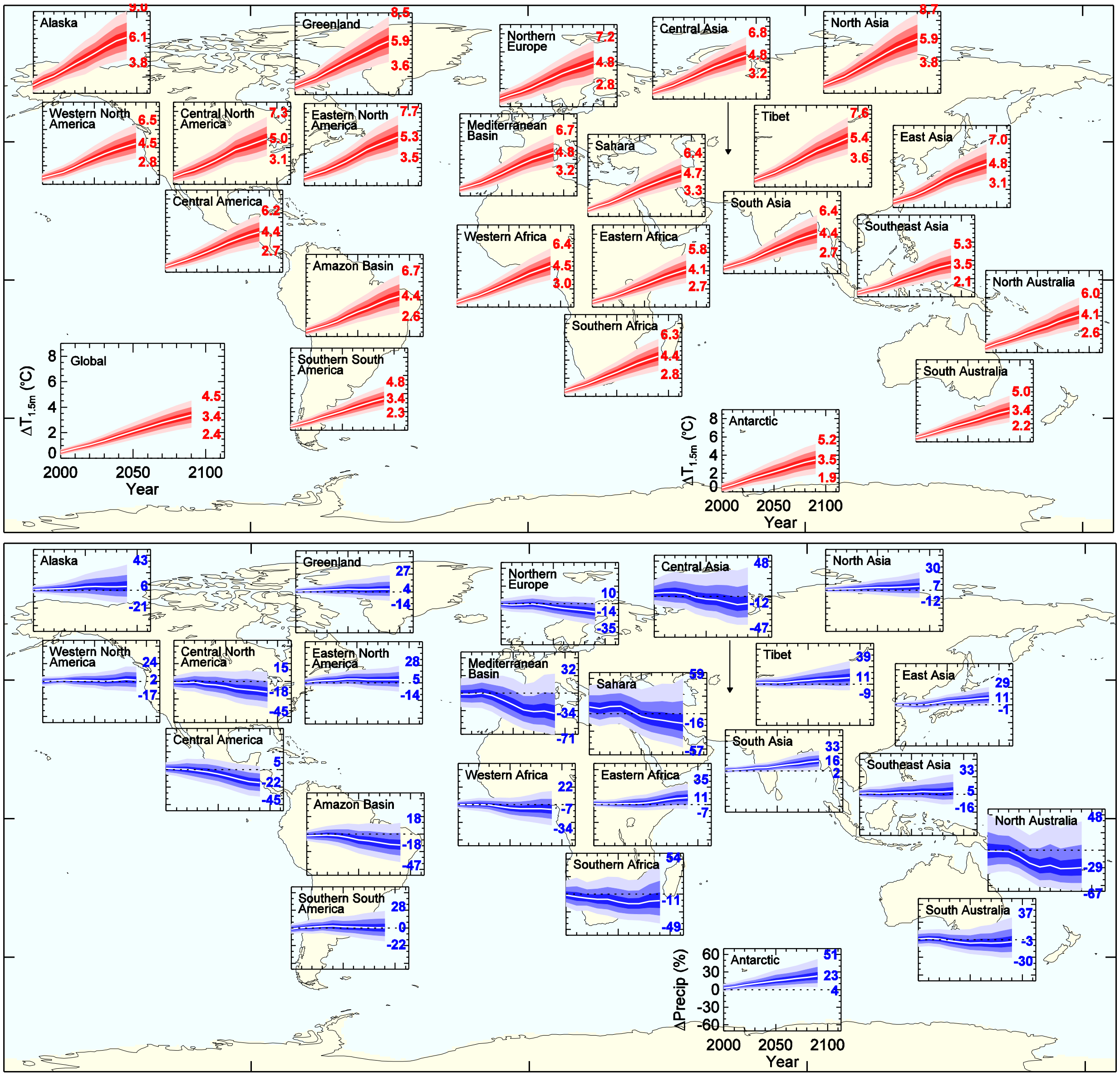

Figure 21-5: Evolution of the 5%, 17%, 33%, 50%, 66%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (upper panel) and annual precipitation (lower panel) for the Giorgi-Francisco (2000) regions and the globe with the SRES A1B forcing scenario combining results from a perturbed physics ensemble and the CMIP3 ensemble. Twenty year means relative to the 1961-1990 baseline are plotted in decadal steps using a common y-axis scale. The 5%, 50% and 95% percentile values for the period 2080-2099 are displayed for each region. (From Harris et al. 2012).

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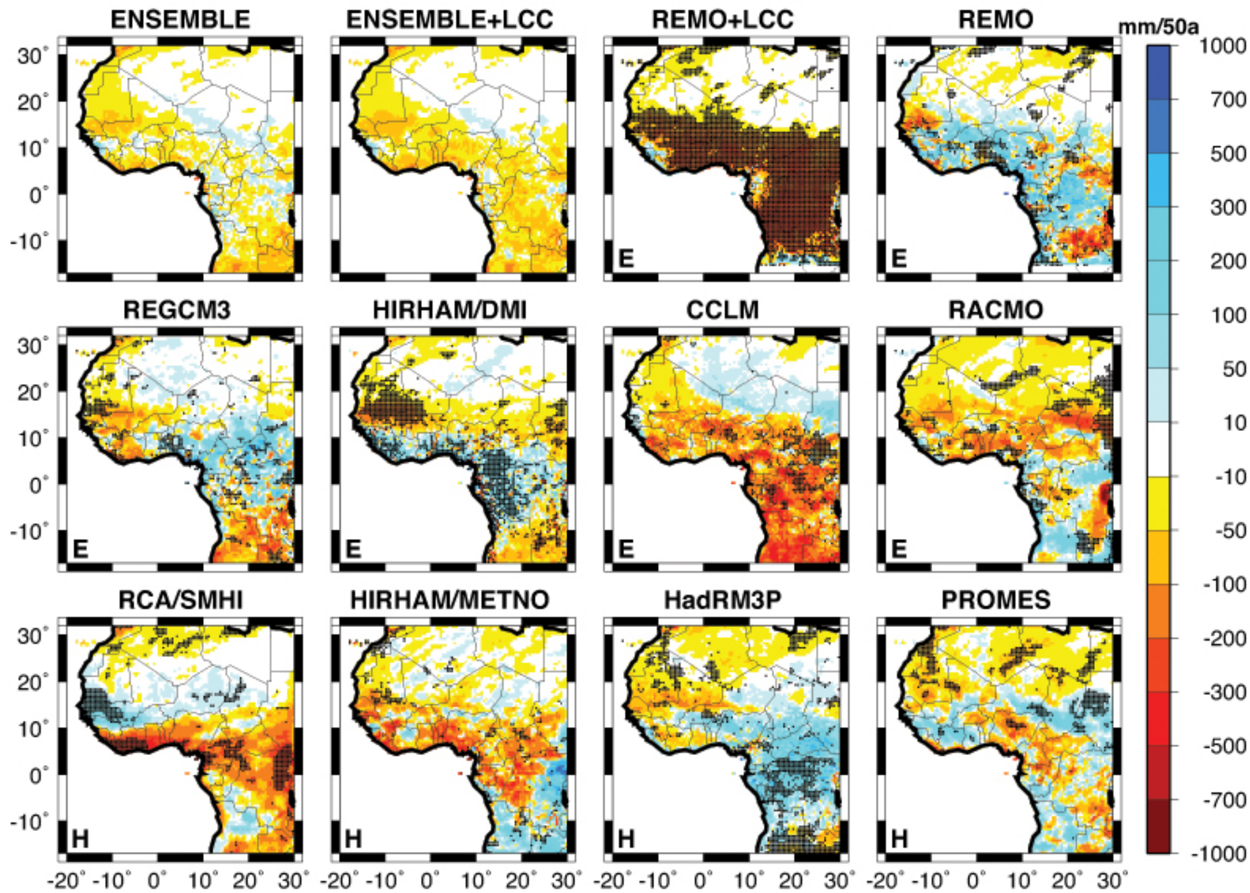

Figure 21-6: Linear changes (i.e. changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001-2050 period from 10 individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land cover changes (see Paeth et al. 2011 for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 95% level are marked by black dots. From Paeth et al. (2011).
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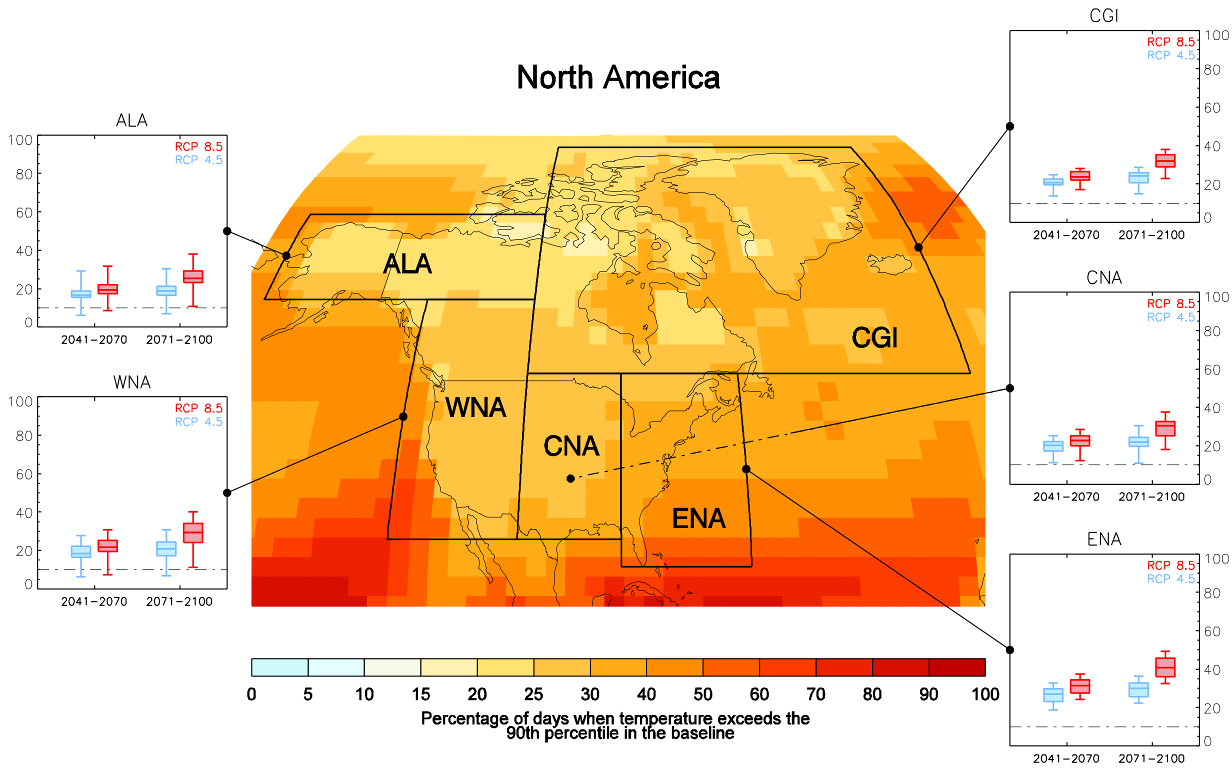

Figure 21-7: The frequency of 'warm days' (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961-1990) projected for the 2071-2100 period by 26 CMIP5 GCMs for North America. Map: Ensemble median frequency of 'warm days' during 2071-2100 under RCP8.5. Graphs: Box-and-whisker plots indicate the range of regionally-averaged 'hot-day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5 across the 26 CMIP5 models for each SREX sub-regions in North America. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of 'warm days' of 10% is represented on the graphs by the dashed line. A full list of CMIP5 models for which data is shown here can be found in supplementary material Table SM21-4.
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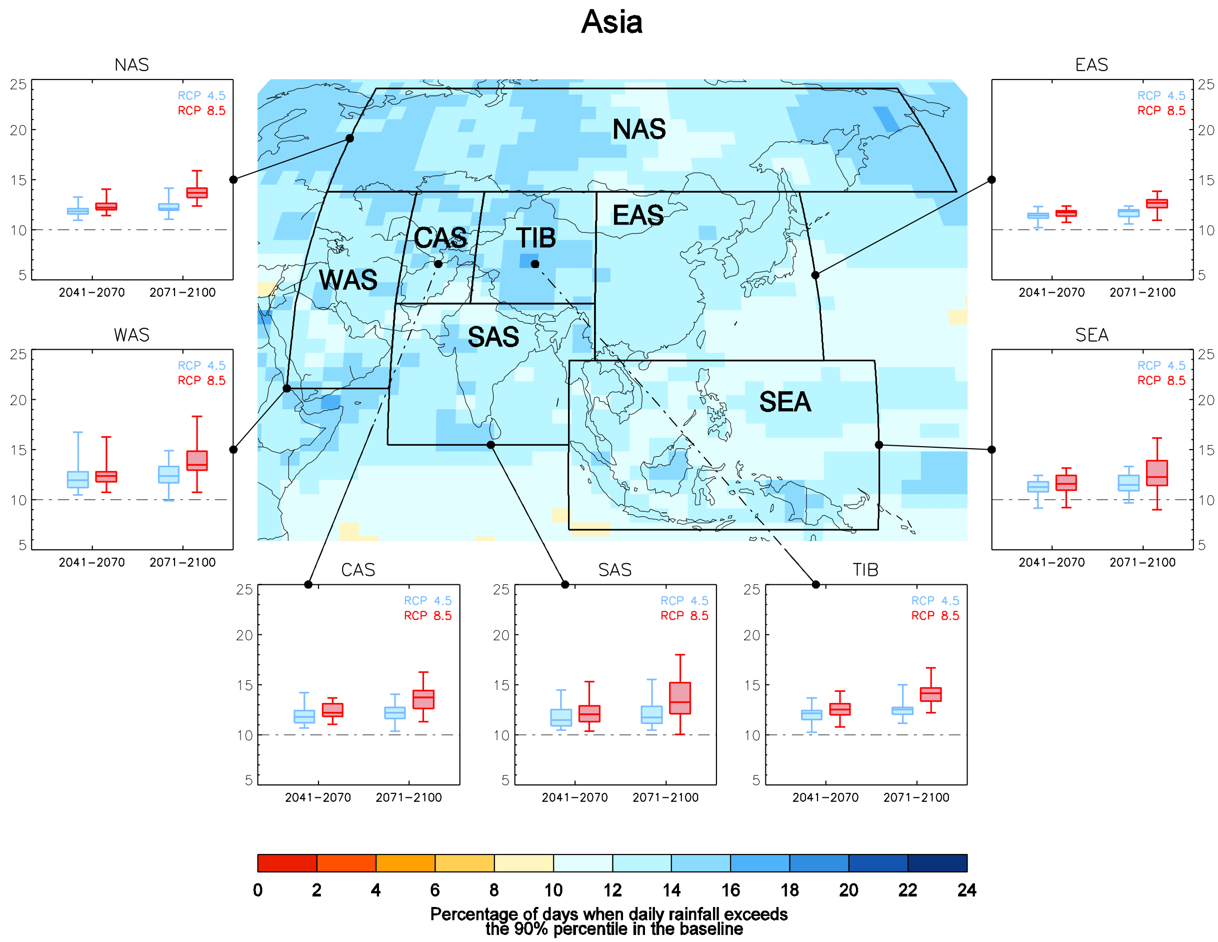

Figure 21-8: The frequency of 'very wet days' (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961-1990 with wet days defined as days with 1mm of precipitation or more) projected for the 2071-2100 period by 26 CMIP5 GCMs for Asia. Map: Ensemble median frequency of 'very wet days' during 2071-2100 under RCP8.5. Graphs: Box-and-whisker plots indicate the range of regionally-averaged 'very wet day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5 across the 26 CMIP5 models for each SREX sub-regions in Asia Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘Very wet days’ of 10% is represented on the graphs by the dashed line. A full list of CMIP5 models for which data is shown here can be found in supplementary material Table SM21-4. (Note the WMO Expert Team on Climate Change Detection Indices defines “very wet days” threshold as the 95%-ile daily precipitation event. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

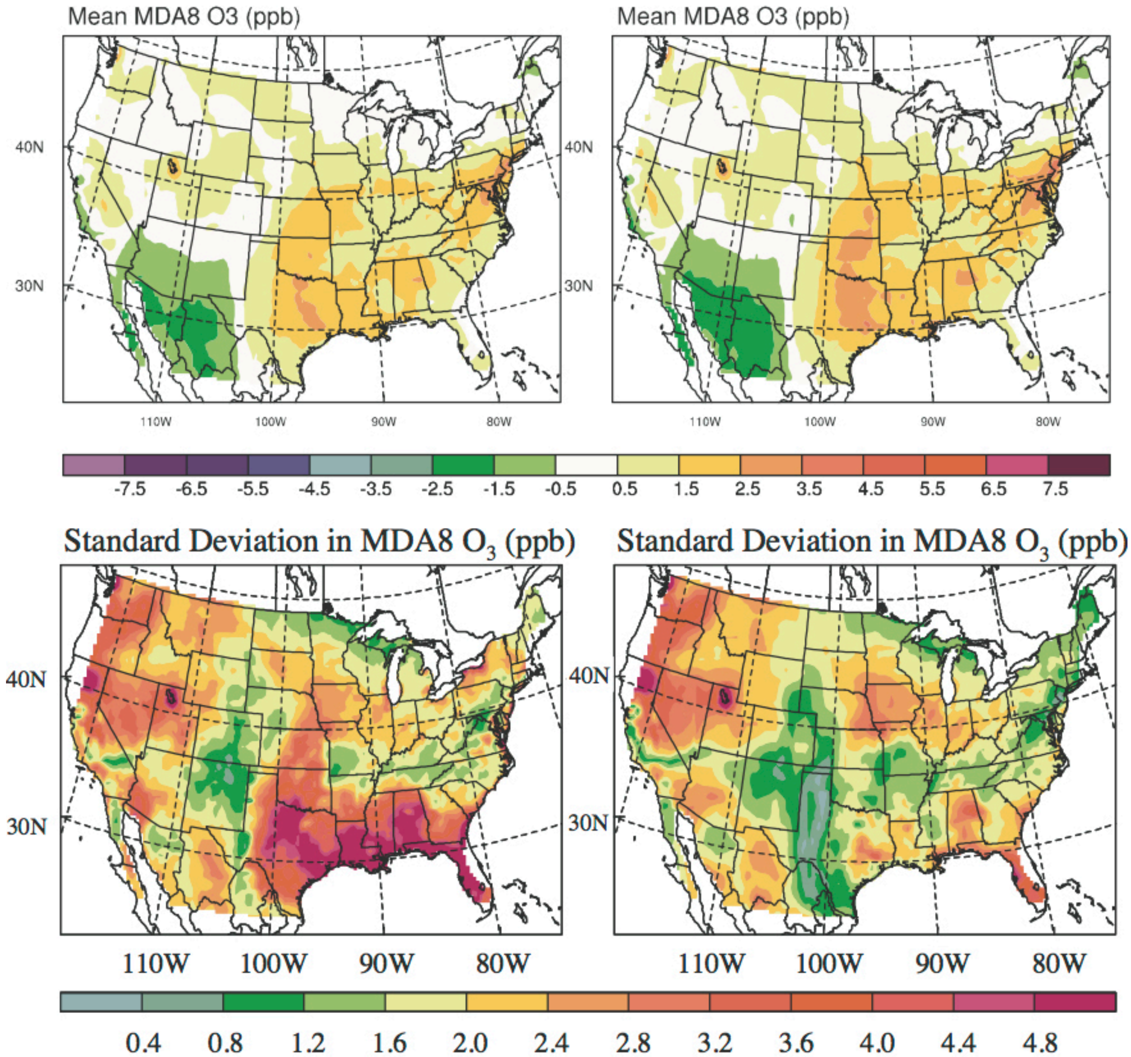

Figure 21-9: Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2050s minus 1990s) MDA8 summer ozone concentrations across (left-hand panels) all seven experiments (five regional and 2 global) and for comparison purposes (right hand panels), not including the WSU experiment (which simulated July only conditions). The different experiments use different pollutant emission and SRES GHG emission scenarios. The pollutant emissions are the same in the present and future simulations (from Weaver et al., 2009).
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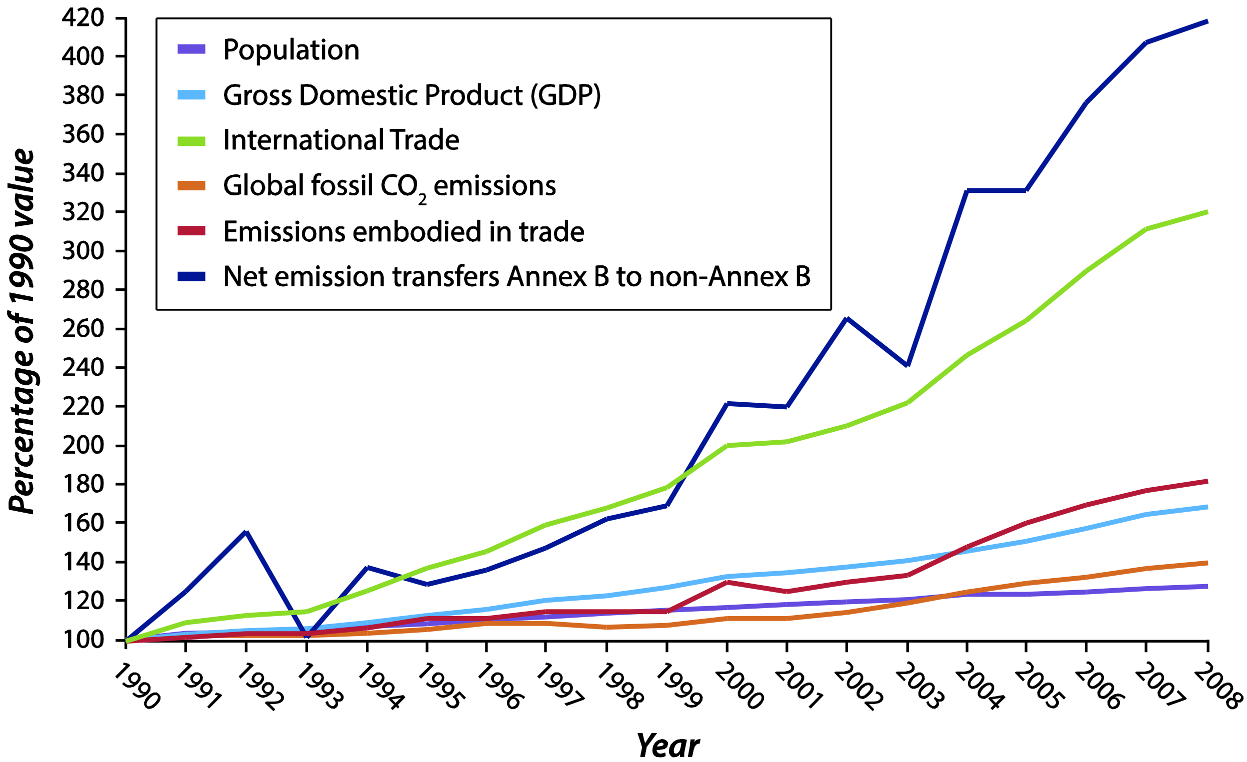

Figure 21-10: Growth rates from 1990-2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macrovariables, all indexed to 1990 (Peters et al., 2011). Annex B and non-Annex B Parties to the UNFCCC are listed in the supplementary material. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

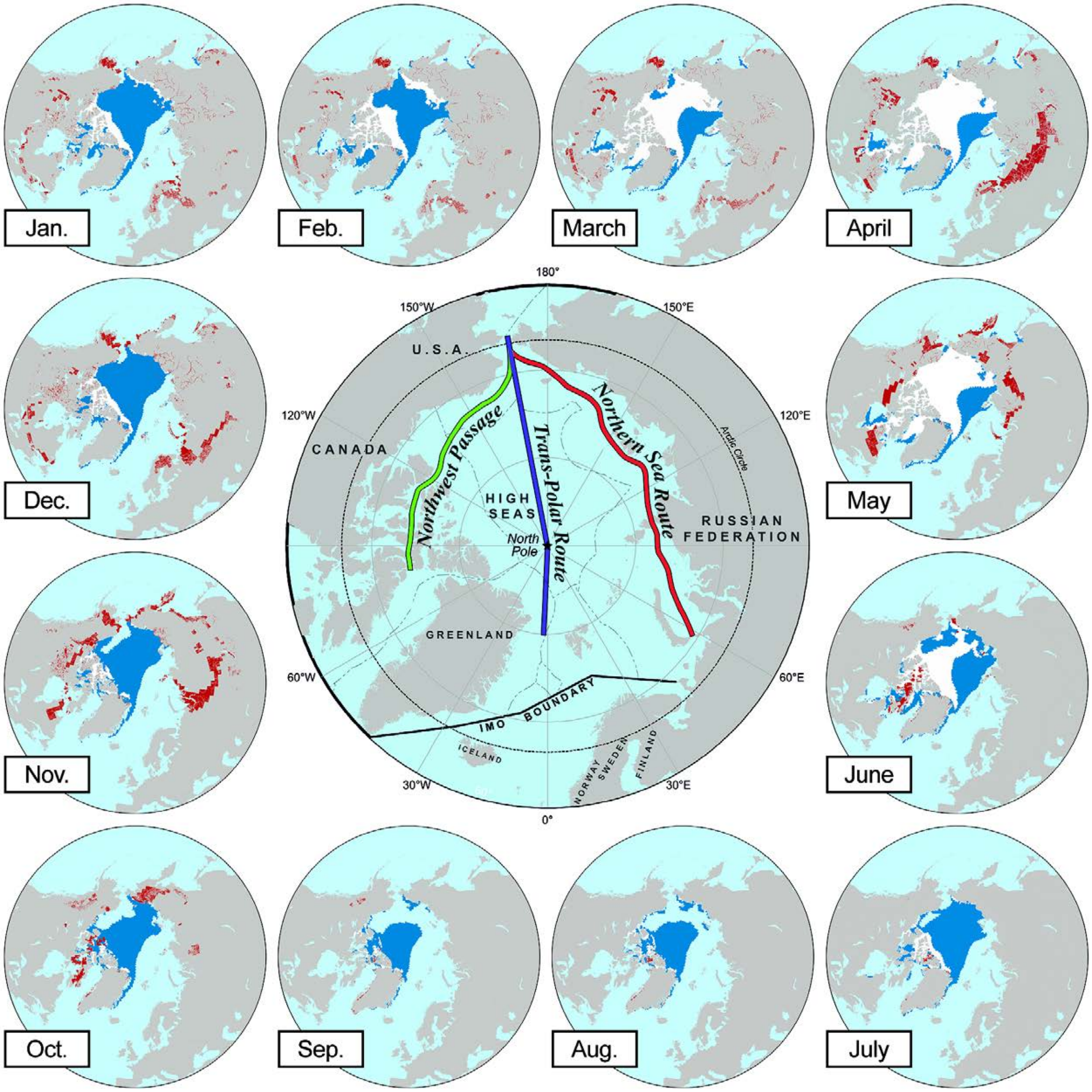

Figure 21-11: Central map: Marine exclusive environmental zones (EEZs – dashed lines) of Canada, Greenland/Denmark, Norway, Russia, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the IMO Guidelines Boundary for Arctic shipping (thick black border). After Stephenson et al. (2013). Peripheral monthly maps: Projected change in accessibility of maritime and land-based transportation by mid-century (2045-2059 relative to 2000-2014) using the Arctic Transport Accessibility Model and CCSM3 climate and sea ice estimates assuming an SRES A1B scenario. Dark blue areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).
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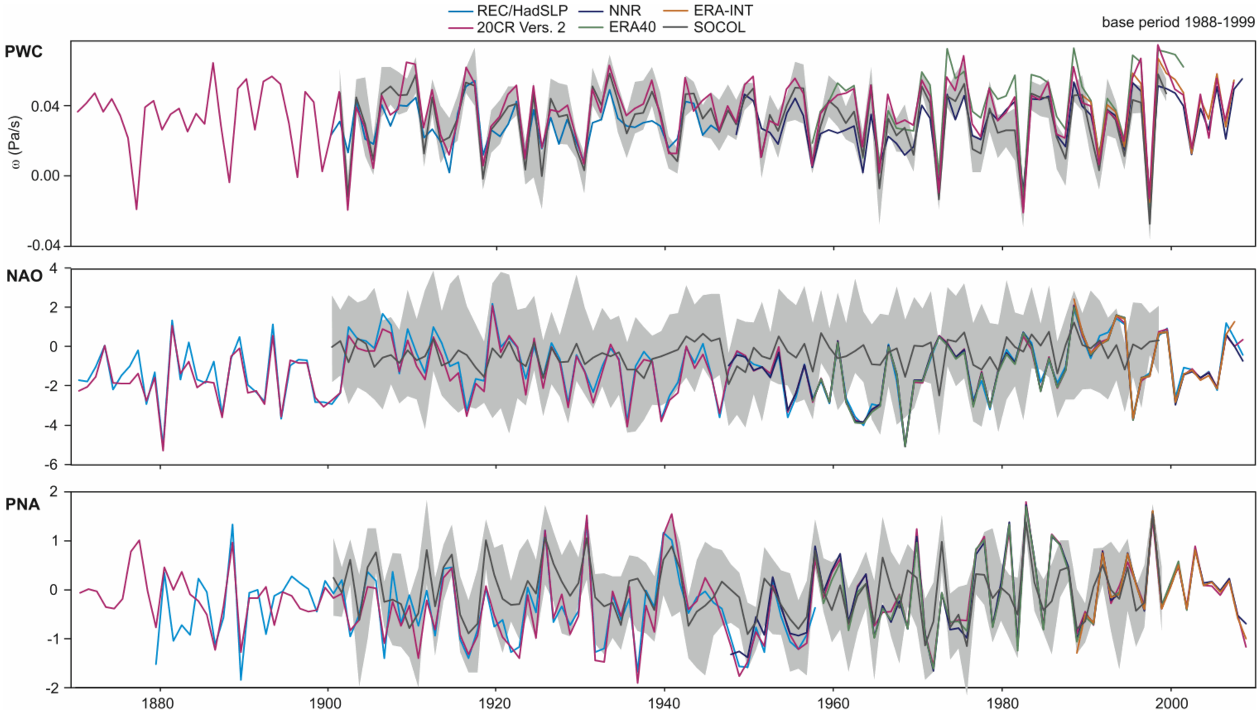

Figure 21-12: Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann etal. (2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis and model sources: statistical reconstructions of the PWC, the PNA and the NAO, see Brönnimann et al. (2009) for details, (all cyan); 20CR (pink); NCEP–NCAR reanalyses (NNR; dark blue); ERA-40 (green); ERA-Interim (orange). The black line and grey shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed seas-surface temperatures and sea-ice from the HadISST dataset (Rayner et al. 2003), see Brönnimann etal. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea-surface temperature and sea-ice alone and demonstrate that the reanalyses have significantly higher skill in reproduces these modes of variability. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

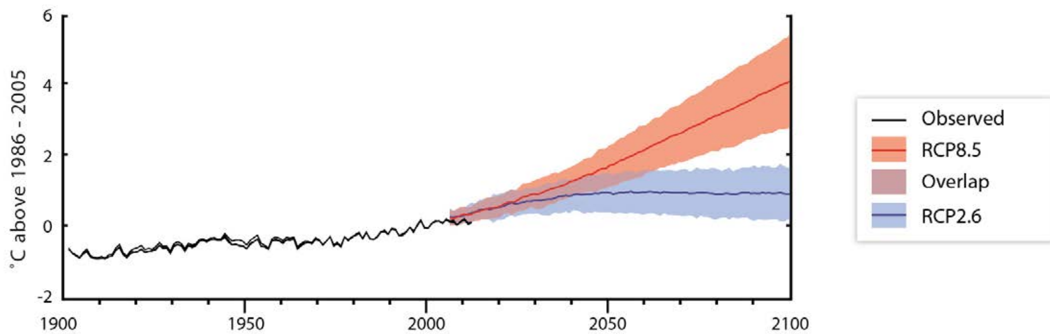

Figure RC-1: Observed and projected changes in global annual average temperature. Values are expressed relative to 1986-2005. Black lines show the GISTEMP, NCDC-MLOST, and HadCRUT4.2 estimates from observational measurements. Colored shading denotes the ±1.64 standard deviation range based on simulations from 32 models for RCP2.6 (blue) and 39 models for RCP8.5 (red). Blue and red lines denote the scenario mean for RCP2.6 and RCP8.5, respectively. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

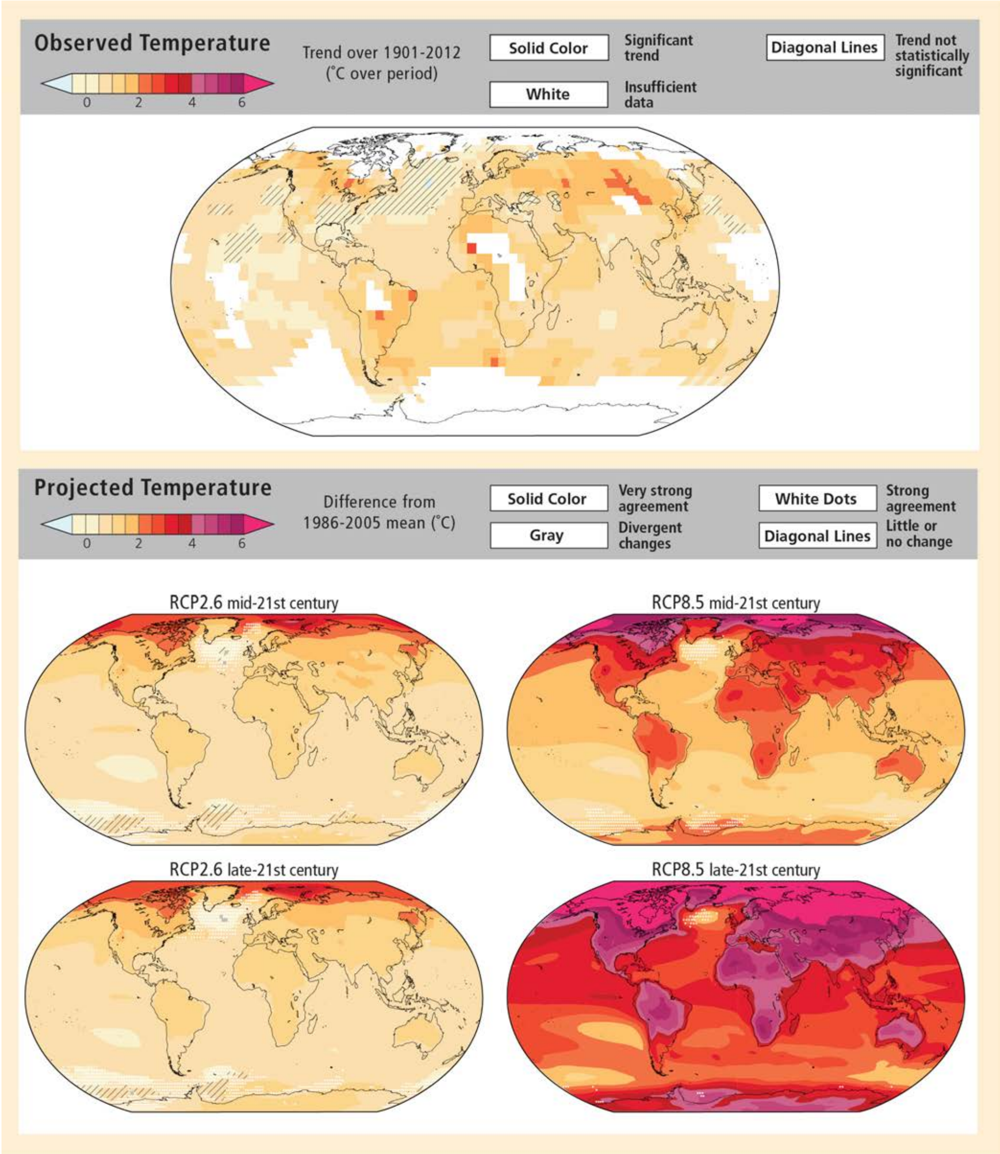

Figure RC-2: Observed and projected changes in annual average temperature. (A) Observed temperature trends from 1901-2012 are determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.1 and 2.21. The range of grid-point values is -0.53 to +2.50°C over period. (B) CMIP5 multi-model mean projections of annual average temperature changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, relative to 1986-2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability (although there may be significant change at shorter timescales such as seasons, months, or days). Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: +0.19 to +4.08˚C for mid-21st century of RCP2.6; +0.06 to +3.85˚C for late-21st century of RCP2.6; +0.70 to +7.04˚C for mid-21st century of RCP8.5; and +1.38 to +11.71°C for late-21st century of RCP8.5.

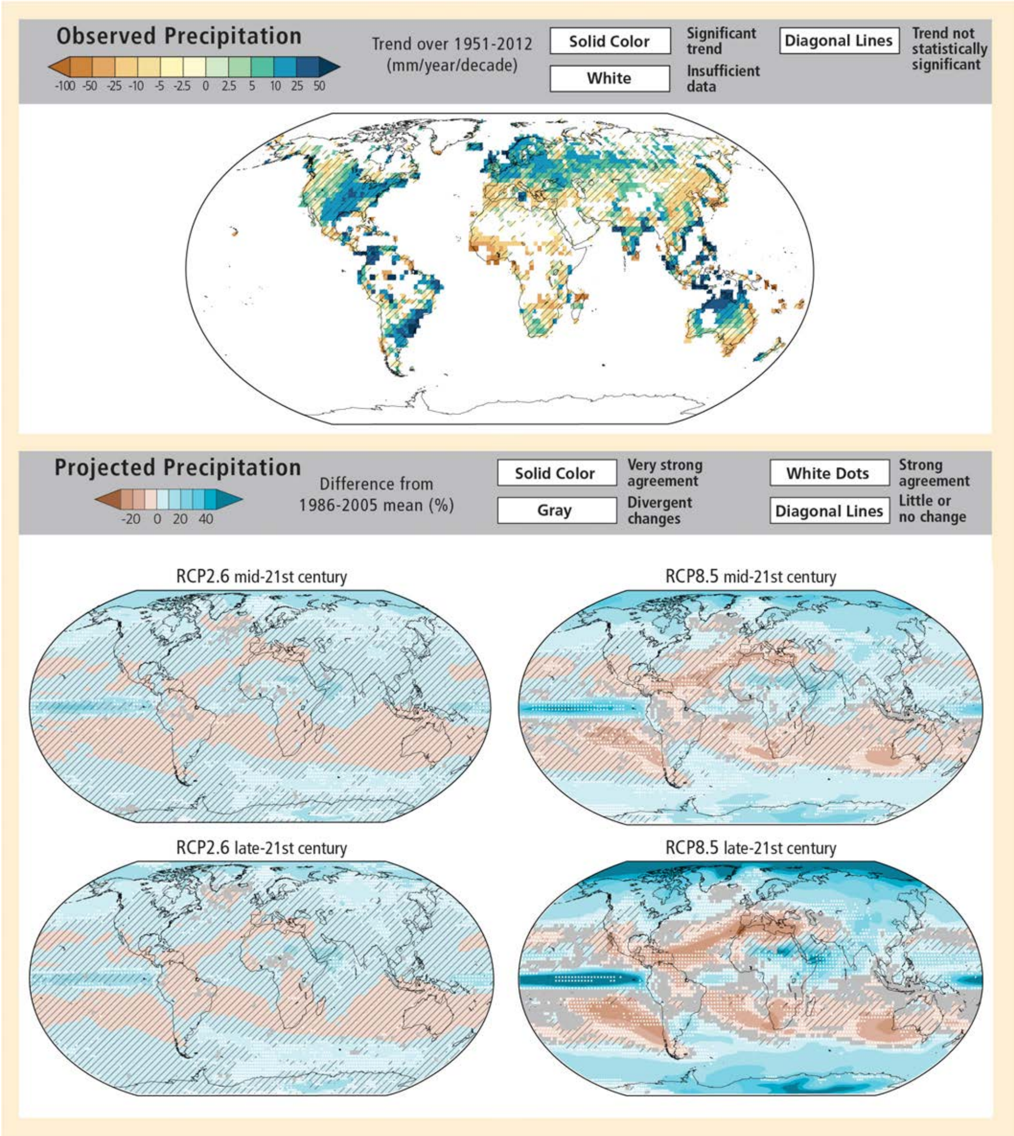

Figure RC-3: Observed and projected changes in annual average precipitation. (A) Observed precipitation trends from 1951-2010 are determined by linear regression. Trends have been calculated where sufficient data permit a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level (after accounting for autocorrelation effects on significance testing). Diagonal lines indicate areas where change is not significant. Observed data are from WGI AR5 Figures SPM.2. The range of grid-point values is -185 to +111 mm/year/decade. (B) CMIP5 multi-model mean projections of annual average precipitation changes for 2046-2065 and 2081-2100 under RCP2.6 and RCP8.5, relative to 1986-2005. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability and >90% of models agree on the sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on the sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on the sign of change. Colors with diagonal lines indicate areas with little or no change, where >66% of models show change less than the baseline variability (although there may be significant change at shorter timescales such as seasons, months, or days). Analysis uses model data from WGI AR5 Figure SPM.8, Box 12.1, and Annex I. The range of grid-point values for the multi-model mean is: -10 to +24% for mid-21st century of RCP2.6; -9 to +22% for late-21st century of RCP2.6; -19 to +57% for mid-21st century of RCP8.5; and -34 to +112% for late-21st century of RCP8.5.

Chapter 22. Africa

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Executive Summary

Evidence of warming over land regions across Africa, consistent with anthropogenic climate change, has increased (*high confidence*). Decadal analyses of temperatures strongly point to an increased warming trend across the continent over the last 50-100 years. [22.2.1.1]

Mean annual temperature rise over Africa, relative to the late 20th Century mean annual temperature, is *likely* to exceed 2° C in the A1B and A2 scenarios by the end of this century (*medium confidence*). Warming projections under medium scenarios indicate that extensive areas of Africa will exceed 2° C by the last two decades of this century relative to the late 20th Century mean annual temperature and all of Africa under high emission scenarios. Under a high RCP, that exceedence could occur by mid-century across much of Africa and reach between 3 and 6° C by the end of the century. It is *likely* that land temperatures over Africa will rise faster than the global land average, particularly in the more arid regions, and that the rate of increase in minimum temperatures will exceed that of maximum temperatures. [22.2.1.2]

A reduction in precipitation is *likely* over Northern Africa and the south-western parts of South Africa by the end of the 21st Century under the A1B and A2 scenarios (*medium to high confidence*). Projected rainfall change over sub-Sarahan Africa in the mid- and late 21st Century is uncertain. In regions of high or complex topography such as the Ethopian Highlands, downscaled projections indicate *likely* increases in rainfall and extreme rainfall by the end of the 21st Century. [22.2.2.2, 22.2.3]

African ecosystems are already being affected by climate change, and futre impacts are expected to be substantial (*high confidence*). There is emerging evidence on shifting ranges of some species and ecosystems due to elevated CO_2 and climate change, beyond the effects of land-use change and other non-climate stressors (*high confidence*). Ocean ecosystems, in particular coral reefs, will be affected by ocean acidification and warming as well as changes in ocean upwellings, thus negatively affecting economic sectors such as fisheries (*medium confidence*). [22.3.2, Table 22-3]

Climate change will amplify existing stress on water availability in Africa (*high confidence*). Water resources are subjected to high hydro-climatic variability over space and time, and are a key constraint on the continent’s continued economic development. The impacts of climate change will be superimposed onto already water-stressed catchments with complex land uses, engineered water systems, and a strong historical socio-political and economic footprint. Strategies that integrate land and water management, and disaster risk reduction, within a framework of emerging climate change risks would bolster resilient development in the face of projected impacts of climate change. [22.3.2.2, 22.3.3]

Climate change will interact with non-climate drivers and stressors to exacerbate vulnerability of agricultural systems, particularly in semi-arid areas (*high confidence*). Increasing temperatures and changes in precipitation are *very likely* to reduce cereal crop productivity. This will have strong adverse effects on food security. New evidence is also emerging that high-value perennial crops could also be adversely affected by temperature rise (*medium confidence*). Pest, weed and disease pressure on crops and livestock is expected to increase as a result of climate change combined with other factors (*low confidence*). Moreover, new challenges to food security are emerging as a result of strong urbanization trends on the continent and increasingly globalized food chains, which require better understanding of the multi-stressor context of food and livelihood security in both urban and rural contexts in Africa. [22.3.4, 22.3.4.3, 22.3.4.5]

Progress has been achieved on managing risks to food production from current climate variability and near-term climate change but these will not be sufficient to address long-term impacts of climate change (*high confidence*). Livelihood-based approaches for managing risks to food production from multiple stressors, including rainfall variability, have increased substantially in Africa since the IPCC's Fourth Assessment Report (AR4). While these efforts can improve the resiliency of agricultural systems in Africa over the near term, current adaptations will be insufficient for managing risks from long-term climate change, which will be variable across regions and farming system types. Nonetheless, processes such as collaborative, participatory research that includes scientists and farmers, strengthening of communication systems for anticipating and responding to climate risks, and increased flexibility in livelihood options, which serve to strengthen coping strategies in agriculture for near-term risks from climate variability, provide potential pathways for strengthening adaptive capacities for climate change. [22.4.5.4, 22.4.5.7, 22.4.6, 22.6.2]

Climate change may increase the burden of a range of climate-relevant health outcomes (*medium confidence*). Climate change is a multiplier of existing health vulnerabilities (*high confidence*) including insufficient access to safe water and improved sanitation, food insecurity, and limited access to health care and education. [22.3.5.1] Detection and attribution of trends is difficult because of the complexity of disease transmission, with many drivers other than weather and climate, and short and often incomplete datasets. Evidence is growing that highland areas, especially in East Africa, could experience increased malaria epidemics due to climate change (medium evidence, very high agreement). The strong seasonality of meningococcal meningitis and associations with weather and climate variability suggest the disease burden could be negatively affected by climate change (*medium evidence* and *high agreement*). The frequency of leishmaniasis epidemics in sub-Saharan Africa is changing, with spatial spread to peri-urban areas and to adjacent geographic regions, with possible contributions from changing rainfall patterns (*low confidence*). Climate change is projected to increase the burden of malnutrition *(medium confidence*), with the highest toll expected in children. [22.3.5.3]

In all regions of the continent, national governments are initiating governance systems for adaptation and responding to climate change, but evolving institutional frameworks cannot yet effectively co-ordinate the range of adaptation initiatives being implemented (*high confidence)*. Progress on national and sub-national policies and strategies has initiated the mainstreaming of adaptation into sectoral planning. [22.4.4] However, incomplete, under-resourced and fragmented institutional frameworks and overall low levels of adaptive capacity, especially competency at local government level, to manage complex socio-ecological change translate into a largely *ad hoc* and project-level approach, which is often donor-driven. [22.4.2, 22.4.4.3, 22.4.4.4] Overall adaptive capacity is considered to be low. [22.4.2] Disaster risk reduction, social protection, technological and infrastructural adaptation, ecosystem-based approaches and livelihood diversification are reducing vulnerability, but largely in isolated initiatives. [22.4.5] and most adaptation remain autonomous and reactive to short-term motivations. [22.4.3, 22.4.4.5]

Conservation agriculture provides a viable means for strengthening resilience in agroecosystems and livelihoods that also advance adaptation goals *(high confidence*). A wide array of conservation agriculture practices, including agroforestry and farmer-managed natural tree regeneration, conservation tillage, contouring and terracing, and mulching are being increasingly adopted in Africa. These practices strengthen resilience of the land base to extreme events and broaden sources of livelihoods, both of which have strongly positive implications for climate risk management and adaptation. Moreover, conservation agriculture has direct adaptation-mitigation co-benefits. Addressing constraints to broader adoption of these practices, such as land tenure/usufruct stability, access to peer-to-peer learning, gender-oriented extension and credit and markets, as well as identification of perverse policy incentives would help to enable larger scale transformation of agricultural landscapes. [22.4.5.6, 22.4.5.7, 22.4.6, 22.6.2]

Despite implementation limitations, Africa's adaptation experiences nonetheless highlight valuable lessons for enhancing and scaling up the adaptation response, including principles for good practice and integrated approaches to adaptation (*high confidence*). Five common principles for adaptation and building adaptive capacity can be distilled: (i) supporting autonomous adaptation through policy that recognises the multiple stressor nature of vulnerable livelihoods; (ii) increasing attention to the cultural, ethical, and rights considerations of adaptation by increasing the participation of women, youth and poor and vulnerable people in adaptation policy and implementation; [22.4.5] (iii) combining 'soft path' options and flexible and iterative learning approaches with technological and infrastructural approaches and blending scientific, local and indigenous knowledge when developing adaptation strategies; (iv) focusing on building resilience and implementing low-regrets adaptation with development synergies, in the face of future climate and socio-economic uncertainties; and (v) building adaptive management and social and institutional learning into adaptation processes at all levels. [22.4] Ecosystem-based approaches and pro-poor integrated adaptation-mitigation initiatives hold promise for a more sustainable and system-orientedapproach to adaptation, as does promoting equity goals, key for future resilience, through emphasising gender aspects and highly vulnerable groups such as children. . [22.4.2, 22.4.5.6, 22.6.2, Table 22-5]

Strengthened inter-linkages between adaptation and development pathways and a focus on building resilience would help to counter the current adaptation deficit and reduce future maladaptation risks (*high confidence*). [22.4.3] Development strategies are currently not able to counter current climate risks, as highlighted by the impacts of recent extreme events; national policies that disregard cultural, traditional and context-specific factors can act as barriers to local adaptation; and there is increased knowledge of maladaptation risks from narrowly conceived development interventions and sectoral adaptation strategies that decrease resilience in other sectors or ecosystems. [22.4.4, 22.4.6] Given multiple uncertainties in the African context, successful adaptation will depend upon building resilience. [22.4, 22.5, 22.6] Options for pro-poor adaptation/resilient livelihoods include improved social protection, social services and safety nets; better water and land governance and tenure security over land and vital assets; enhanced water storage, water harvesting and post-harvest services; strengthened civil society and greater involvement in planning; and more attention to urban and peri-urban areas heavily affected by migration of poor people. [22.4.2, 22.4.4, 22.4.5, 22.4.6]

Growing understanding of the multiple interlinked constraints on increasing adaptive capacity is beginning to indicate potential limits to adaptation in Africa (*medium confidence*). Climate change combined with other external changes (environmental, social, political, technological) may overwhelm the ability of people to cope and adapt, especially if the root causes of poverty and vulnerability are not addressed. Evidence is growing for the effectiveness of flexible and diverse development systems that are designed to reduce vulnerability, spread risk, and build adaptive capacity. These points indicate the benefits of new development trajectories that place climate resilience, ecosystem stability, equity and justice at the centre of development efforts. [22.4.6]

There is increased evidence of the significant financial resources, technological support and investment in institutional and capacity development needed to address climate risk, build adaptive capacity and implement robust adaptation strategies (*high confidence*). Funding and technology transfer and support isto both address Africa's current adaptation deficit and to protect rural and urban livelihoods, societies and economies from climate change impacts at different local scales. [22.4,] [22.6.4] Strengthening institutional capacities and governance mechanisms to enhance the ability of national governments and scientific institutions in Africa to absorb and effectively manage large amounts of funds allocated for adaptation, will assure the effectiveness of adaptation initiatives (*medium confidence*). [22.6.4]

Climate change and climate variability have the potential to exacerbate or multiply existing threats to human security including food, health and economic insecurity, all being of particular concern for Africa (*medium confidence*). [22.6.1, 22.6.1.1] Many of these threats are known drivers of conflict (*high confidence*). Causality between climate change and violent conflict is difficult to establish due to the presence of these and other interconnected causes, including country-specific sociopolitical, economic and cultural factors. For example, the degradation of natural resources as a result of both overexploitation and climate change will contribute to increased conflicts over the distribution of these resources. [22.6.1.1] Many of the interacting social, demographic and economic drivers of observed urbanization and migration in Africa are sensitive to climate change impacts. [22.6.1.2]

A wide range of data and research gaps constrain decisionmaking in processes to reduce vulnerability, build resilience and plan and implement adaptation strategies at different levels in Africa (*high confidence)*.

Overarching data and research gaps identified include data management and monitoring of climate parameters and development of climate change scenarios; monitoring systems to address climate change impacts in the different sectors; research and improved methodologies to assess and quantify the impact of climate change on different sectors and systems; and socio-economic consequences of the loss of ecosystems, of economic activities, of certain mitigation choices, such as biofuels, and of adaptation strategies. [22.7]

Of nine climate-related key regional risks identified for Africa, eight pose medium or higher risk even with highly adapted systems, while only one key risk assessed can be potentially reduced with high adaptation to below a medium risk level, for the end of the 21st century under 2°C global mean temperature increase above pre-industrial levels (*medium confidence*). Key regional risks relating to shifts in biome distribution, loss of coral reefs, reduced crop productivity, adverse effects on livestock, vector- and water-borne diseases, undernutrition, and migration are assessed as either medium or high for the present under current adaptation, reflecting Africa's existing adaptation deficit. [22.3.1, 22.3.2, 22.3.4, 22.3.5, 22.6.1.2] The assessment of significant residual impacts in a 2°C world at the end of the 21st century suggests that even under high levels of adaptation, there could be very high levels of risk for Africa. At a global mean temperature increase of 4°C, risks for Africa's food security (see key risks on livestock and crop production) are assessed as very high, with limited potential for risk reduction through adaptation. [22.3.4, 22.4.5, 22.5, Table 22-6]

22.1. Introduction

Africa as a whole is one of the most vulnerable continents due to its high exposure and low adaptive capacity Climate, ecology and political boundaries in Africa vary across the continent. Since the African Union, together with its Regional Economic Communities (RECs), are encharged of the adaptation policies we have used these divisions for regional assessment within the chapter.

22.1.1. Structure of the Regions

The African continent (including Madagascar) is the world's second largest and most populous continent (1,031,084,000 in 2010) behind Asia (UN DESA, 2013). The continent is organized at the regional level under the African Union (AU).[1] The AU's Assembly of Heads of State and Government has officially recognized eight Regional Economic Communities (RECs) (Ruppel, 2009). Except for the Sahrawi Arab Democratic Republic,[2] all AU member states are affiliated with one or more of these RECs. These RECs include the Arab Maghreb Union (AMU), with 5 countries in Northern Africa; the Community of Sahel-Saharan States (CEN-SAD), grouping 27 countries; the Common Market for Eastern and Southern Africa (COMESA), grouping 19 countries in Eastern and Southern Africa; the East African Community (EAC), with 5 countries; the Economic Community of Central African States (ECCAS), with 10 countries; the Economic Community of West African States (ECOWAS), with 15 countries; the Intergovernmental Authority on Development (IGAD) with 8 countries; and the Southern African Development Community (SADC), with 15 countries. The regional subdivision of African countries into REC's is a structure used by the AU and the New Partnership for Africa (NEPAD).

[FOOTNOTE 1: Due to the controversies regarding the Sahrawi Arab Democratic Republic, Morocco withdrew from the Organization of African Unity (OAU) in protest in 1984 and, since South Africa's admittance in 1994, remains the only African nation not within what is now the AU.]

[FOOTNOTE 2: Although the Sahrawi Arab Democratic Republic has been a full member of the OAU since 1984 and remains a member of the AU, the republic is not generally recognized as a sovereign state and has no representation in the UN.]

22.1.2. Major Conclusions from Previous Assessments

22.1.2.1. Regional Special Report and Assessment Reports

Refer to Table 22-1 for a brief summary of conclusions from previous IPCC assessments.

[INSERT TABLE 22-1 HERE
Table 22-1: Major conclusions from previous IPCC assessments.]

22.1.2.2. Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)

The Special Report of the IPCC on managing the risks of extreme events and disasters to advance climate change adaptation (IPCC, 2012) is of particular relevance to the African continent. There is *low* to *medium confidence* in historical extreme temperature and heavy rainfall trends over most of Africa because of partial lack of data, literature and lack of consistency of reported patterns in the literature (Seneviratne *et al.*, 2012). However, most regions within Africa for which data is available have recorded an increase in extreme temperatures (Seneviratne *et al.*, 2012). For projected temperature extreme there is *high confidence* that heat waves and warm spell durations will increase, suggesting an increased persistence of hot days (90^{th} percentile) toward the end of the century (Tebaldi *et al.*, 2006; Orlowsky and Seneviratne, 2012). There is *high confidence* for projected shorter extreme maximum temperature return periods across the B1, A1B and A2 scenarios for the near and far future as well as a reduction of the number of cold extremes (Seneviratne *et al.*, 2012). In East and southern Africa, there is *medium confidence* that droughts will intensify in the 21st Century in some seasons, due to reduced precipitation and/or increased evapotranspiration. There is *low confidence* in projected increases of heavy precipitation over most of Africa except over East Africa where there is a *high confidence* in a projected increase in heavy precipitation (Seneviratne *et al.*, 2012).

22.2. Observed Climate Trends and Future Projections

22.2.1. Temperature

22.2.1.1. Observed Trends

Near surface temperatures have increased by 0.5°C or more during the last 50-100 years over most parts of Africa with minimum temperatures warming more rapidly than maximum temperatures (Hulme *et al.*, 2001; Jones and Moberg, 2003; Kruger and Shongwe, 2004; Schreck and Semazzi, 2004; New *et al.*, 2006; IPCC, 2007; Rosenzweig *et al*., 2007; Trentberth *et al.*, 2007; Christy *et al.*, 2009; Collins 2011; Grab and Craparo, 2011; Hoffman *et al.*, 2011; Mohamed, 2011; Stern *et al.* 2011; Funk *et al*., 2012; Nicholson *et al.*, 2013). Near surface air temperature anomalies in Africa were significantly higher for the period 1995–2010 compared to the period 1979–1994 (Collins, 2011). Figure 22-1 shows that it is *very likely* that mean annual temperature has increased over the past century over most of the African continent, with the exception of areas of the interior of the continent where the data coverage has been determined to be insufficient to draw conclusions about temperature trends (Figure 22-1, Box CC-RC). There is strong evidence of an anthropogenic signal in continent-wide temperature increases in the 20th century (WGI 10.3.1; Stott, 2003; Min and Hense, 2007, Stott *et al.*, 2010; Stott *et al.*, 2011).

In recent decades North African annual and seasonal observed trends in mean near surface temperature indicates an overall warming that is significantly beyond the range of changes due to natural (internal) variability (Barkhordarian *et al*., 2012a). During the warm seasons (March-April-May, June-July-August) an increase in near surface temperature is shown over north Algeria and Morocco which is very unlikely due to natural variability or natural forcing alone (Barkhordarian et al., 2012b). The region has also experienced positive trends in annual minimum and maximum temperature (Vizy and Cook, 2012).

Over West Africa and the Sahel near surface temperatures have increased over the last 50 years. Using indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI), New *et al.* (2006) show the number of cold days and cold nights have decreased and the number of warm days and warm nights have increased between 1961 and 2000. Many of these trends are statistically significant at the 90% level and they find similar trends in extreme temperature indices. Collins (2011) shows statistically significant warming of between 0.5-0.8 degrees between 1970 and 2010 over the region using remotely sensed data with a greater magnitude of change in the latter 20 years of the period compared to the former.

The equatorial and southern parts of eastern Africa have experienced a significant increase in temperature since the beginning of the early 1980s (Anyah and Qiu, 2012). Similarly, recent reports from the Famine Early Warning Systems Network (FEWS NET) indicate that there has been an increase in seasonal mean temperature in many areas of Ethiopia, Kenya, South Sudan, and Uganda over the last 50 years (Funk *et al.*, 2011, 2012). In addition, warming of the near surface temperature and an increase in the frequency of extreme warm events has been observed for countries bordering the western Indian Ocean between 1961 and 2008 (Vincent *et al.*, 2011b).

In recent decades, most of southern Africa has also experienced upward trends in annual mean, maximum, and minimum temperature over large extents of the subregion during the last half of the 20th century, with the most significant warming occurring during the last two decades (Zhou *et al.*, 2010; Collins, 2011; Kruger and Sekele, 2012). Minimum temperatures have increased more rapidly relative to maximum temperatures over inland southern Africa (New *et al.*, 2006).

22.2.1.2. Projected Trends

Temperatures in Africa are projected to rise faster than the global average increase during the 21st Century (Christensen *et al.*, 2007; Joshi *et al.* 2011; Sanderson *et al.*, 2011; James and Washington, 2013). Global average near-surface air temperature are projected to move beyond 20th Century simulated variability by 2069 (±18 years) under RCP4.5 and by 2047 (±14 years) under RCP8.5 (Mora *et al.* 2013). However, in the tropics, especially tropical West Africa, these unprecedented climates are projected to occur one to two decades earlier the global average because the relatively small natural climate variability in this region generates narrow climate bounds that can be easily surpassed by relatively small climate changes. Figure 22-1 shows projected temperature increases based on the CMIP5 ensemble. Increases in mean annual temperature over all land areas are *very likely* in the mid- and late-21st-century periods for RCP2.6 and RCP8.5 (Figure 22-1, Box CC-RC). Ensemble-mean changes in mean annual temperature exceed 2˚C above the late-20th-century baseline over most land areas of the continent in the mid-21st-century for RCP8.5, and exceed 4˚C over most land areas in the late-21st-century for RCP8.5. Changes in mean annual temperature for RCP8.5 follow a pattern of larger changes in magnitude over northern and southern Africa, with (relatively) smaller changes in magnitude over central Africa. The ensemble-mean changes are less than 2˚C above the late-20th-century baseline in both the mid- and late-21st-century for RCP2.6.

Over North Africa under the A1B scenario, both annual minimum and maximum temperature are *likely* to increase in the future, with greater increase in minimum temperature (Vizy and Cook, 2012). The faster increase in minimum temperature is consistent with greater warming at night, resulting in a decrease in the future extreme temperature range (Vizy and Cook, 2012). Higher temperature increases are projected during boreal summer by CMIP5 GCMs (WGI Annex 1). A strengthening of the North African thermal low in 21st century is associated with a surface temperature increase (Paeth *et al.*, 2009; Patricola and Cook, 2010; Barkhordarian *et al.*, 2012a; Cook and Vizy, 2012).

Temperature projections over West Africa for the end of the 21st Century from both the CMIP3 GCMs (A2 and A1B scenarios) and CMIP5 GCMs (RCP4.5 and RCP8.5) range between 3-6°C above the late 20th Century baseline (Meehl *et al.* 2007; Fontaine *et al*. 2011; Diallo *et al.*, 2012; Monrie *et al*. 2012; Figure 22-1; Figure 22-2). Regional downscalings over the region produce a similar range of projected change (Patricola and Cook, 2010; Mariotti *et al.*, 2011; Patricola and Cook, 2011; Vizy *et al.*, 2012). Diffenbaugh and Giorgi (2012) identify the Sahel and tropical West Africa as a hotspot of climate change for both RCP4.5 and RCP8.5 pathways and unprecedented climates are projected to occur earliest (late 2030s to early 2040s) in these regions (Mora *et al.*, 2013).

Climate model projections under the A2 and B1 scenarios over Ethiopia show warming in all four seasons across the country, which may cause a higher frequency of heat waves as well as higher rates of evaporation (Conway and Schipper, 2011). Projected maximum and minimum temperatures over equatorial eastern Africa show a significant increase in the number of days warmer than 2°C above the 1981–2000 average by the middle and end of the 21st century under the A1B and A2 scenarios (Anyah and Qiu, 2012). Elshamy *et al*. (2009) show a temperature increase over the upper Blue Nile of between 2°C and 5°C at the end of the 21st Century under the A1B scenario compared to a 1961-1990 baseline.

Mean land surface warming in Southern Africa is *likely* to exceed the global mean land surface temperature increase in all seasons (Sillmann and Roeckner, 2008; Watterson, 2009; Mariotti *et al.*, 2011; James and Washington, 2013; Orlowsky and Seneviratne, 2012). Furthermore, towards the end of the 21st Century the projected warming of between 3.4-4.2ºC above the 1981-2000 average under the A2 scenario far exceeds natural climate variability (Moise and Hudson, 2008). High warming rates are projected over the semi-arid southwestern parts of the subregion covering northwestern South Africa, Botswana, and Namibia (WGI Annex 1; Moise and Hudson, 2008; Engelbrecht *et al.*, 2009; Watterson, 2009; Shongwe *et al.*, 2009). Observed and simulated variations in past and projected future annual average temperature over five African regions (UMA, SADC, ECCAS, ECOWAS, and COMESA) are captured in Figure 22-2 which indicates the projected temperature rise is *very likely* to exceed the 1986-2005 baseline by between 3 and 6 °C across these regions by the end of this century under RCP8.5.

[INSERT FIGURE 22-1 HERE
Figure 22-1: Observed and simulated variations in past and projected future annual average precipitation and temperature. Observed differences in the Climate Research Unit, University of East Anglia data (CRU) are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Grey indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st Century period is 2081-2100. The mid-21st century period is 2046-2065.]

[INSERT FIGURE 22-2 HERE
Figure 22-2: Observed and simulated variations in past and projected future annual average temperature over EAC-IGAD-Egypt, ECCAS, ECOWAS, SADC and UMA. Black lines show various estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the "RCP2.6" emissions scenario (63), and the "RCP8.5" (63). Data are anomalies from the 1986-2005 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

22.2.2. Precipitation

22.2.2.1. Observed Changes

Most areas of the African continent lack sufficient observational data to draw conclusions about trends in annual precipitation over the past century (Figure 22-1, Box CC-RC). Additionally, in many regions of the continent discrepancies exist between different observed precipitation datasets (Nikulin *et al.* 2012; Sylla *et al.*, 2012; Kim *et* *al*. 2013; Kalognomou *et al.*, 2013). Areas where there are sufficient data include *very likely* decreases in annual precipitation over the past century over parts of the western and eastern Sahel region in northern Africa, along with *very likely* increases over parts of eastern and southern Africa.

Over the last few decades the northern regions of North Africa (north of the Atlas Mountains and along the Mediterranean coast of Algeria and Tunisia) have experienced a strong decrease in the amount of precipitation received in winter and early spring (Barkhordarian *et al.,* 2013). The observed record also indicates greater than 330 dry days (with less than 1 mm/day rainfall) per year over the 1997 - 2008 time period (Vizy and Cook, 2012). However, in autumn (September, October, November) observations show a positive trend in precipitation in some parts of North Algeria and Morocco (Barkhordarian *et al.*, 2013). The Sahara Desert, which receives less than 25 mm/year, shows little seasonal change (Liebmann *et al*., 2012).

Rainfall over the Sahel has experienced an overall reduction over the course of the 20th Century with a recovery toward the last 20 years of the century (WGI 14.3.7.1; Nicholson *et al.*, 2000; Lebel and Ali, 2009; Ackerley *et al.,* 2011; Mohamed, 2011; Biasutti, 2013). The occurrence of a large number of droughts in the Sahel during the 1970s and 1980s is well documented and understood (Biasutti and Giannini, 2006; Biasutti *et al.*, 2008; Greene *et al.*, 2009). The recovery of the rains may be due to natural variability (Mohino *et al*., 2011) or a forced response to increased greenhouse gases (Haarsma *et al*., 2005; Biasutti, 2013) or reduced aerosols (Ackerley *et al.*, 2011).

Precipitation in eastern Africa shows a high degree of temporal and spatial variability dominated by a variety of physical processes (Rosell and Holmer, 2007; Hession and Moore, 2011). Williams and Funk (2011) and Funk *et al*. (2008) indicate that over the last three decades rainfall has decreased over eastern Africa between March and May/June. The suggested physical link to the decrease in rainfall is the rapid warming of Indian Ocean, which causes an increase in convection and precipitation over the tropical Indian Ocean and thus contributes to increased subsidence over eastern Africa and a decrease in rainfall during March to May/June (Funk *et al.*, 2008; Williams and Funk, 2011). Similarly, Lyon and DeWitt (2012) show a decline in the March–May seasonal rainfall over eastern Africa. Summer (June–September) monsoonal precipitation has declined throughout much of the Great Horn of Africa over the last 60 years [during the 1948–2009 period; Williams *et al.*, (2012)] as a result of the changing sea level pressure (SLP) gradient between Sudan and the southern coast of the Mediterranean Sea and the southern tropical Indian Ocean region (Williams *et al.*, 2012).

Over Southern Africa a reduction in late austral summer precipitation has been reported over its western parts, extending from Namibia, through Angola, and toward the Congo during the second half of the 20th Century (Hoerling *et al.*, 2006; New *et al*., 2006). The drying is associated with an upward trend in tropical Indian Ocean Sea Surface Temperatures (SSTs). Modest downward trends in rainfall are found in Botswana, Zimbabwe, and western South Africa. Apart from changes in total or mean summer rainfall, certain intra-seasonal characteristics of seasonal rainfall such as onset, duration, dry spell frequencies, and rainfall intensity as well as delay of rainfall onset have changed (Tadross *et al.*, 2005; Thomas *et al.*, 2007; Tadross *et al.*, 2009; Kniveton *et al.*, 2009). An increasing frequency of dry spells is accompanied by an increasing trend in daily rainfall intensity which has implications for run-off characteristics (New *et al.*, 2006).

22.2.2.2. Projected Changes

Precipitation projections are more uncertain than temperature projections (Rowell, 2012) and exhibit higher spatial and seasonal dependence than temperature projections (Orlowsky and Seneviratne, 2012). The CMIP5 ensemble projects *very likely* decreases in mean annual precipitation over the Mediterranean region of northern Africa in the mid- and late-21st century periods for RCP8.5 (Figure 22-1, Box CC-RC). CMIP5 also projects *very likely* decreases in mean annual precipitation over areas of southern Africa beginning in the mid-21st-century for RCP8.5 and expanding substantially in the late-21st-century for RCP8.5. In contrast, CMIP5 projects *likely* increases in mean annual precipitation over areas of central and eastern Africa beginning the mid-21st-century for RCP8.5. Most areas of the African continent do not exhibit changes in mean annual precipitation that exceed the baseline variability in more than 66% of the models in either the mid- or late-21st-century periods for RCP2.6. Observed and simulated variations in past and projected future annual average precipitation over five African regions (UMA, ECCAS, ECOWAS, SADC and COMESA) are captured in Figure 22-2.

A reduction in rainfall over northern Africa is *very likely* by the end of the 21st Century. The annual and seasonal drying/warming signal over the Northern African region (including North of Morocco, Algeria, Libya, Egypt and Tunisia) is a consistent feature in the global (Giorgi and Lionello, 2008; Barkhordarian et al., 2013) and the regional (Lionello and Giorgi, 2007; Gao and Giorgi, 2008; Paeth *et al*., 2009; Patricola and Cook, 2010) climate change projections for the 21st Century under the A1B and A2 scenarios. Furthermore, over the northern basin of Tunisia, climate models under the A1B scenario project a significant decrease in the median, and 10th and 90th percentiles values of precipitation in winter and spring seasons (Bargaoui *et al*., 2013).

West African precipitation projections in the CMIP-3 and CMIP-5 archives show inter-model variation in both the amplitude and direction of change that is partially attributed to the inability of GCMs to resolve convective rainfall (WGI 14.8.7; Biasutti *et al.*, 2008; Druyan, 2011; Fontaine *et al*., 2011; Roehrig *et al.*, 2013). Many CMIP-5 models indicate a wetter core rainfall season with a small delay to rainy season by the end of the 21st Century (WGI 14.8.7; Biasutti, 2013). However, regional climate models (RCMs) can alter the sign of rainfall change of the driving GCM especially in regions of high or complex topography (WGI 14.3.7.1; WGI 9.6.4; Sylla *et al.*, 2012; Cook and Vizy, 2013; Saeed *et al.* 2013). There is therefore *low* to *medium confidence* in the robustness of projected regional precipitation change until a larger body of regional results become available through, for example, the coordinated regional downscaling experiment, CORDEX (Giorgi *et al*., 2009, Jones *et al*., 2011, Hewitson *et al.*, 2012).

An assessment of 12 CMIP-3 GCMs over eastern Africa suggest that by the end of the 21st Century there will be a wetter climate with more intense wet seasons and less severe droughts during October-November-December (OND) and March-April-May (MAM) (WGI 14.8.7; Moise and Hudson, 2008; Shongwe *et al.*, 2011). These results indicate a reversal of historical trend in these months (Williams and Funk, 2011; Funk *et al*. 2008). Lyon and DeWitt (2012) ascribe this reversal to recent cooling in the eastern equatorial Pacific that offsets the equatorial Pacific SST warming projected by CMIP3 GCMs in future scenarios. However, GCM projections over Ethiopia indicate a wide range of rainfall spatial pattern changes (Conway and Schipper, 2011) and in some regions GCMs do not agree on the direction of precipitation change, e.g. in the upper Blue Nile basin in the late 21st Century (Elshamy *et al*., 2009). Regional climate model studies suggest drying over most parts of Uganda, Kenya, and South Sudan in August and September by the end of the 21st Century as a result of a weakening Somali jet and Indian monsoon (Patricola and Cook, 2011). Cook and Vizy (2013) indicate truncated boreal spring rains in the mid-21st Century over eastern Ethiopia, Somalia, Tanzania and southern Kenya while the boreal fall season is lengthened in the southern Kenya and Tanzania (Nakaegawa *et al*., 2012). These regional studies highlight the importance of resolving both regional scale atmospheric processes and local effects like land surface on rainfall simulation across the region (WGI 14.8.7).

Over southern Africa CMIP3 GCM projections show a drying signal in the annual mean over the climatologically dry southwest, extending northeastward from the desert areas in Namibia and Botswana (Moise and Hudson, 2008; James and Washington, 2013; Orlowsky and Seneviratne, 2012). This pattern is replicated by CMIP5 GCMs (see Figure 22-1). During the austral summer months, dry conditions are projected in the southwest while downscaled projections indicate wetter conditions in the southeast of South Africa and the Drakensberg mountain range (Hewitson and Crane, 2006; Engelbrecht *et al.*, 2009). Consistent with the AR4, drier winters are projected over a large area in southern Africa by the end of the century as a result of the poleward displacement of mid-latitude storm tracks (WGI 14.8.7; Moise and Hudson, 2008; Engelbrecht *et al.*, 2009; Shongwe *et al.*, 2009; Seth *et al.*, 2011; James and Washington, 2013). Rainfall decreases are also projected during austral spring months, implying a delay in the onset of seasonal rains over a large part of the summer rainfall region of Southern Africa (Shongwe *et al.*, 2009; Seth *et al.*, 2011). The sign, magnitude and spatial extent of projected precipitation changes are dependent on the coupled general circulation model (CGCM) employed, due primarily to parameterization schemes used and their interaction with model dynamics (Hewitson and Crane, 2006; Rocha *et al.*, 2008). Changes in the parameterization schemes of a single regional climate model produced opposite rainfall biases over the region (Crétat *et al*., 2012) so multiple ensemble downscalings, such as those being produced through CORDEX, are important to more fully describe the uncertainty associated with projected rainfall changes across the African continent (WGI 9.6.5; Laprise *et al.*, 2013).

22.2.3. Observed and Projected Changes in Extreme Temperature and Rainfall

In Northern Africa the north western Sahara experienced 40-50 heat wave days per year during the 1989-2009 time period (Vizy and Cook, 2012). There is a projected increase in this number of heat wave days over the 21st century (Patricola and Cook, 2010; Vizy and Cook, 2012).

Over West Africa there is *low* to *medium confidence* in projected changes of heavy precipitation by the end of the 21st Century based on CMIP-3 GCMs (Seneviratne *et al.*, 2012). Regional model studies suggest an increase in the number of extreme rainfall days over West Africa and the Sahel during May and July (Vizy and Cook, 2012) and more intense and more frequent occurrences of extreme rainfall over the Guinea Highlands and Cameroun Mountains (Sylla *et al.*, 2012; Haensler *et al*., 2013. The ability of regional climate models to resolve complex topography captures the amplifying role of topography in producing extreme rainfall that GCMs cannot.

Extreme precipitation changes over Eastern Africa such as droughts and heavy rainfall have been experienced more frequently during the last 30-60 years (Funk *et al.*, 2008; Williams and Funk, 2011; Shongwe *et al.*, 2011; Lyon and DeWitt, 2012). A continued warming in the Indian–Pacific warm pool has been shown to contribute to more frequent East African droughts over the past 30 years during the spring and summer seasons (Williams and Funk, 2011). It is unclear whether these changes are due to anthropogenic influences or multidecadal natural variability (Lyon and DeWitt, 2012; Lyon *et al.*, 2013). Projected increases in heavy precipitation over the region have been reported with high certainty in the SREX (Seneviratne *et al.*, 2012) and Vizy and Cook (2012) indicate an increase in the number of extreme wet days by the mid-20th Century.

Over southern Africa an increase in extreme warm ETCCDI indices (hot days, hot nights, hottest days) and a decrease in extreme cold indices (cold days and cold nights) in recent decades is consistent with the general warming trend (New *et al.*, 2006; Tebaldi *et al.*, 2006; Aguilar et al. 2009; Kruger and Sekele, 2012). The probability of austral summer heat waves over South Africa increased over the last two decades of the 20th century compared to 1961 to 1980 (Lyon, 2009). Enhanced heat wave probabilities are associated with deficient rainfall conditions that tend to occur during El Niño events. The southwestern regions are projected to be at a high risk to severe droughts during the 21st Century and beyond (Hoerling *et al.*, 2006; Shongwe *et al.*, 2011). Large uncertainties surround projected changes in tropical cyclone landfall from the southwest Indian Ocean that have resulted in intense floods during the 20th Century. Future precipitation projections show changes in the scale of the rainfall probability distribution, indicating that extremes of both signs may become more frequent in the future (Kay and Washington, 2008).

22.3. Vulnerability and Impacts

This section highlights Africa's vulnerability to climate change, as well as the main observed and potential impacts on natural resources, ecosystems, and economic sectors. Figure 22-3 summarizes the main conclusions regarding observed changes in regional climate and their relation to anthropogenic climate change (described in 22.2) as well as regarding observed changes in natural and human systems and their relation to observed regional climate change (described in this section). Confidence in detection and attribution of anthropogenically-driven climate change is highest for temperature measures. In many regions of Africa, evidence is constrained by limited monitoring. However, impacts of observed precipitation changes are amongst the observed impacts with the highest assessment of confidence, implying that some of the potentially more significant impacts of anthropogenic climate change for Africa are of a nature that challenges detection and attribution analysis (18.5.1).

[INSERT FIGURE 22-3 HERE
Left: Confidence in detection and in attribution of observed climate change over Africa to anthropogenic emissions. All detection assessments are against a reference of no change, while all attribution assessments concern a major role of anthropogenic emissions in the observed changes. See 22.2, and SREX-3, and WGI AR5 10 for details. Right: Confidence in detection and in attribution of the impacts of observed regional climate change on various African systems. All detection assessments are against a reference of no change, except "Kenyan Highlands malaria"

(changes due to vaccination, drug resistance, demography, and livelihoods), "Great Lakes fisheries" (changes due to fisheries management and land use) and “Adapting South African farmers” (economic changes). Attribution is to a major role or a minor role of observed climate change, as indicated. See 22.2.2, 22.3.2.1, 22.3.2.2, 2.3.3, 22.4.2, 22.3.4.4, 22.3.5.4, 22.4.5.7 and Tables 18-5, 18-6, 18-7, and 18-9 for details. Assessments follow the methods outlined in 18.2.]

22.3.1. Socioeconomic and Environmental Context Influencing Vulnerability and Adaptive Capacity

Equitable socioeconomic development in Africa may strengthen its resilience to various external shocks, including climate change. In 2009, the Human Rights Council adopted Resolution 10/4[3] which noted the effects of climate change on the enjoyment of human rights, and reaffirmed the potential of human rights obligations and commitments to inform and strengthen international and national policy making.

[FOOTNOTE 3: U.N. Doc. A/HRC/10/L.11.]

The impacts of climate change on human rights have been explicitly recognised by the African Commission on Human and Peoples’ Rights (hereafter African Commission) in its Resolution on Climate Change and Human Rights and the Need to Study its Impact in Africa (ACHPR/Res 153 XLV09). The 1981 African (Banjul) Charter on Human and Peoples’ Rights (hereafter African Charter) protects the right of peoples to a ‘general satisfactory environment favorable to their development’ (Article 24). The recognition of this right and the progressive jurisprudence by the African Commission in environmental matters underline the relevance of potential linkages between climate change and human rights (Ruppel, 2012).

The link between climate change and humans is not only associated with human rights. Rather, strong links exist between climate change and the MDGs: climate change may adversely affect progress toward attaining the MDGs, as climate change can increase the pressure not only economic activities, such as agriculture (22.3.4) and fishing (22.3.4.4) but also adversely affect urban areas located in coastal zones (22.3.6). Slow progress in attaining most MDGs may, meanwhile, reduce the resilience and adaptive capabilities of African individuals, communities, states, and nations (ECA *et al.*, 2009, 2012; UNDP *et al*., 2011).

The African continent has made significant progress on some MDGs; however, not all MDGs have been achieved, yet with high levels of spatial and group disparities. Additionally, progress on all MDG indicators is skewed in favor of higher-income groups and urban populations, which means further marginalization of already excluded groups (UN *et al.*, 2008; AfDB *et al.*, 2010; World Bank and IMF, 2010). As a whole, the continent is experiencing a number of demographic and economic constraints, with the population having more than doubled since 1980; exceeding one billion in 2010 and expected to reach three billion by the year 2050, should fertility remain constant (Muchena *et al.*, 2005; Fermont *et al.*, 2008; UN DESA, 2011). The global economic crisis is adding additional constraints on economic development efforts leading to increased loss of livelihood and widespread poverty (Moyo, 2009; Easterly, 2009; Adesina, 2010). The percent of the population below the poverty line has decreased from 56.5% in 1990 to 47.5% in 2008 (excluding North Africa); however a significant proportion of the population living below the poverty line remains chronically poor (ECA *et al.*, 2012). Although poverty in rural areas in Sub-Saharan Africa has declined from 64.9% in 1998 to 61.6% in 2008, it is still double the prevailing average in developing countries in other regions (IFAD, 2010).

Agriculture, which is the main economic activity in terms of employment share, is 98% rain fed in the sub-Saharan region (FAO, 2002).[4] Stagnant agricultural yields, relative to the region’s population growth, have led to a fall in per capita food availability since the 1970s (UN *et al.*, 2008).[5] Such stagnation was reversed with an improved performance of the agricultural sector in sub Saharan Africa during the 2000–2010. However, most of this improvement was the result of countries recovering from the poor performance of the 1980s and 1990s along with favorable domestic prices (Nin-Pratt *et al.*, 2012).

In addition, recent increases in global food prices aggravate food insecurity among the urban poor, increasing the risk of malnutrition and its consequences (UN *et al.*, 2008). For example, it was estimated that the global rise in food prices has contributed to the deaths of an additional 30,000 to 50,000 children suffering from malnutrition in 2009 in sub-Saharan Africa (Friedman and Schady, 2009) see Table 22.2. This situation may be complicated further by changes in rainfall variability and extreme weather events affecting the agriculture sector (Yabi and Afouda, 2012).

In response, the New Partnership for Africa's Development (NEPAD) was founded in 2001, for Africans to take the lead in efforts to achieve the development vision espoused in the AU Constitutive Act as well as the MDGs and to support regional integration as a mechanism for inclusive growth and development in Africa (NEPAD *et al.*, 2012). Furthermore, the Comprehensive Africa Agriculture Development Program (CAADP), which works under the umbrella of NEPAD, was established in 2003 to help African countries reach a higher path of economic growth through agriculture-led development. For this to happen, it focuses on four pillars for action: land and water management, market access, food supply and hunger, and agricultural research (NEPAD, 2010).

[INSERT TABLE 22-2 HERE
Table 22-2: Under-nourishment in Africa, by number and % of total population.]

[FOOTNOTE 4: However, mining and energy sectors, where active, are undergoing expansion, stimulating growth and adding potentially to state revenues but are also highly vulnerable to global recession. overall, the limited production and export structures of the continent are likely to maintain its historical vulnerability to external shocks (ECA and AUC, 2011).]

[FOOTNOTE 5: Lack of extension services for farmers in Africa can also contribute to low utilization and spread of innovations and technologies that can help mitigate climate change.]

Africa has made much progress in the achievement of universal primary education; however, the results are unevenly distributed. Nevertheless, a considerable number of children, especially girls from poor backgrounds and rural communities, still do not have access to primary education (UN *et al.*, 2008).

From the livelihood perspective, African women are vulnerable to the impacts of climate change because they shoulder an enormous but imprecisely recorded portion of the responsibility for subsistence agriculture, the productivity of which can be expected to be adversely affected by climate change and over-exploited soil (Viatte *et al.*, 2009; see also 22.4.2 and Table 22-5).[6] Global financial crises, such as the one experienced in 2007/2008, as well as downturn economic trends at national level, may cause job losses in the formal sector and men may compete for jobs in the informal sector that were previously undertaken by women, making them more vulnerable (AfDB *et al.*, 2010).

[FOOTNOTE 6: For instance, 84% of women in sub-Saharan Africa, compared with 69.5% of men, are engaged in such jobs. In Northern Africa, even though informal or self-employment is less predominant, the gender gap is stark, with much higher proportion of women compared to men are in the more vulnerable informal and self-employed status (56.7% of women compared with 34.9% of men) (UN DESA, 2011).]

Significant efforts have been made to improve access to safe drinking water and sanitation in Africa, with access to safe drinking water increasing from 56 to 65% between 1990 and 2008 (UNDP *et al*., 2011), with sub-Saharan Africa nearly doubling the number of people using an improved drinking water source – from 252 to 492 million over the same period (UN, 2011). Despite such progress, significant disparities in access to safe water and sanitation, between not only urban and rural but also between large- and medium- and small-sized cities, still exist (UNDP *et al.*, 2011). Use of improved sanitation facilities, meanwhile, is generally low in Africa, reaching 41% in 2010 compared to 36% in 1990 (UNDP *et al.*, 2011).

22.3.2. Ecosystems

It is recognized that interactions between the different drivers of ecosystem structure, composition, and function are complex, which makes the prediction of the impacts of climate change more difficult (see Chapter 4). In AR4, the chapter on Africa indicated that extensive pressure is exerted on different ecosystems by human activities (deforestation, forest degradation, biomass utilisation for energy) as well as processes inducing changes such as fires or desertification (see WGII AR4 9.2.2.7). Even if the trend is toward better preservation of ecosystems and a decrease in degradation (like deforestation), pressures linked, for example, to agriculture and food security, energy demand, and urbanization are increasing, putting these ecosystems at risk. This chapter emphasizes new information since AR4 regarding the vulnerability to and impacts of climate change for some terrestrial, fresh water and coastal/ocean ecosystems.

22.3.2.1. Terrestrial Ecosystems

Changes are occurring in the distribution and dynamics of all types of terrestrial ecosystems in Africa, including deserts, grasslands and shrublands, savannas and woodlands, and forests (*high confidence*) (see also 4.3.2.5). Since AR4, three primary trends have been observed at the continental scale. The first is a small overall expansion of desert and contraction of the total vegetated area (Brink and Eva, 2009) (*low confidence*). The second is a large increase in the extent of human influence within the vegetated area, accompanied by a decrease in the extent of natural vegetation (Brink and Eva, 2009; Potapov *et al.*, 2012; Mayaux *et al.*, 2013) (*high confidence*). The third is a complex set of shifts in the spatial distribution of the remaining natural vegetation types, with net decreases in woody vegetation in western Africa (Vincke *et al.*, 2010; Ruelland *et al.*, 2011; Gonzalez *et al.*, 2012) and net increases in woody vegetation in central, eastern, and southern Africa (Wigley *et al*., 2009; Wigley *et al*., 2010; Buitenwerf *et al*., 2012; Mitchard and Flintrop, 2013) (*high confidence*).

Overall, the primary driver of these changes is anthropogenic land use change, particularly the expansion of agriculture, livestock grazing, and fuelwood harvesting (Brink and Eva, 2009; Kutsch *et al*., 2011; Bond and Midgley, 2012; Gonzalez *et al.*, 2012) (*high confidence*). Natural climate variability, anthropogenic climate change, and interactions between these drivers and anthropogenic land use change have important additional and interacting effects (Foden *et al*., 2007; Touchan *et al*., 2008; Brink and Eva, 2009; Bond and Midgley, 2012; Gonzalez *et al.*, 2012) (*high confidence*). Due to these interactions, it has been difficult to determine the role of climate change in isolation from the other drivers (Malhi *et al*., 2013). In general, while there are already many examples of changes in terrestrial ecosystems that are consistent with a climate change signal and have been detected with *high confidence*, attribution to climate change has tended to be characterized by *low confidence* [see Table 22-3]. New observations and approaches are improving confidence in attribution (*e.g.*, Buitenwerf *et al*., 2012, Gonzalez *et al.*, 2012, Pettorelli *et al.*, 2012, Otto *et al*., 2013).

There is *high agreement* that continuing changes in precipitation, temperature, and CO_2 associated with climate change are *very likely* to drive important future changes in terrestrial ecosystems throughout Africa (*high confidence*) [see examples in 4.3.3.1, 4.3.3.2]. Modeling studies focusing on vegetation responses to climate have projected a variety of biome shifts, primarily related to the extent of woody vegetation (Delire *et al.*, 2008; Gonzalez *et al.*, 2010; Bergengren *et al.*, 2011; Zelazowski *et al.*, 2011; Midgley, 2013). For an example of such projections, see Figure 22-4. However, substantial uncertainties are inherent in these projections because vegetation across much of the continent is not deterministically driven by climate alone (*high confidence*). Advances in understanding how vegetation dynamics are affected by fire, grazing, and the interaction of fire and grazing with climate are expected to enable more sophisticated representations of these processes in coupled models (Scheiter and Higgins, 2009; Staver *et al*., 2011a; Staver *et al*., 2011b). Improvements in forecasting vegetation responses to climate change should reduce the uncertainties that are currently associated with vegetation feedbacks to climate forcing, as well as the uncertainties about impacts on water resources, agriculture, and health (Alo and Wang, 2008; Sitch *et al.*, 2008) [see 4.5].

[INSERT FIGURE 22-4 HERE
Figure 22-4: Left – Projected biome change from the periods 1961-1990 to 2071-2100 using the MC1 Dynamic Vegetation Model. Change is indicated if any of nine combinations of three GCMs (CSIRO Mk3, HadCM3, MIROC 3.2 medres) and three emissions scenarios (B1, A1B, A2) project change and is thus a worst-case scenario. Colours represent the future biome predicted. Right – Vulnerability of ecosystems to biome shifts based on historical climate (1901-2002) and projected vegetation (2071-2100), where all nine GCM-emissions scenario combinations agree on the projected biome change. Source: Gonzalez et al. (2010).]

22.3.2.2. Freshwater Ecosystems

Freshwater ecosystems in Africa are at risk from anthropogenic land use change, over-extraction of water and diversions from rivers and lakes, and increased pollution and sedimentation loading in water bodies (Vörösmarty *et al*., 2005; Vié *et al.*, 2009; Darwall *et al.*, 2011). Climate change is also beginning to affect freshwater ecosystems (see also Chapter 3.5.2.4, as evident by elevated water temperatures reported in surface waters of Lakes Kariba, Kivu, Tanganyika, Victoria, and Malawi (Odada *et al.*, 2006; Verburg and Hecky, 2009; Marshall *et al.*, 2009; Hecky *et al.*, 2010; Magadza, 2010; Tierney *et al.*, 2010; Olaka *et al.*, 2010; Magadza, 2011; Ndebele-Murisa, 2011; Woltering *et al.*, 2011; Osborne, 2012; Ndebele-Murisa *et al.*, 2012) (*medium confidence*).

Small variations in climate cause wide fluctuations in the thermal dynamics of freshwaters (Odada *et al.*, 2006; Stenuite *et al.*, 2007; Verburg and Hecky, 2009; Moss, 2010; Olaka *et al.*, 2010). Thermal stratification in the regions' lakes, for instance, isolates nutrients from the euphotic zone, and is strongly linked to hydrodynamic and climatic conditions (Sarmento *et al.*, 2006; Ndebele-Murisa *et al.*, 2010). Moderate warming may be contributing to reduced lake water inflows and therefore nutrients, which subsequently destabilizes plankton dynamics and thereby adversely affects food resources for higher trophic levels of mainly planktivorous fish (*low confidence*) (Magadza, 2008; Verburg and Hecky, 2009; Magadza, 2010; Ndebele-Murisa *et al.*, 2011). However, the interacting drivers of fisheries decline in African lakes are uncertain, given the extent to which other factors, such as overfishing, pollution, and invasive species also impact lake ecosystems and fisheries production (Phoon *et al*., 2004; Sarvala *et al*., 2006; Verburg *et al*., 2007; Tumbare, 2008; Hecky *et al*., 2010; Marshall, 2012).

22.3.2.3. Coastal and Ocean Systems

Coastal and ocean systems are important for the economies and livelihoods of African countries, and climate change will increase challenges from existing stressors, such as overexploitation of resources, habitat degradation, loss of biodiversity, salinization, pollution, and coastal erosion (Arthurton *et al.*, 2006; UNEP and IOC-UNESCO, 2009; Diop *et al.*, 2011). Coastal systems will experience impacts through sea level rise. They will also experience impacts through high sea levels combined with storm swells, for example as observed in Durban in March 2007, when a storm swell up to 14 m due to winds generated by a cyclone combined with a high astronomic tide at 2.2 m, leading to damages estimated at US$ 100 million (Mather and Stretch, 2012). Other climate change impacts (such as flooding of river deltas or an increased migration toward coastal towns due to increased drought induced by climate change (Rain *et al.*, 2011) will also affect coastal zones.

Some South African sea bird species have moved farther south over recent decades, but land use change may also have contributed to this migration (Hockey and Midgley, 2009; Hockey *et al.*, 2011). However, it is considered that South African seabirds could be a valuable signal for climate change, particularly of the changes induced on prey species related to changes in physical oceanography, if we are able to separate the influences of climate parameters from other environmental ones (Crawford and Altwegg, 2009).

Upwellings, including Eastern Boundary Upwelling Ecosystems (EUBEs) and Equatorial Upwelling Systems (EUSs) are the most biologically active systems in the Oceans (Box CC-UP). In addition to equatorial upwelling, the primary upwelling systems that affect Africa are the Benguela and Canary currents along the Atlantic coast (both EBUEs).The waters of the Benguela current have not shown warming over the period 1950-2009 (30.5.5.1.2), whereas most observations suggest that the Canary current has warmed since the early 1980s, and there is *medium evidence* and *agreement* that primary production in the Canary current has decreased over the past two decades (30.5.5.1.1). Changing temperatures in the Canary current has resulted in changes to important fisheries species (e.g., Mauritanian waters have become increasingly suitable for *Sardinella aurita*) (30.5.5.1.1). Upwellings are areas of naturally low pH and high CO_2 concentrations, and, consequently, may be vulnerable to ocean acidification and its impacts (Box CC-OA, Box CC-UP, 30.5.5). Warming is projected to continue in the Canary current, and the synergies between this increase in water temperature and ocean acidification could influence a number of biological processes (30.5.5.2). Regarding the Benguela current upwelling, there is *medium agreement* despite *limited evidence* that the Benguela system will experience changes in upwelling intensity as a result of climate change (30.5.5.1.2). There is considerable debate as to whether or not climate change will drive an intensification of upwelling (e.g. Bakun *et al.*, 2010; Narayan *et al.*, 2010) in all regions. Discussion of the various hypotheses for how climate change may affect coastal upwelling is presented in Box 30-1.

Ocean acidification (OA) is the term used to describe the process whereby increased CO_2 in the atmosphere, upon absorption, causes lowering of the pH of seawater (CC-OA). Projections indicate that severe impairment of reef accretion by organisms such as corals (Hoegh-Guldberg *et al.*, 2007) and coralline algae (Kuffner *et al.*, 2008) are substantial potential impacts of ocean acidification, and the combined effects of global warming and ocean acidification have been further demonstrated to lower both coral reef productivity (Anthony *et al.*, 2008) and resilience (Anthony *et al.*, 2011). These effects will have consequences for reef biodiversity, ecology, and ecosystem services (6.3.1, 6.3.2, 6.3.5, 6.4.1, 30.3.2, Box CC-CR).

Coral vulnerability to heat anomalies is high in the Western Indian Ocean (30.5.6.1.2). Corals in the southwestern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, Réunion and Rodrigues) appeared to be more resilient than those in eastern locations (30.5.6.1.2). Social adaptive capacity to cope with such change varies, and societal responses (such as closures to fishing) can have a positive impact on reef recovery, as observed in Tanzania (McClanahan *et al.*, 2009). In Africa, fisheries mainly depend on either coral reefs (on the eastern coast) or coastal upwelling (on the western coast). These two ecosystems will be affected by climate change through ocean acidification, a rise in sea surface temperatures, and changes in upwelling (see Box CC-OA, Box CC-CR, Box CC-UP).

[INSERT TABLE 22-3
Table 22-3: Examples of detected changes in species, natural ecosystems, and managed ecosystems in Africa that are both consistent with a climate change signal and published since the AR4. Confidence in detection of change is based on the length of study, and the type, amount and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate being a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change.]

22.3.3. Water Resources

Knowledge has advanced since the AR4 regarding current drivers of water resource abundance in Africa, and in understanding of potential future impacts on water resources from climate change and other drivers. However, inadequate observational data in Africa remains a systemic limitation with respect to fully estimating future freshwater availability (Neumann *et al.*, 2007; Batisani, 2011). Detection of and attribution to climate change are difficult given that surface and groundwater hydrology are governed by multiple, interacting drivers and factors, such as land use change, water withdrawals, and natural climate variability (see also Chapter 3.2.1 and Box CC-WE). There is poor understanding in Africa of how climate change will affect water quality. This is an important knowledge gap.

A growing body of literature generated since the AR4 suggests that climate change in Africa will have an overall modest effect on future water scarcity relative to other drivers, such as population growth, urbanization, agricultural growth, and land use change (*high confidence)* (Alcamo *et al.*, 2007; Carter and Parker, 2009; MacDonald *et al.*, 2009; Taylor *et al.*, 2009; Calow and MacDonald, 2009; Abouabdillah *et al.*, 2010; Beck and Bernauer, 2011; Droogers *et al.*, 2012; Notter *et al.*, 2012; Tshimanga and Hughes, 2012). However, broad-scale assumptions about drivers of future water shortages can mask significant sub-regional variability of climate impacts, particularly in water-stressed regions that are projected to become drier, such as northern Africa and parts of southern Africa. For example, rainfed agriculture in northern Africa is highly dependent on winter precipitation and would be negatively impacted if total precipitation and the frequency of wet days declines across North Africa as has been indicated in recent studies (Born *et al.*, 2008; Driouech *et al.*, 2010; Abouabdillah *et al.*, 2010; García-Ruiz *et al.*, 2011). Similarly, climate model predictions based on average rainfall years do not adequately capture interannual and interdecadal variability that can positively or negatively influence surface water runoff (Beck and Bernauer, 2011; Notter *et al.*, 2012; Wolski *et al.*, 2012). Key challenges for estimating future water abundance in Africa lie in better understanding relationships between evapotranspiration, soil moisture, and land use change dynamics under varying temperature and precipitation projections (Goulden *et al.*, 2009a) and to understand how compound risks such as heat waves and seasonal rainfall variability might interact in the future to impact water resources.

Several studies from Africa point to a future decrease in water abundance due to a range of drivers and stresses, including climate change in Southern and northern Africa (*medium confidence*). For example, all countries within the Zambezi River Basin could contend with increasing water shortages (A2 scenario) although non-climate drivers (e.g., population and economic growth, expansion of irrigated agriculture, and water transfers) are expected to have a strong influence on future water availability in this basin (Beck and Bernauer, 2011). In Zimbabwe, climate change is estimated to increase water shortages for downstream users dependent on the Rozva dam (Ncube *et al.*, 2011). Water shortages are also estimated for the Okavango Delta, from both climate change and increased water withdrawals for irrigation (Murray-Hudson *et al.*, 2006; Milzow *et al.*, 2010; Wolski *et al.*, 2012), and the Breede River in South Africa (Steynor *et al.*, 2009). For North Africa, Droogers *et al.* (2012) estimated that in 2050 climate change will account for 22% of future water shortages in the region while 78% of increased future water shortages can be attributed to socioeconomic factors. Abouabdillah *et al.* (2010) estimated that higher temperatures and declining rainfall (A2 and B1 scenarios) would reduce water resources in Tunisia. Reduced snowpack in the Atlas Mountains from a combination of warming and reduced precipitation, combined with more rapid springtime melting is expected to reduce supplies of seasonal meltwater for lowland areas of Morocco (García-Ruiz *et al.*, 2011).

In Eastern Africa, potential climate change impacts on the Nile Basin are of particular concern given the basin’s geopolitical and socioeconomic importance. Reduced flows in the Blue Nile are estimated by late century due to a combination of climate change (higher temperatures and declining precipitation) and upstream water development for irrigation and hydropower (Elshamy *et al.*, 2009; McCartney and Menker Girma, 2012). Beyene *et al.* (2010) estimated that streamflow in the Nile River will increase in the medium term (2010–2039) but will decline in the latter half of this century (A2 and B1 scenarios) as a result of both declining rainfall and increased evaporative demand, with subsequent diminution of water allocation for irrigated agriculture downstream from the High Aswan Dam. Kingston and Taylor (2010) reached a similar conclusion about an initial increase followed by a decline in surface water discharge in the Upper Nile Basin in Uganda. Seasonal runoff volumes in the Lake Tana Basin are estimated to decrease by the 2080s under the A2 and B2 scenarios (Abdo *et al.*, 2009), while Taye *et al.* (2011) reported inconclusive findings as to changes in runoff in this basin. The Mara, Nyando, and Tana rivers in Eastern Africa, are projected to have increased flow in the second half of this century (Taye *et al.*, 2011; Dessu and Melesse, 2012; Nakaegawa *et al*., 2012)).

Estimating the influence of climate change on water resources in West Africa is limited by the significant climate model uncertainties with regards to the region’s future precipitation. For example, Itiveh and Bigg (2008) estimate higher future rainfall in the Niger River Basin (A1, A2 and B1 scenarios), whereas Oguntunde and Abiodun (2013) report a strong seasonal component with reduced precipitation in the basin during the rainy season and increased precipitation during the dry season (A1B scenario). The Volta Basin is projected to experience a slight mean increase in precipitation (Kunstmann *et al.*, 2008), and the Bani River Basin in Mali is estimated to experience substantial reductions in runoff (A2 scenario) due to reduced rainfall (Ruelland *et al.*, 2012). The impact of climate change on total runoff in the Congo Basin is estimated to be minimal (A2 scenario) (Tshimanga and Hughes, 2012). Continental wide studies (e.g. De Wit and Stankiewicz, 2006) indicate that surface drainage in dry areas is more sensitive to, and will be more adversely affected by, reduced rainfall than would surface drainage in wetter areas that experience comparable rainfall reductions.

The overall impact of climate change on groundwater resources in Africa is expected to be relatively small in comparison with impacts from non-climatic drivers such as population growth, urbanization, increased reliance on irrigation to meet food demand, and land use change (Calow and MacDonald, 2009; Carter and Parker, 2009; MacDonald *et al.*, 2009; and Taylor *et al.*, 2009). Climate change impacts on groundwater will vary across climatic zones. (See also Chapter 3.4.6). An analysis by MacDonald *et al.* (2009) indicated that changes in rainfall would not be expected to impact the recharge of deep aquifers in areas receiving below 200 mm rainfall per year, where recharge is negligible due to low rainfall. Groundwater recharge may also not be significantly affected by climate change in areas that receive more than 500 mm per year, where sufficient recharge would remain even if rainfall diminished, assuming current groundwater extraction rates. By contrast, areas receiving between 200 to 500 mm per year, including the Sahel, the Horn of Africa, and southern Africa, may experience a decline in groundwater recharge with climate change to the extent that prolonged drought and other precipitation anomalies becomes more frequent with climate change, particularly in shallow aquifers, which respond more quickly to seasonal and yearly changes in rainfall than do deep aquifers (Barthel *et al.*, 2009).

Coastal aquifers are additionally vulnerable to climate change because of high rates of groundwater extraction, which leads to saltwater intrusion in aquifers, coupled with increased saltwater ingression resulting from sea level rise (Moustadraf *et al.*, 2008; Bouchaou *et al.*, 2008; Al-Gamal and Dodo, 2009; Kerrou *et al.*, 2010). Some studies have shown additional impacts of sea level rise on aquifer salinization with salinity potentially reaching very high levels (Carneiro *et al.*, 2010; Niang *et al.*, 2010; Research Institute for Groundwater, 2011). Although these effects are expected to be localized, in some cases they will occur in densely populated areas (Niang *et al.*, 2010). The profitability of irrigated agriculture in Morocco is expected to decline (under both B1 and A1B scenarios) due to increased pumping of groundwater and increased salinization risk for aquifers (Heidecke and Heckelei, 2010).

The capacity of groundwater delivery systems to meet demand may take on increasing importance with climate change (Calow and MacDonald, 2009). For example, where groundwater pumping and delivery infrastructure is poor, and the number of point sources limited, prolonged pumping can lead to periodic drawdowns and increased failure of water delivery systems or increased saline intrusion (Moustadraf *et al.*, 2008). To the extent that drought conditions become more prevalent in Africa with climate change, stress on groundwater delivery infrastructures will increase.

Future development of groundwater resources to address direct and indirect impacts of climate change, population growth, industrialization, and expansion of irrigated agriculture, will require much more knowledge of groundwater resources and aquifer recharge potentials than currently exists in Africa. Observational data on groundwater resources in Africa are extremely limited and significant effort needs to be expended to assess groundwater recharge potential across the continent (Taylor *et al.*, 2009). A preliminary analysis by MacDonald et al. (2012) indicates that total groundwater storage in Africa is 0.66 million km^3, which is “more than 100 times the annual renewable freshwater resources, and 20 times the freshwater stored in African lakes.” However, borehole yields are variable and in many places water yields are relatively low. Detailed analysis of groundwater conditions for water resource planning would need to consider these constraints.

22.3.4. Agriculture and Food Security

Africa’s food production systems are among the world’s most vulnerable because of extensive reliance on rainfed crop production, high intra- and inter-seasonal climate variability, recurrent droughts and floods that affect both crops and livestock, and persistent poverty that limits the capacity to adapt (Boko *et al.*, 2007). In the near term, better managing risks associated with climate variability may help to build adaptive capacities for climate change (Washington *et al.*, 2006; Cooper *et al.*, 2008; Funk *et al.*, 2008). However, agriculture in Africa will face significant challenges in adapting to climate changes projected to occur by mid-century, as negative effects of high temperatures become increasingly prominent under an A1B scenario (Battisti and Naylor, 2009; Burke *et al.*, 2009a), thus increasing the likelihood of diminished yield potential of major crops in Africa (Schlenker and Lobell, 2010; Sultan et al., 2013). Changes in growing season length are possible, with a tendency towards reduced growing season length (Thornton *et al.*, 2011), though with potential for some areas to experience longer growing seasons (Cook and Vizy, 2012). The composition of farming systems from mixed crop-livestock to more livestock dominated food production may occur as a result of reduced growing season length for annual crops and increases in the frequency and prevalence of failed seasons (Jones and Thornton, 2009; Thornton *et al.*, 2010). Transition zones, where livestock keeping is projected to replace crop cultivation by 2050, include the West African Sahel and coastal and mid-altitude areas in eastern and southeastern Africa (Jones and Thornton, 2009), areas that currently support 35 million people and are chronically food insecure.

22.3.4.1. Crops

Climate change is *very likely* to have an overall negative effect on yields of major cereal crops across Africa, with strong regional variability in the degree of yield reduction (see also Chapter 7.3.2.1) (Lobell *et al.*, 2008; Liu *et al.*, 2008; Walker and Schulze, 2008; Thornton *et al.*, 2009a; Lobell *et al.*, 2011; Roudier *et al.*, 2011; Berg *et al.*, 2013) (*high confidence*). One exception is in eastern Africa where maize production could benefit from warming at sites above roughly 1,700 m in elevation (A1FI scenario) (Thornton *et al.*, 2009a), although the majority of current maize production occurs at lower elevations thereby implying a potential change in the distribution of maize cropping. Maize-based systems, particularly in southern Africa, are among the most vulnerable to climate change (Lobell *et al.*, 2008). Estimated yield losses at mid-century range from 18% for southern Africa (Zinyengere *et al.*, 2013) to 22% aggregated across SSA, with yield losses for South Africa and Zimbabwe in excess of 30% (Schlenker and Lobell, 2010). Simulations that combine all regions south of the Sahara suggest consistently negative effects of climate change on major cereal crops in Africa, ranging from 2% for sorghum to 35% for wheat by 2050 under an A2 scenario (Nelson *et al.*, 2009). Studies in North Africa by Eid *et al.*, 2007; Hegazy *et al.*, 2008; Drine, 2011; Mougou *et al.*, 2011 also indicate a high vulnerability of wheat production to projected warming trends. In West Africa, temperature increases above 2° C (relative to a 1961-1990 baseline) are estimated to counteract positive effects on millet and sorghum yields of increased precipitation (for B1, A1B and A2 scenarios) (Figure 22.5), with negative effects stronger in the savannah than in the Sahel, and with modern cereal varieties compared with traditional ones (Sultan et al., 2013).

Several recent studies since the AR4 indicate that climate change will have variable impacts on non-cereal crops, with both production losses and gains possible (*low confidence*). Cassava yields in eastern Africa are estimated to moderately increase up to the 2030s assuming CO2 fertilization and under a range of low to high emissions scenarios (Liu *et al.*, 2008), findings that were similar to Lobell et al. (2008). Suitability for growing cassava is estimated to increase with the greatest improvement in suitability in eastern and central Africa (A1B scenario) (Jarvis *et al.*, 2012). However, Schlenker and Lobell (2010) estimated negative impacts from climate change on cassava at mid-century, although with impacts estimated to be less than those for cereal crops. Given cassava's hardiness to higher temperatures and sporadic rainfall relative to many cereal crops, it may provide a potential option for crop substitution of cereals as an adaptation response to climate change (Rosenthal and Ort, 2012; Jarvis *et al.*, 2012). Bean yields in Eastern Africa are estimated to experience yield reductions by the 2030s under an intermediate emissions scenario (A1B) (Jarvis *et al.*, 2012) and by the 2050s under low (B1) and high (A1FI) emissions scenarios (Thornton *et al.*, 2011). For peanuts, some studies indicate a positive effect from climate change (A2 and B2 scenarios) (Tingem and Rivington, 2009) and others a negative one (Lobell *et al.*, 2008; Schlenker and Lobell, 2010). Bambara groundnuts (*Vigna subterranea*) are estimated to benefit from moderate climate change (Tingem and Rivington, 2009) (A2 and B2 scenarios) although the effect could be highly variable across varieties (Berchie *et al.*, 2012). Banana and plantain production could decline in West Africa and lowland areas of East Africa, whereas in highland areas of East Africa it could increase with temperature rise (Ramirez *et al.*, 2011). Much more research is needed to better establish climate change impacts on these two crops.

Suitable agro-climatic zones for growing economically important perennial crops are estimated to significantly diminish, largely due to the effects of rising temperatures (Läderach *et al.*, 2010; Eitzinger *et al.*, 2011a; Läderach *et al.*, 2011a; Eitzinger *et al.*, 2011b; Läderach *et al.*, 2011b; Läderach *et al.*, 2011c). Under an A2 scenario, by mid-century suitable agro-climatic zones that are currently classified as very good to good for perennial crops may become more marginal, and what are currently marginally suitable zones may become unsuitable; the constriction of crop suitability could be severe in some cases (Table 22-4). Movement of perennial crops to higher altitudes would serve to mitigate the loss of suitability at lower altitudes but this option is limited. Loss of productivity of high-value crops such as tea, coffee and cocoa would have detrimental impacts on export earnings.

[INSERT TABLE 22-4 HERE
Table 22-4. Projected changes in agro-climatic suitability for perennial crops in Africa by mid-century under an A2 scenario.]

[INSERT FIGURE 22-5 HERE
Figure 22-5: The effect of rainfall and temperature changes on mean crop yield. Mean crop yield change (%) relative to the 1961–90 baseline for 7 temperatures (x-axis) and 5 rainfall (y-axis) scenarios. Results are shown as the average over the 35 stations across West Africa and the 6 cultivars of sorghum and millet. White triangles and circles are the projected anomalies computed by several CMIP3 GCMs and three IPCC emission scenarios (B1, A1B, A2) for 2071–90 and 2031–50, respectively. Projections from CMIP5 GCMs and three RCPs (4.5, 6.0 and 8.5) are represented by grey triangles and circles. Models and scenarios names are displayed in figure S2 (available atstacks.iop.org/ERL/8/014040/mmedia). Past observed climate anomalies from CRU data are also projected by computing 10-year averages (e.g. '1940' is for 1941–50). All mean yield changes are significant at a 5% level except boxes with a diagonal line. Source: Sultan et al., 2013.].

22.3.4.2. Livestock

Livestock systems in Africa face multiple stressors that can interact with climate change and variability to amplify the vulnerability of livestock-keeping communities. These stressors include rangeland degradation, increased variability in access to water, fragmentation of grazing areas, sedentarization, changes in land tenure from communal towards private ownership, in-migration of non-pastoralists into grazing areas, lack of opportunities to diversify livelihoods, conflict and political crisis, weak social safety nets, and insecure access to land, markets, and other resources (Solomon *et al.*, 2007; Smucker and Wisner, 2008; Galvin, 2009; Thornton *et al.*, 2009b; Dougill *et al.*, 2010; Ifejika Speranza, 2010). (See also Chapter 7.3.2.4.)

Loss of livestock under prolonged drought conditions is a critical risk given the extensive rangeland in Africa that is prone to drought. Regions that are projected to become drier with climate change, such as Northern and Southern Africa, are of particular concern (Solomon *et al.*, 2007; Masike and Urich, 2008; Thornton *et al.*, 2009b; Dougill *et al.*, 2010; Freier *et al.*, 2012; Schilling *et al.*, 2012). Adequate provision of water for livestock production could become more difficult under climate change. For example, Masike and Urich (2009) estimated that the cost of supplying livestock water from boreholes in Botswana will increase by 23% by 2050 under an A2 scenario due to increased hours of groundwater pumping needed to meet livestock water demands under warmer and drier conditions. Although small in comparison to the water needed for feed production, drinking water provision for livestock is critical, and can have a strong impact on overall resource use efficiency in warm environments (Peden *et al.*, 2009; van Breugel *et al.*, 2010; Descheemaeker *et al.*, 2010; Descheemaeker *et al.*, 2011). Livestock production will be indirectly affected by water scarcity through its impact on crop production and subsequently the availability of crop residues for livestock feeding. Thornton et al. (2010) estimated that maize stover availability per head of cattle will decrease in several East African countries by 2050.

The extent to which increased heat stress associated with climate change will affect livestock productivity has not been well established, particularly in the tropics and sub-tropics (Thornton *et al.*, 2009b), although a few studies point to the possibility that keeping heat-tolerant livestock will become more prevalent in response to warming trends. For example, higher temperatures in lowland areas of Africa could result in reduced stocking of dairy cows in favor of cattle (Kabubo-Mariara, 2008), a shift from cattle to sheep and goats (Kabubo-Mariara, 2008; Seo and Mendelsohn, 2008), and decreasing reliance on poultry (Seo and Mendelsohn, 2008). Livestock keeping in highland areas of East Africa, which is currently cold-limited, would potentially benefit from increased temperatures (Thornton *et al.*, 2010). Lunde and Lindtjørn (2013) challenge a finding in the AR4 that there is direct proportionality between range-fed livestock numbers and changes in annual precipitation in Africa. Their analysis indicates that this relationship may hold in dry environments but not in humid ones.

22.3.4.3. Agricultural Pests, Diseases, and Weeds

Since the AR4, understanding of how climate change will potentially affect crop and livestock pests and diseases and agricultural weeds in Africa is beginning to emerge. Climate change in interaction with other environmental and production factors could intensify damage to crops from pests, weeds and diseases (7.3.2.3).

Warming in highland regions of eastern Africa could lead to range expansion of crop pests into cold-limited areas (*low confidence*). For example, in highland arabica coffee-producing areas of eastern Africa, warming trends may result in the coffee berry borer (*Hypothenemus hampei*) becoming a serious threat in coffee-growing regions of Ethiopia, Kenya, Uganda, Rwanda, and Burundi (Jaramillo *et al.*, 2011). Temperature increases in highland banana-producing areas of eastern Africa enhance the risk of altitudinal range expansion of the highly destructive burrowing nematode, *Radopholus similis* (Nicholls *et al.*, 2008); however, no detailed studies have assessed this risk. Ramirez et al. (2011) estimated that increasing minimum temperatures by 2020 would expand the suitable range of Black Leaf Streak disease (Mycosphaerella fijiensis M.) of banana in Angola and Guinea.

Climate change may also affect the distribution of economically important pests in lowland and dryland areas of Africa (*low confidence*). Under A2A and B2A for 2020, Cotter et al. (2012) estimated that changes in temperature, rainfall, and seasonality will result in more suitable habitats for *Striga hermonthica* in central Africa, whereas the Sahel region may become less suitable for this weed. Striga weed infestations are a major cause of cereal yield reduction in Sub-Saharan Africa. Climate change could also lead to an overall decrease in the suitable range of major cassava pests – whitefly, cassava brown streak virus, cassava mosaic geminivirus, and cassava mealybug (Jarvis *et al.*, 2012), although southeast Africa and Madagascar is estimated to experience increased suitability for cassava pests (Bellotti *et al.*, 2012).

In the case of livestock, Olwoch et al. (2008) estimated that the distribution of the main tick vector species (*Rhipicephalus appendiculatus*) of East Coast fever disease in cattle could be altered by a 2°C temperature increase over mean annual temperatures throughout the 1990s, and changes in mean precipitation resulting in the climatically suitable range of the tick shifting southward. However, a number of environmental and socio-economic factors (e.g., habitat destruction, land use and cover change, and host density) in addition to climatic ones influence tick distribution and need to be considered in assigning causality (Rogers and Randolph, 2006).

22.3.4.4. Fisheries

Fisheries are an important source of food security in Africa. Capture fisheries (marine and inland) and aquaculture combined contribute over one-third of Africa's animal protein intake (Welcomme, 2011), while in some coastal countries fish contribute up to two-thirds of total animal protein intake (Allison *et al.*, 2009). Demand for fish is projected to increase substantially in Africa over the next few decades (De Silva and Soto, 2009). To meet fish food demand by 2020, De Silva and Soto (2009) estimated that aquaculture production in Africa would have to increase nearly 500%.

The vulnerability of national economies to climate change impacts on fisheries can be linked to exposure to the physical effects of climate change, the sensitivity of the country to impacts on fisheries, and adaptive capacity within the country (Allison *et al.*, 2009). In an analysis of fisheries in 132 countries Allison et al. (2009) estimated that two-thirds of the most vulnerable countries were in Africa. Among these countries, the most vulnerable were Angola, DR Congo, Mauritania and Senegal, due to the importance of fisheries to the poor and the close link between climate variability and fisheries production. Coastal countries of West Africa will experience a significant negative impact from climate change. Lam et al. (2012) projected that by 2050 (under an A1B scenario) the annual landed value of fish for that region is estimated to decline by 21%, resulting in a nearly 50% decline in fisheries-related employment and a total annual loss of US$ 311 million to the region's economy.

22.3.4.5. Food Security

Food security in Africa faces multiple threats stemming from entrenched poverty, environmental degradation, rapid urbanization, high population growth rates, and climate change and variability. The intertwined issues of markets and food security have emerged as an important issue in Africa and elsewhere in the developing world since the AR4. Price spikes for globally traded food commodities in 2007–2008 and food price volatility and higher overall food prices in subsequent years have undercut recent gains in food security across Africa (Brown *et al.*, 2009; Hadley *et al.*, 2011; Mason *et al.*, 2011; Tawodzera, 2011; Alem and Söderbom, 2012; Levine, 2012). Among the most affected groups are the urban poor, who typically allocate more than half of their income to food purchases (Cohen and Garrett, 2010; Crush and Frayne, 2010). The proportion of smallholder farmers that are net food buyers of staple grains exceeds 50% in Mozambique, Kenya and Ethiopia (Jayne et al., 2006), thus food security of rural producers is also sensitive to food spikes, particularly in the case of female-headed households, which generally have fewer assets than male-headed households (Kumar and Quisumbing, 2011). Although the recent spike in global food prices can be attributed to a convergence of several factors, the intensification of climate change impacts could become more important in the future in terms of exerting upward pressure on food prices of basic cereals (Nelson *et al.*, 2009; Hertel *et al.*, 2010), which would have serious implications for Africa's food security. As the recent wave of food price crises demonstrates, factors in other regions profoundly impact food security in Africa. Much more research is needed to understand better the potential interactions between climate change and other key drivers of food prices that act at national, regional, and global scales. (See also Chapter 7.2.2.)

Africa is undergoing both rapid urbanization and subsequent transformation of its food systems to accommodate changes in food processing and marketing as well as in food consumption patterns. Considering the increasing reliance on purchased food in urban areas, approaches for addressing the impacts of climate change on food security will need to encompass a food systems approach (production as well as processing, transport, storage, and preparation) that moves food from production to consumption (Battersby, 2012). Weaknesses in the food system may be exacerbated by climate change in the region as high temperatures increase spoilage and the potential for increased flooding places food transportation infrastructure at higher risk of damage. In this respect, high post-harvest losses in Africa resulting in a large part from inadequate transport and storage infrastructure (Godfray *et al.*, 2010; Parfitt *et al.*, 2010) are an important concern.

22.3.5. Health

22.3.5.1. Introduction

Africa currently experiences high burdens of health outcomes whose incidence and geographic range could be affected by changing temperature and precipitation patterns, including malnutrition, diarrheal diseases, and malaria and other vector-borne diseases, with most of the impact on women and children (WHO 2013a). In 2010, there were 451,000 to 813,000 deaths from malaria in Africa, continuing a slow decline since approximately 2004 (WHO, 2012). There are insufficient data series to assess trends in incidence in most affected countries in Africa. Parasite prevalence rates in children less than 5 years of age are highest in poorer populations and rural areas; factors increasing vulnerability include living in housing with little mosquito protection and limited access to health care facilities offering effective diagnostic testing and treatment. Of the 3.6 million annual childhood deaths in Africa, 11% are due to diarrheal diseases (Liu *et al*., 2012).

Drivers of these and other climate-relevant health outcomes include inadequate human and financial resources, inadequate public health and health care systems, insufficient access to safe water and improved sanitation, food insecurity, and poor governance. Although progress has been made on improving safe water and sanitation coverage, sub-Saharan Africa still has the lowest coverage, highlighting high vulnerability to the health risks of climate change (UNICEF and WHO, 2008; UNICEF and WHO, 2012). Vulnerabilities also arise from policies and measures implemented in other sectors, including adaptation and mitigation options. Collaboration between sectors is essential. For example, the construction of the Akosombo dam in the 1960s to create Lake Volta in Ghana was associated with a subsequent increase in the prevalence of schistosomiasis (Scott *et al*., 1982).

22.3.5.2. Food- and Water-Borne Diseases

Cholera is primarily associated with poor sanitation, poor governance, and poverty, with associations with weather and climate variability suggesting possible changes in incidence and geographic range with climate change (Rodó *et al.*, 2002; Koelle *et al.*, 2005; Olago *et al.*, 2007; Murray *et al.*, 2012). The frequency and duration of cholera outbreaks are associated with heavy rainfall in Ghana, Senegal, other coastal West African countries, and South Africa, with a possible association with the El Niño-Southern Oscillation (ENSO) (de Magny *et al.*, 2007;

Mendelsohn and Dawson, 2008; de Magny *et al*., 2012). In Zanzibar, Tanzania, and Zambia, an increase in temperature or rainfall increases the number of cholera cases (Luque Fernández *et al*., 2009; Reyburn *et al*., 2011). The worst outbreak of cholera in recent African history occurred in Zimbabwe from August 2008 to June 2009. The epidemic was associated with the rainy season and caused more than 92,000 cases and 4,000 deaths. Contamination of water sources spread the disease (Mason, 2009). Poor governance, poor infrastructure, limited human resources, and underlying population susceptibility (high burden of malnutrition) contributed to the severity and extent of the outbreak (Murray *et al.*, 2012). Other mechanisms for increases in cholera incidence have been described in Chapter 11 (11.5.2.1). As discussed above in section 22.2 there are projected increases in precipitation in areas in Africa for example West Africa where cholera is already endemic. This possibly will lead to more frequent cholera outbreaks in the sub-regions affected. However, further research is needed to quantify the climatic impacts.

22.3.5.3. Nutrition

Malnutrition: Detailed spatial analyses of climate and health dynamics among children in Mali and Kenya suggest associations between livelihoods and measures of malnutrition, and between weather variables and stunting (Grace *et al*., 2012; Jankowska *et al*., 2012). Projections of climate and demographic change to 2025 for Mali (based on 2010-2039 climatology from the Famine Early Warning System Network FCLIM method), suggest approximately 250,000 children will suffer stunting, nearly 200,000 will be malnourished, and over 100,000 will become anemic, assuming constant morbidity levels; the authors conclude that climate change will cause a statistically significant proportion of stunted children (Jankowska *et al*., 2012).

Using a process-driven approach, (Lloyd *et al.*, 2011) projected future child malnutrition (as measured by severe stunting) in 2050 for four regions in sub-Saharan Africa, taking into consideration food and nonfood (socioeconomic) causes, and using regional scenario data based on the A2 scenario. Current baseline prevalence rates of severe stunting were 12-20%. Considering only future socioeconomic change, the prevalence of severe stunting in 2050 would be 7-17% (e.g. a net decline). However, including climate change, the prevalence of severe stunting would be 9-22%, or an increase of 31-55%in the relative percent of children severely stunted. Western sub-Saharan Africa was projected to experience a decline in severe stunting from 16% at present to 9% in 2050 when considering socioeconomic and climate change. Projected changes for central, south, and east sub-Saharan Africa are close to current prevalence rates, indicating climate change would counteract the beneficial consequences of socioeconomic development. Local economic activity and food accessibility can reduce the incidence of malnutrition (Funk *et al.*, 2008; Rowhani *et al.*, 2011).

22.3.5.4. Vector-Borne Diseases and Other Climate-Sensitive Health Outcomes

A wide range of vector-borne diseases contribute to premature morbidity and mortality in Africa, including malaria, leishmaniasis, Rift Valley fever, as well as tick- and rodent-borne diseases.

Malaria: Weather and climate are among the environmental, social, and economic determinants of the geographic range and incidence of malaria (Reiter 2008). The association between temperature and malaria varies regionally, (Chaves and Koenraadt, 2010; Paaijmans *et al.*, 2010a; Alonso *et al.*, 2011; Gilioli and Mariani, 2011). Malaria transmission peaks at 25°C and declines above 28°C (Lunde *et al.*, 2013; Mordecai *et al*., 2013). Total precipitation, rainfall patterns, temperature variability, and the water temperature of breeding sites are expected to alter disease susceptibility (Bomblies and Eltahir, 2010; Paaijmans *et al.*, 2010b; Afrane *et al.*, 2012; Blanford *et al.*, 2013; Lyons *et al.*, 2013). ENSO events also may contribute to malaria epidemics (Mabaso *et al.*, 2007; Ototo *et al.*, 2011). The complexity of the malaria transmission cycle makes it difficult to determine whether the distribution of the pathogen and vector are already changing due to climate change. Other factors like the Indian Ocean Dipole have been proposed to affect malaria incidence (Hashizume et al., 2009, Chaves et al., 2012, Hashizume et al., 2012).

Climate change is expected to affect the geographic range and incidence of malaria, particularly along the current edges of its distribution, with contractions and expansions, and increasing and decreasing incidence (Yé *et al.*, 2007; Peterson, 2009; Parham and Michael, 2010; Paaijmans *et al.*, 2010b; Alonso *et al.*, 2011; Egbendewe-Mondzozo *et* *al.*, 2011; Chaves *et al.*, 2012; Paaijmans *et al.*, 2012; Parham *et al.*, 2012; Ermert *et al.*, 2012), depending on other drivers, such as public health interventions, factors influencing the geographic range and reproductive potential of malaria vectors, land use change (e.g., deforestation), and drug resistance, as well as the interactions of these drivers with weather and climate patterns (Chaves *et al.*, 2008; Kelly-Hope *et al.*, 2009; Paaijmans *et al.*, 2009; Saugeon *et al.*, 2009; Artzy-Randrup *et al.*, 2010; Dondorp *et al.*, 2010; Gething *et al.*, 2010; Jackson *et al.*, 2010; Kulkarni *et al.*, 2010; Loha and Lindtjørn, 2010; Tonnang *et al.*, 2010; Stern *et al.*, 2011; Caminade *et al.*, 2011; Omumbo *et al.*, 2011; Afrane *et al.*, 2012; Edlund *et al.*, 2012; Githeko *et al.*, 2012; Himeidan and Kweka, 2012; Jima *et al.*, 2012; Lyons *et al.*, 2012; Ermert *et al.*, 2012; Stryker and Bomblies, 2012; Mordecai *et al.*, 2013). Movement of the parasite into new regions is associated with epidemics with high morbidity and mortality. Because various *Anopheles* species are adapted to different climatic conditions, changing weather and climate patterns could affect species composition differentially, which could, in turn affect malaria transmission (Afrane *et al.*, 2012; Lyons *et al.*, 2013).

Consensus is growing that highland areas, especially in East Africa, will experience increased malaria epidemics, with areas above 2,000 m, with temperatures currently too low to support malaria transmission, particularly affected (Pascual *et al.*, 2006; Peterson, 2009; Gething *et al.*, 2010; Lou and Zhao, 2010; Paaijmans *et al.*, 2010a; Ermert *et al.*, 2012). Reasons for different projections across models include use of different scenarios; use of global versus regional climate models (Ermert *et al.*, 2012); the need for finer-scale and higher-resolution models of the sharp climate variations with altitude (Bouma *et al.*, 2011); and the extent to malaria transmission and the drivers of its geographic range and incidence of malaria respond to and interact with climate change.

Leishmaniasis: Directly or indirectly, climate change may increase the incidence and geographic range of leishmaniasis, a highly neglected disease that has recently become a significant health problem in northern Africa (Postigo, 2010), with a rising concern in western Africa because of co-infection with HIV (Kimutai *et al.*, 2006). The epidemiology of the disease appears to be changing (Dondji, 2001; Yiougo *et al.*, 2007; WHO, 2009; Postigo, 2010). During the 20th century, zoonotic cutaneous leishmaniasis emerged as an epidemic disease in Algeria, Morocco, and Tunisia, and is now endemic (Salah *et al.*, 2007; Aoun *et al.*, 2008; Rhajaoui, 2011; Toumi *et al.*, 2012; Bounoua *et al.*, 2013). Previously an urban disease in Algeria, leishmaniasis now has a peri-urban distribution linked to changes in the distribution of the rodent host and of the vector since the early 1990s (Aoun *et al.*, 2008). Cutaneous leishmaniasis has expanded its range from its historical focus at Biskra, Algeria into the semi-arid steppe, with an associated upward trend in reported cases. In Morocco, sporadic cases of leishmania major (vector *Phlebotomus papatasi*) appeared early in the 20th century; since that time there have been occasional epidemics of up to 2,000 cases, interspersed with long periods with few or no cases (Rhajaoui, 2011). Outbreaks of zoonotic cutaneous leishmaniasis have become more frequent in Tunisia (where it emerged as an epidemic disease in 1991) (Salah *et al.*, 2007; Toumi *et al*., 2012). The disease has since spread to adjacent areas in West Africa and East Africa (Dondji, 2001; Yiougo *et al.*, 2007; WHO, 2009). Disease incidence is associated with rainfall and minimum temperature (Toumi *et al.*, 2012; Bounoua *et al.*, 2013). Relationships between decadal shifts over 1990-2009 in northwest Algeria and northeast Morocco in the number of cases and climate indicators suggested increased minimum temperatures created conditions suitable for endemicity (Bounoua *et al.*, 2013). Environmental modifications, such as construction of dams, can change the temperature and humidity of the soil and thus affect vegetation that may result in changes in the composition and density of sandfly species and rodent vectors. More research however, is needed to quantity the climate related impacts because there are multiple underlying factors.

Rift Vally fever (RVF): RVF epidemics in the Horn of Africa are associated with altered rainfall patterns. Additional climate variability and change could further increase its incidence and spread. Rift Valley fever is endemic in numerous African countries, with sporadic repeated epidemics. Epidemics in 2006–2007 in the Horn of Africa (Nguku *et al.*, 2007; WHO, 2007; Adam *et al.*, 2010; Andriamandimby *et al.*, 2010; Hightower *et al*., 2012) and southern Africa were associated with heavy rainfall (Chevalier *et al.*, 2011), strengthening earlier analyses by Anyamba *et al.* (2009) showing that RVF epizootics and epidemics are closely linked to the occurrence of the warm phase of ENSO and La Nina events (Linthicum *et al.*, 1999; Anyamba *et al.*, 2012) and elevated Indian Ocean temperatures. These conditions lead to heavy rainfall and flooding of habitats suitable for the production of the immature *Aedes* and *Culex* mosquitoes that serve as the primary RVF virus vectors in East Africa. Flooding of mosquito habitats also may introduce the virus into domestic animal populations.

Ticks and tick-borne diseases: Changing weather patterns could expand the distribution of ticks causing animal disease, particularly in East and South Africa. Ticks carry theileriosis (East Coast Fever), which causes anemia and skin damage that expose cattle to secondary infections. Habitat destruction, land use and cover change, and host density also affect tick distribution (Rogers and Randolph, 2006). Using a climate envelope and a species prediction model, Olwoch *et al*. (2007) projected that by 2020s, under the A2 scenario, East Africa and South Africa would be particularly vulnerable to climate-related changes in tick distributions and tick-borne diseases: more than 50% of the 30 *Rhipicephalus* species examined showed significant range expansion and shifts. More than 70% of this range expansion was found in tick species of economic importance.

Schistosomiasis: Worldwide, approximately 243 million people required treatment for schistosomiasis in 2011, of which 90% lived in underdeveloped areas of Africa (WHO, 2013b). Water resource development, such as irrigation dams recommended for adaptation in agriculture, can amplify the risk of schistosomiasis (Huang and Manderson, 1992; Hunter *et al.*, 1993; Jobin, 1999). Migration and sanitation play a significant role in the spread of schistosomiasis from rural areas to urban environments (Babiker *et al.*, 1985; WHO, 2013b). Temperature and precipitation patterns may play a role in transmission (Odongo-Aginya *et al.*, 2008; Mutuku *et al.*, 2011; Huang *et al*., 2011). Projections for the period 2070-2099, under A2 and B2 emission scenarios, suggest that although the geographic areas suitable for transmission will increase with climate change, snail regions are expected to contract and/or move to cooler areas; these results highlight the importance of understanding how climate change could alter snail habitats when projecting future human schistosomiasis prevelance under different scenarios (Stensgaard *et al*. 2011).

Meningococcal meningitis: There is a strong environmental relationship between the seasonal cycle of meningococcal meningitis and climate, including a relationship between the seasonal pattern of the Harmattan dusty winds and onset of disease. Transmission of meningitis occurs throughout Africa in the dry season and coincides with periods of very low humidity and wind-driven dusty conditions, ending with the onset of the rains (Molesworth *et al.*, 2003). Research corroborates earlier hypothesized relationships between weather and meningitis (Yaka *et al.*, 2008; Palmgren, 2009; Roberts, 2010; Dukić *et al.*, 2012; Agier *et al*., 2013). In the northern region of Ghana, exposure to smoke from cooking fires increased the risk of contracting meningococcal meningitis (Hodgson *et al.*, 2001). This increased risk suggests that exposure to elevated concentrations of air pollutants, such as carbon monoxide (CO) and particulate matter, may be linked to illness. More research is needed to clarify the possible impact of climate change on atmospheric concentrations of aerosols and particulates that can impact human health and any associations between meningitis and these aerosols and particles. The relationship between the environment and the location of the epidemics suggest connections between epidemics and regional climate variability (Molesworth *et al.*, 2003; Sultan *et al.*, 2005; Thomson *et al.*, 2006) which may allow for early warning systems for predicting the location and onset of epidemics.

Hantavirus: Novel hantaviruses with unknown pathogenic potential have been identified in some insectivores (shrews and a mole) in Africa (Klempa, 2009), with suggestions that weather and climate, among other drivers, could affect natural reservoirs and their geographic range, and thus alter species composition in ways that could be epidemiologically important (Klempa, 2009).

Other health issues: Research into other health issues has begun. It has been noted that any increase in food insecurity due to climate change would be expected to further compromise the poor nutrition of people living with HIV/AIDs (Drimie and Gillespie, 2010). Laboratory studies suggest that the geographic range of the tsetse fly (*Glossina* species), the vector of human and animal trypanosomiasis in Africa, may be reduced with climate change (Terblanche *et al.*, 2008). More studies are needed to clarify the role of climate change on HIV and other disease vectors.

Heat waves and high ambient temperatures: Heat waves and heat-related health effects are only beginning to attract attention in Africa. High ambient temperatures are associated with increased mortality in Ghana, Burkina Faso, and Nairobi with associations varying by age, gender, and cause of death (Azongo *et al*., 2012; Diboulo *et al*., 2012; Egondi *et al*., 2012). Children are particularly at risk. Heat-related health effects also may be of concern in West and southern Africa (Dapi *et al.*, 2010; Mathee *et al.*, 2010). Chapter 11 (11.4.1) assesses the literature on the health impacts of heat waves and high ambient temperatures. Low ambient temperatures are associated with mortality in

Nairobi and Tanzania (Egondi *et al*., 2012; Mrema *et al*., 2012). Chapter 11 discusses the relationship between heat and work capacity loss. This is an important issue for Africa because of the number of workers engaged in agriculture.

Air quality: Climate change is anticipated to affect the sources of air pollutants as well as the ability of pollutants to be dispersed in the atmosphere (Denman *et al.*, 2007). Assessments of the impacts of projected climate change on atmospheric concentrations of aerosols and particules that can adversely affect human health indicate that changes in surface temperature, land cover, and lightning may alter natural sources of ozone precursor gases and consequently ozone levels over Africa (Stevenson *et al.*, 2005; Brasseur *et al.*, 2006; Zeng *et al.*, 2008). However, insufficient climate and emissions data for Africa prevent a more comprehensive assessment and further research is needed to better understand the implications of climate change on air quality in Africa.

22.3.6. Urbanization

The urban population in Africa is projected to triple by2050, increasing by 0.8 billion (UN DESA, 2010). African countries are experiencing some of the world's highest urbanization rates (UN-Habitat, 2008). Many of Africa's evolving cities are unplanned and have been associated with growth of informal settlements, inadequate housing and basic services, and urban poverty (Yuen and Kumssa, 2011).[7]

[FOOTNOTE 7: However, community-driven upgrading may contribute to reducing the vulnerability of such informal areas (for more details see Chapter 8).]

Climate change could affect the size and characteristics of rural and urban human settlements in Africa because the scale and type of rural-urban migration are partially driven by climate change (UN-Habitat and UNEP, 2010; Yuen and Kumssa, 2011). The majority of migration flows observed in response to environmental change are within country boundaries (Jäger *et al.*, 2009; Tacoli, 2009). For large urban centers located on mega-deltas (e.g., Alexandria in Egypt in the Nile delta, and Benin City, Port Harcourt, and Aba in Nigeria in the Niger delta), urbanization through migration may also lead to increasing numbers of people vulnerable to coastal climate change impacts (Seto, 2011). Floods are exerting considerable impacts on cities and smaller urban centers in many African nations – for example, heavy rains in East Africa in 2002 caused floods and mudslides, which forced tens of thousands to leave their homes in Rwanda, Kenya, Burundi, Tanzania and Uganda, and the very serious floods in Port Harcourt and Addis Ababa in 2006 (Douglas *et al.*, 2008).

Additionally sea level rise along coastal zones including coastal settlements could disrupt economic activities such as tourism and fisheries (Naidu *et al*., 2006; Kebede *et al.*, 2012, Kebede and Nicholls, 2012). More than a quarter of Africa's population lives within 100 km of the coast and more than half of Africa's total population living in low-elevation coastal zones is urban, accounting for 11.5% of the total urban population of the continent (UN-Habitat, 2008).

In eastern Africa, an assessment of the impact of coastal flooding due to sea level rise in Kenya found that, by 2030, 10,000 to 86,000 people would be affected, with associated economic costs ranging between US$ 7 million to US$ 58 million (SEI, 2009). Detailed assessments of damages arising from extreme events have also been made for some coastal cities, including Mombasa and Dar-es-Salaam. In Mombasa, by 2030 the population and assets at risk of 1 in 100-year return period extreme water levels is estimated to be between 170,700 to 266,300 inhabitants, while economic assets at risk are between US$ 0.68 billion and 1.06 billion (Kebede *et al.*, 2012). In Dar-es-Salaam, the population and economic assets at risk of 1 in 100-year return period extreme water levels by 2030 range between 30,300 and 110,000 inhabitants and US$ 35.6 million to US$ 404.1 million (Kebede and Nicholls, 2012). For both city assessments, the breadth of these ranges encompasses three different population growth scenarios and four different sea-level rise scenarios (low (B1), medium (A1B), high (A1FI), and Rahmstorf (based on Rahmstorf, 2007)); these four sea-level rise scenarios were also the basis for the broader assessment of the coast of Kenya (SEI, 2009). The scale of the damages projected in the city-specific studies highlights the risks of extremes in the context of projected sea-level rise.

In southern Africa, urban climate change risk assessments have been made at the regional scale (Theron and Rossouw, 2008) as well as at the city level for Durban, Cape Town, and the uMhlathuze local municipality. For these cities, risk assessments have focused on a broad range of sectors, including business and tourism; air quality, heath, and food security; infrastructure and services; biodiversity; and water resources (Naidu *et al.*, 2006; Cartwright, 2008; Zitholele Consulting, 2009).

Assessments for western Africa (Appeaning Addo *et al.*, 2008; Niang *et al.*, 2010) and northern Africa (Snoussi *et al.*, 2009; World Bank, 2011) share similarities with those for eastern and southern Africa. For instance, it was suggested that by the end of the 21st century, about 23 %, 42 %, and 49 % of the total area of coastal governorates of the Nile Delta would be susceptible to inundation under the A1FI, Rahmstorf and Pfeffer scenarios of SLR. It was also suggested that a considerable proportion of these areas (ranging between 32% and 54 %) are currently either wetland or undeveloped areas (Hassaan and Abdrabo, 2013). Another study, assessing the economic impacts of sea level rise on the Nile Delta, suggested that losses in terms of housing and road would range between 1 and 2 billion EGP in 2030 and between 2 and 16 billion EGP in 2060 under the A1FI and B1 emissions scenarios as well as current sea level rise trends (Smith *et al.*, 2013).

African cities and towns represent highly vulnerable locations to the impacts of climate change and climate variability (Boko *et al.*, 2007; Diagne, 2007; Dossou and Gléhouenou-Dossou, 2007; Douglas *et al.*, 2008; Adelekan, 2010; Kithiia, 2011). Rapid rates of urbanization represent a burden on the economies of African urban areas, due to the massive investments needed to create job opportunities and provide infrastructure and services. Basic infrastructure services are not keeping up with urban growth, which has resulted in a decline in the coverage of many services, compared to 1990 levels (Banerjee *et al.*, 2007). Squatter and poor areas typically lack provisions to reduce flood risks or to manage floods when they happen (Douglas *et al.*, 2008).

African small- and medium-sized cities have limited adaptive capacity to deal not only with future climate impacts but also with the current range of climate variability (Satterthwaite *et al*., 2009; UN-Habitat, 2011); for more details see Chapter 5 and Chapter 8). African cities, despite frequently having more services compared to rural areas (e.g., piped water, sanitation, schools and healthcare) that lead to human life spans above their respective national averages, show a shortfall in infrastructure due to low quality and short lifespan which may be of particular concern, when climate change impacts are taken into consideration (Satterthwaite *et al*., 2009). It is not possible, however, “to climate-proof infrastructure that is not there” (Satterthwaite *et al.*, 2009). At the same time, hard infrastructural responses such as seawalls and channelized drainage lines are costly and can be maladaptive (Dossou and Gléhouenou-Dossou, 2007; Douglas *et al.*, 2008; Kithiia and Lyth, 2011).

High levels of vulnerability and low adaptive capacity results from structural factors, particularly local governments with poor capacities and resources (Kithiia, 2011). Weak local government creates and exacerbates problems including the lack of appropriate regulatory structures and mandates; poor or no planning; lack of or poor data; lack of disaster risk reduction strategies; poor servicing and infrastructure (particularly waste management and drainage); uncontrolled settlement of high-risk areas such as floodplains, wetlands, and coastlines; ecosystem degradation competing development priorities and timelines; and a lack of coordination among government agencies (AMCEN and UNEP, 2006; Diagne, 2007; Dossou and Gléhouenou-Dossou, 2007; Mukheibir and Ziervogel, 2007; Douglas *et al.*, 2008; Roberts, 2008; Adelekan, 2010; Kithiia and Dowling, 2010; Kithiia, 2011).

22.4. Adaptation

22.4.1. Introduction

Since 2007, Africa has gained experience in conceptualizing, planning and beginning to implement and support adaptation activities, from local to national levels and across a growing range of sectors (22.4.4, 22.4.5). However, across the continent, most of the adaptation to climate variability and change is reactive in response to short-term motivations, is occurring autonomously at the individual / household level, and lacks support from government stakeholders and policies (Vermuelen *et al.*, 2008; Ziervogel *et al.*, 2008; Berrang-Ford *et al.*, 2011). A complex web of interacting barriers to local-level adaptation, manifesting from national to local scales, both constrains and highlights potential limits to adaptation (22.4.6).

22.4.2. Adaptation Needs, Gaps, and Adaptive Capacity

Africa's urgent adaptation needs stem from the continent's foremost sensitivity and vulnerability to climate change, together with its low levels of adaptive capacity (Ludi *et al.*, 2012; 22.3). While overall adaptive capacity is considered low in Africa due to economic, demographic, health, education, infrastructure, governance and natural factors, levels vary within countries and across sub-regions, with some indication of higher adaptive capacity in North Africa and some other countries; individual or household level adaptive capacity depends, in addition to functional institutions and access to assets, on the ability of people to make informed decisions to respond to climatic and other changes (Vincent, 2007; Ludi *et al.*, 2012).

Inherent adaptation-related strengths in Africa include the continent's wealth in natural resources, well-developed social networks, and longstanding traditional mechanisms of managing variability through, for example, crop and livelihood diversification, migration and small-scale enterprises, all of which are underpinned by local or indigenous knowledge systems for sustainable resource management (Eyong, 2007; Nyong *et al.*, 2007; UNFCCC, 2007; Cooper *et al.*, 2008; Macchi *et al.*, 2008; Nielsen, 2010; Castro *et al.*, 2012;). However, it is uncertain to what extent these strategies will be capable of dealing with future changes, among them climate change and its interaction with other development processes (Leary *et al.*, 2008b; Paavola, 2008; van Aalst *et al.*, 2008; Conway, 2009; Jones, 2012, section 22.4.6). Since Africa is extensively exposed to a range of multiple stressors (22.3) that interact in complex ways ith longer term climate change, adaptation needs are broad, encompassing institutional, social, physical and infrastructure needs, ecosystem services and environmental needs, and financial and capacity needs.

Making climate change information more reliable and accessible is one of the most pressing and cross-cutting adaptation needs, but providing information is insufficient to guarantee adaptation, which requires behavioural change (22.4.5.5, 22.4.6). As noted in the AR4 and emphasised in subsequent literature, monitoring networks in Africa are insufficient and characterised by sparse coverage and short and fragmented digitised records, which makes modelling difficult (Boko *et al.*, 2007; Goulden *et al.*, 2009b; Ziervogel and Zermoglio, 2009; Jalloh *et al.*, 2011a). Adding to this is the shortage of relevant information and skills, in particular for downscaling climate models and using scenario outputs for development and adaptation planning, which is exacerbated by under-resourcing of Meteorological Agencies and a lack of in-country expertise on climate science; and the capacity of civil society and government organisations' to access, interpret and use climate information for planning and decisionmaking (Ziervogel and Zermoglio, 2009; Brown *et al.*, 2010; Ndegwa *et al.*, 2010; Dinku *et al.*, 2011; Jalloh *et al.*, 2011a).

Given its economic dependence on natural resources, most research on strengthening adaptive capacity in Africa is focused on agriculture, forestry or fisheries-based livelihoods (Collier *et al.*, 2008; Berrang-Ford *et al.*, 2011). The rural emphasis is now being expanded through a growing focus on requirements for enhancing peri-urban and urban adaptive capacity (Lwasa, 2010; Ricci, 2012). Many African countries have prioritised the following knowledge needs: vulnerability and impact assessments with greater continuity in countries; country-specific socio-economic scenarios and greater knowledge on costs and benefits of different adaptation measures; comprehensive programmes that promote adaptation through a more holistic development approach, including integrated programmes on desertification, water management and irrigation; promoting sustainable agricultural practices and the use of appropriate technologies and innovations to address shorter growing seasons, extreme temperatures, droughts, and floods; developing alternative sources of energy; and approaches to deal with water shortages, food security and loss of livelihoods (UNFCCC, 2007; Bryan *et al.*, 2009; Eriksen and Silva, 2009; Chikozho, 2010; Gbetibouo *et al.*, 2010b; Jalloh *et al.*, 2011b; Sissoko *et al.*, 2011; AAP, 2012). The literature, however, stresses the vast variety of contexts that shape adaptation and adaptive capacity - even when people are faced with the same climatic changes and livelihood stressors, responses vary greatly (Cooper *et al.*, 2008; Vermuelen *et al.*, 2008; Ziervogel *et al.*, 2008; Gbetibouo, 2009; Westerhoff & Smit, 2009)

Despite significant data and vulnerability assessment gaps, the literature highlights that delayed action on adaptation due to this would not be in the best interests of building resilience commensurate with the urgent needs (UNFCCC, 2007; Jobbins, 2011). See section 22.6.4 for a discussion of adaptation costs and climate finance.

22.4.3. Adaptation, Equity, and Sustainable Development

Multiple uncertainties in the African context mean that successful adaptation will depend upon developing resilience in the face of uncertainty (*high confidence)* (Adger *et al.,* 2011; Conway, 2011; Ludi *et al.,* 2012). The limited ability of developmental strategies to counter current climate risks, in some cases due to significant implementation challenges related to complex cultural, political and insitutional factors, has led to an adaptation deficit, which reinforces the desirability for strong inter-linkages between adaptation and development, and for low-regrets adaptation strategies (see AR5 Glossary) that produce developmental co-benefits (*high confidence*) (Bauer and Scholz, 2010; Smith *et al.*, 2011).

Research has highlighted that no single adaptation strategy exists to meet the needs of all communities and contexts in Africa (*high confidence*) (22.4.4, 22.4.5). In recognition of the socioeconomic dimensions of vulnerability (Bauer and Scholz, 2010), the previous focus on technological solutions to directly address specific impacts is now evolving toward a broader view that highlights the importance of building resilience, through social, institutional, policy, knowledge, and informational approaches (ADF, 2010; Chambwera and Anderson, 2011), as well as on linking the diverse range of adaptation options to the multiple livelihood–vulnerability risks faced by many people in Africa (Tschakert and Dietrich, 2010), and on taking into account local norms and practices in adaptation strategies (Nyong *et al.*, 2007; Ifejika Speranza *et al.*, 2010; section 22.4.5.4). Moreover, effective adaptation responses necessitate differentiated and targeted actions from the local to national levels, given the differentiated social impacts based on gender, age, disability, ethnicity, geographical location, livelihood, and migrant status (Tanner and Mitchell, 2008; IPCC, 2012). Additional attention to equity and social justice aspects in adaptation efforts in Africa, including the differential distribution of adaptation benefits and costs, would serve to enhance adaptive capacity (Burton *et al.*, 2002; Brooks *et al.,* 2005; Thomas and Twyman, 2005; Madzwamuse, 2010); nevertheless, some valuable experience has been gained recently on gender-equitable adaptation, human rights based-approaches, and involvement of vulnerable or marginalized groups such as indigenous peoples and children, aged and disabled people, internally displaced persons and refugees (ADF, 2010; UNICEF, 2010; Levine *et al.*, 2011; UNICEF, 2011; Romero González *et al.*, 2011; IDS, 2012; Tanner and Seballos, 2012) (Table 22-5). See also CC-GC on Gender and Climate Change.

[INSERT TABLE 22-5 HERE
Table 22-5: Cross-cutting approaches for equity and social justice in adaptation.]

22.4.4. Experiences in Building the Governance System for Adaptation, and Lessons Learned

22.4.4.1. Introduction

Section 22.4.4 assesses progress made in developing policy, planning and institutional systems for climate adaptation at regional, national and sub-national levels in Africa, with some assessment of implementation. This includes an assessment of community-based adaptation, as an important local level response, and a consideration of adaptation decisionmaking and monitoring.

22.4.4.2. Regional and National Adaptation Planning and Implementation

Regional policies and strategies for adaptation, as well as transboundary adaptation, are still in their infancy. Early examples include the Climate Change Strategies and Action Plans being developed by the Southern African Development Community and the Lake Victoria Basin Committee, as well as efforts being made by six highly forested Congo basin countries to co-ordinate conservation and sustainable forest management of the Central African forest ecosystem, and obtain payments for ecosystem services (Harmeling *et al.*, 2011; AfDB, 2012).

At the national level, African countries have initiated comprehensive planning processes for adaptation by developing National Adaptation Programmes of Action (NAPAs), in the case of the Least Developed Countries, or National Climate Change Response Strategies (NCCRS); implementation is, however, lagging and integration with economic and development planning is limited but growing (*high confidence*). Prioritized adaptation measures in the NAPAs tend to focus narrowly on agriculture, food security, water resources, forestry, and disaster management; and onprojects, technical solutions, education and capacity development, with little integration with economic planning and poverty reduction processes (Madzwamuse, 2010; Mamouda, 2011; Pramova *et al.*, 2012). Only a small percentage of the NAPA activities have been funded to date, although additional funding is in the pipeline (Prowse *et al.*, 2009; Madzwamuse, 2010; Mamouda, 2011; Romero González *et al.*, 2011).

Subsequent to the NAPAs and early experience with the NCCRS, there is some evidence of evolution to a more integrated, multi-level and multi-sector approach to adaptation planning (*medium confidence*). Examples include Ethiopia’s Programme of Adaptation to Climate Change, which includes sectoral, regional, national and local community levels (Hunde, 2012); Lesotho’s co-ordinated policy framework involving all ministries and stakeholders (Corsi *et al.*, 2012); and Mali’s experience with a methodology for integrating adaptation into multiple sectors (Fröde *et al.*, 2013). Cross-sectoral adaptation planning and risk management is occurring through mainstreaming initiatives like the twenty country Africa Adaptation Programme (AAP), initiated in 2008 (UNDP, 2009; Siegel, 2011). Examples of the more programmatic approach of national climate resilient development strategies include Rwanda’s National Strategy on Climate Change and Low Carbon Development, under development in 2012, and the Pilot Programmes for Climate Resilience in Niger, Zambia and Mozambique (Climate Investment Fund, 2009). Inter-sectoral climate risk management approaches can be detected in integrated water resources management, integrated coastal zone management, disaster risk reduction, and land use planning initiatives (Boateng, 2006; Koch *et al*., 2007; Awuor *et al.*, 2008; Cartwright *et al.*, 2008; Kebede and Nicholls, 2011; Kebede *et al.*, 2012), while in South Africa, climate change design principles have been incorporated into existing systematic biodiversity planning to guide land use planning (Petersen and Holness, 2011).

The move to a more integrated approach to adaptation planning is occurring within efforts to construct enabling national policy environments for adaptation in many countries. Examples include Namibia’s National Policy on Climate Change; Zambia’s National Climate Change Response Strategy and Policy, and South Africa’s National Climate Change Response Policy White Paper. Ten countries were developing new climate change laws or formal policies at the end of 2012, including the proposed National Coastal Adaptation Law in Gabon (Corsi *et al.*, 2012).

Despite this progress in mainstreaming climate risk in policy and planning, significant disconnects still exist at the national level, and implementation of a more integrated adaptation response remains tentative (*high confidence*) (Koch *et al.*, 2007; Fankhauser and Schmidt-Traub, 2010; Madzwamuse, 2010; Oates *et al*., 2011; UNDP-UNEP Poverty-Environment Initiative, 2011a). Legislative and policy frameworks for adaptation remain fragmented, adaptation policy approaches seldom take into account realities in the political and institutional spheres, and national policies are often at odds with autonomous local adaptation strategies, which can act as a barrier to adaptation, especially where cultural, traditional and context-specific factors are ignored (Dube and Sekhwela, 2008; Patt and Schröter, 2008; Stringer *et al.*, 2009; Bele *et al.* 2010; Hisali *et al.*, 2011; Kalame *et al.* 2011; Naess *et al.*, 2011; Lockwood, 2012; Sonwa *et al.* 2012; section 22.4.6). While climate resilience is starting to be mainstreamed into economic planning documents - for example, Zambia’s Sixth National Development Plan 2011-2015, and the new Economic and Social Investment Plan in Niger (Corsi *et al.*, 2012), measures to promote foreign direct investment and industrial competitiveness can undercut adaptive capacity of poor people (Madzwamuse, 2010), while poor business environments impede both foreign direct investment and adaptation (Collier *et al*., 2008). Stakeholders in climate-sensitive sectors – for example, Botswana’s tourism industry - have yet to develop and implement adaptation strategies (Saarinen *et al*., 2012).

22.4.4.3. Institutional Frameworks for Adaptation

Global adaptation institutions, both within and outside of the UNFCCC, are critically important for Africa's ability to move forward on adaptation (14.2.3). Regional institutions focused on specific ecosystems rather than on political groupings, such as the Commission of Central African Forests (COMIFAC), present an opportunity to strengthen the institutional framework for adaptation. National frameworks include a number of institutions that cover all aspects of climate change: most countries have inter-ministerial coordinating bodies and inter-sectoral technical working groups, while an increasing number now have multi-stakeholder co-ordinating bodies (Harmeling et al, 2011) and are establishing national institutions to serve as conduits for climate finance (Gomez-Echeverri, 2010; Smith *et al.*, 2011).

Many studies in Africa show that under uncertain climatic futures, replacing hierarchical governance systems that operate within siloes with more adaptive, integrated, multi-level and flexible governance approaches, and with inclusive decisionmaking that can operate successfully across multiple scales – or adaptive governance and co-management – will enhance adaptive capacity and the effectivess of the adaptation response (Folke *et al.*, 2005; Olsson *et al.*, 2006; Koch *et al.*, 2007; Berkes, 2009; Pahl-Wostl, 2009; Armitage and Plummer, 2010; Bunce *et al.*, 2010a; Plummer, 2012). Despite some progress with developing the institutional framework for governing adaptation, there are significant problems with both transversal and vertical coordination, including institutional duplication with other inter-sectoral platforms, such for disaster risk reduction; while in fragile states, institutions for reducing climate risk and promoting adaptation may be extremely weak or almost non-existent (Hartmann and Sugulle, 2009; Sietz *et al.*, 2011; Simane *et al.*, 2012). Facilitating institutional linkages and co-ordinating responses across all boundaries of government, private sector and civil society would enhance adaptive capacity (Brown *et al.*, 2010). Resolving well-documented institutional challenges of natural resource management, including lack of co-ordination, monitoring and enforcement, is a fundamental step towards more effective climate governance. For example, concerning groundwater, developing organizational frameworks and strengthening institutional capacities for more effectively assessing and managing groundwater resources over the long term are critically important (Nyenje and Batelaan, 2009; Braune and Xu, 2010).

22.4.4.4. Sub-National Adaptation Governance

Since AR4, there has been additional effort on sub-national adaptation planning in African countries, but adaptation strategies at provincial and municipal levels are mostly still under development, with many local governments lacking the capacity and resources for the necessary decentralised adaptation response (*high confidence*). Provinces in some countries have developed policies and strategies on climate change: for example, Lagos State's 2012 Adaptation Strategy in Nigeria (BNRCC, 2012); mainstreaming adaptation into district development plans in Ghana; and communal climate resilience plans in Morocco (Corsi *et al.*, 2012). Promising approaches include sub-national strategies that integrate adaptation and mitigation for low-carbon climate resilient development, as is being done in Delta State in Nigeria, and in other countries (UNDP, 2011a). In response to the identified institutional weaknesses, capacity development has been implemented in many cities and towns, including initiatives in Lagos, Nigeria, Durban and Cape Town in South Africa: notable examples include Maputo's specialized local government unit to implement climate change response, ecosystem-based adaptation and improved city wetlands; and participatory skills development in integrating community-based disaster risk reduction and climate adaptation into local development planning in Ethiopia (Madzwamuse, 2010; ACCRA, 2012; Castán Broto, *et al.*, 2013).

22.4.4.5. Community-Based Adaptation and Local Institutions

Since AR4, there has been progress in Africa in implementing and researching community-based adaptation (*high confidence*), with broad agreement that support to local-level adaptation is best achieved by starting with existing local adaptive capacity, and incorporating and building upon present coping strategies and norms, including indigenous practices (Dube and Sekhwela, 2007; Archer *et al.*, 2008; Huq, 2011). Community-based adaptation (CBA) is community initiated, and/or draws upon community knowledge or resources – refer to AR5 glossary. Some relevant initiatives include the Community-based Adaptation in Africa (CBAA) project, which implemented community-level pilot projects in eight African countries (Sudan, Tanzania, Uganda, Zambia, Malawi, Kenya, Zimbabwe, South Africa) through a learning-by-doing approach; the Adaptation Learning Program, implemented in Ghana, Niger, Kenya and Mozambique (CARE International, 2012); and UNESCO Biosphere Reserves where good practices were developed in Ethiopia, Kenya, South Africa and Senegal (German Commission for UNESCO, 2011). See also section 22.4.5.6 on institutions for CBA. The literature includes a wide range of case studies detailing involvement of local communities in adaptation initiatives and projects facilitated by NGOs and researchers (for example, Leary *et al*., 2008a; CCAA, 2011; CARE International, 2012; Chishakwe *et al.,* 2012); these and other initiatives have generated process-related lessons (22.4.5), with positive assessments of effectiveness in improving adaptive capacity of African communities, local organisations and researchers (Lafontaine *et al*., 2012).

The key role for local institutions in enabling community resilience to climate change has been recognised, particularly with respect to natural resource dependent communities – for example, the role of NGOs and CBOs in catalysing agricultural adaptation or in building resilience through enhanced forest governance and sustainable management of non-timber forest products; institutions managing access to and tenure of land and other natural resources, which are vital assets for the rural and peri-urban poor, are particularly crucial for enabling CBA and enhancing adaptive capacity in Africa (Bryan *et al*., 2009; Brown *et al*., 2010; Mogoi *et al.*, 2010). Local studies and adaptation planning have revealed the following priorities for pro-poor adaptation: social protection, social services and safety nets; better water and land governance; action research to improve resilience of under-researched food crops of poor people; enhanced water storage and harvesting; better post-harvest services; strengthened civil society and greater involvement in planning; and more attention to urban and peri-urban areas heavily affected by migration of poor people (Moser and Satterthwaite, 2008; Urquhart, 2009; Bizikova *et al*., 2010).

22.4.4.6. Adaptation Decisionmaking and Monitoring

Emerging patterns in Africa regarding adaptation decision-making, a critical component of adaptive capacity, include limited inclusive governance at the national level, with greater involvement in local initiatives of vulnerable and exposed people in assessing and choosing adaptation responses (*high confidence*). Civil society institutions and communities have to date played a limited role in formulation of national adaptation policies and strategies, highlighting the need for governments to widen the political space for citizens and institutions to participate in decision-making, for both effectiveness and to ensure rights are met (Madzwamuse, 2010; Castro *et al*., 2012). Building African leadership for climate change may assist with this (CCAA, 2011; Chandani, 2011; Corsi *et al.*, 2012). A critical issue is how planning and decisionmaking for adaptation uses scientific evidence and projections, while also managing the uncertainties within the projections (Conway, 2011; Dodman and Carmin, 2011).

A range of tools has been used in adaptation planning in Africa, including vulnerability assessment (22.4.5), risk assessment, cost-benefit analysis, cost-effectiveness, multi-criteria analysis, and participatory scenario planning (see for example Cartwright *et al.*, 2008; Kemp-Benedict and Agyemang-Bonsu, 2008; Njie *et al*., 2008; Mather and Stretch, 2012), but further development and uptake of decision tools would facilitate enhanced decisionmaking. A related point is that monitoring and assessing adaptation is still relatively undeveloped in Africa, with national co-ordinating systems for collating data and synthesizing lessons not in place. Approaches for assessing adaptation action at local and regional levels have been developed (see for example Hahn *et al.,* 2009; Gbetibouo *et al.,* 2010a; Below *et al*., 2012), while there are positive examples of local monitoring of adaptation at the project level (see for example Archer *et al.*, 2008; Below *et al*., 2012). Chapter 2 contains additional discussion of the foundations for decisionmaking on climate change matters.

22.4.5. Experiences with Adaptation Measures in Africa and Lessons Learned

22.4.5.1. Overview

Section 22.4.5 provides a cross-cutting assessment of experience gained in Africa with a range of adaptation approaches, encompassing climate risk reduction measures; processes for participatory learning and knowledge development and sharing; communication, education and training; ecosystem-based measures; and technological and infrastructural approaches; concluding with a discussion of maladaptation.

Common priority sectors across countries for implementing adaptation measures since 2008 include agriculture, food security, forestry, energy, water, and education (Corsi *et al.*, 2012), which reflects a broadening of focus since the AR4. While there has been little planning focus on regional adaptation (22.4.4.2, 22.4.4.3), the potential for this has been recognized (UNFCCC, 2007; Sonwa *et al.*, 2009; Niang, 2012).

Attention is increasing on identifying opportunities inherent in the continent's adaptation needs, as well as delineating key success factors for adaptation. A number of studies identify the opportunity inherent in implementing relatively low-cost and simple low-regrets adaptation measures that reduce people's vulnerability to current climate variability, have multiple developmental benefits, and are well-positioned to reduce vulnerability to longer-term climate change as well (UNFCCC, 2007; Conway and Schipper, 2011; see also Section 22.4.3). Responding to climate change provides an opportunity to enhance awareness that maintaining ecosystem functioning underpins human survival and development in a most fundamental way (Shackleton and Shackleton, 2012), and to motivate for new development trajectories (22.4.6). While it is difficult to assess adaptation success, given temporal and spatial scale issues, and local specificities, Osbahr *et al.* (2010) highlight the role of social networks and institutions, social resilience, and innovation as possible key success factors for adaptation in small-scale farming livelihoods in southern Africa. Kalame *et al.* (2008) note opportunities for enhancing adaptation through forest governance reforms to improve community access to forest resources, while Martens *et al.* (2009) emphasise the importance of 'soft path' measures for adaptation strategies (see also section 22.4.5.6).

The following discussion of adaptation approaches under discrete headings does not imply that these are mutually exclusive – adaptation initiatives usually employ a range of approaches simultaneously, and indeed, the literature increasingly recognizes the importance of this for building resilience.

22.4.5.2. Climate Risk Reduction, Risk Transfer, and Livelihood Diversification

Risk reduction strategies used in African countries to offset the impacts of natural hazards on individual households, communities, and the wider economy include early warning systems, emerging risk transfer schemes, social safety nets, disaster risk contingency funds and budgeting, livelihood diversification, and migration (World Bank, 2010; UNISDR, 2011).

Disaster risk reduction (DRR) platforms are being built at national and local levels, with the synergies between DRR and adaptation to climate change being increasingly recognized in Africa (Westgate, 2010; UNISDR, 2011; Hunde, 2012); however, Conway and Schipper (2011) find that additional effort is needed for a longer-term vulnerability reduction perspective in disaster management institutions.

Early warning systems (EWS) are gaining prominence as multiple stakeholders strengthen capabilities to assess and monitor risks and warn communities of a potential crisis, through regional systems such as the Permanent Inter-States Committee for Drought Control in the Sahel (CILSS) and the Famine Early Warning System Network (FEWS-NET), as well as national, local and community-based EWS on for example food and agriculture (Pantuliano and Wekesa, 2008; Sissoko *et al.*, 2011; FAO, 2011). Some of the recent EWS emphasise a gendered approach, and may incorporate local knowledge systems used for making short-, medium-, and long-term decisions about farming and livestock-keeping, as in Kenya (UNDP, 2011b). The health sector has employed EWS used to predict disease for adaptation planning and implementation, such as the prediction of conditions expected to lead to an outbreak of Rift Valley fever in the Horn of Africa in 2006/2007 (Anyamba *et al.*, 2010). Progress has been made in prediction of meningitis and in linking climate/weather variability and extremes to the disease (Thomson *et al.*, 2006; Cuevas *et al.*, 2007).

Local projects often use participatory vulnerability assessment or screening to design adaptation strategies (van Vliet, 2010; GEF Evaluation Office, 2011; Hambira, 2011), but vulnerability assessment at the local government level is often lacking, and assessments to develop national adaptation plans and strategies have not always been conducted in a participatory fashion (Madzwamuse, 2010). Kienberger (2012) details spatial modelling of social and economic vulnerability to floods at the district level in Búzi, Mozambique. Lessons from vulnerability analysis highlight that the highest exposure and risk do not always correlate with vulnerable ecosystems, socially marginalized groups, and areas with at-risk infrastructure, but may also lie in unexpected segments of the population (Moench, 2011).

Community-level DRR initiatives include activities that link food security, household resilience, environmental conservation, asset creation, and infrastructure development objectives and co-benefits (Parry *et al.*, 2009a; UNISDR, 2011; Frankenberger *et al.*, 2012). Food security and nutrition-related safety nets and social protection mechanisms can mutually reinforce each other for DRR that promotes adaptation, as in Uganda's Karamoja Productive Assets Programme (Government of Uganda and WFP 2010; WFP, 2011). Initiatives in Kenya, South Africa, Swaziland and Tanzania have also sought to deploy local and traditional knowledge for the purposes of disaster preparedness and risk management (Mwaura, 2008; Galloway McLean, 2010). Haan *et al.* (2012) highlight the need for increased donor commitment to the resilience-building agenda within the framework of DRR, based on lessons from the 2011 famine in Somalia.

Social protection[8], a key element of the African Union social policy framework, is being increasingly used in Ethiopia, Rwanda, Malawi, Mozambique, South Africa, and other countries to buffer against shocks by building assets and increasing resilience of chronically and transiently poor households; in some cases this surpasses repeated relief interventions to address slower onset climate shocks, as in Ethiopia's Productive Safety Net Program (Brown *et al.*, 2007; Heltberg *et al.* 2009). While social protection is helping with *ex post* and *ex ante* DRR and will be increasingly important for securing livelihoods should climate variability increase, less evidence exists for its effectiveness against the most extreme climatic shocks associated with higher emissions scenarios, which would require reducing dependence on climate-sensitive livelihood activities (Davies *et al.*, 2009; Wiseman *et al.*, 2009; Pelham *et al.*, 2011; Béné *et al.*, 2012). Social protection could further build adaptive capacity if based on improved understanding of the structural causes of poverty, including political and institutional dimensions (Brown *et al.*, 2007; Davies *et al.*, 2009; Levine *et al.*, 2011).

[FOOTNOTE 8: Social protection can include social transfers (cash or food), minimum standards such as for child labor, and social insurance.]

Risk spreading mechanisms used in the African context include kinship networks; community funds; and disaster relief and insurance, which can provide financial security against extreme events such as droughts, floods, and tropical cyclones, and concurrently reduce poverty and enhance adaptive capacity[9] (Leary *et al.*, 2008a; Linnerooth-Bayer *et al.* 2009; Coe and Stern, 2011). Recent developments include the emergence of index-based insurance contracts (Box 22-1), which pay out not with the actual loss, but with a measurable event that could cause loss.

[FOOTNOTE 9: Climate (or disaster) risk financing instruments include contingency funds; agricultural and property (private) insurance; sovereign insurance; reallocation of program expenditures; weather derivatives; and bonds.]

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Box 22-1. Experience with Index-Based Weather Insurance in Africa

Malawi's initial experience of dealing with drought risk through index-based weather insurance directly to smallholders appears positive: 892 farmers purchased the insurance in the first trial period, which was bundled with a loan for groundnut production inputs (Hellmuth *et al.*, 2009). In the next year, the pilot expanded, with the addition of maize, taking numbers up to 1,710 farmers and stimulating interest among banks, financiers, and supply chain participants such as processing and trading companies and input suppliers. A pilot insurance project in Ethiopia was designed to pay claims to the government based on a drought index that uses a time window between observed lack of rain and actual materialization of losses. This allows stakeholders to address threats to food security in ways that prevent the depletion of farmers' productive assets, which reduces the future demand for humanitarian aid by enabling households to produce more food during subsequent seasons (Krishnamurty, 2011).

Another key innovation in Ethiopia is the insurance for work program that allows cash-poor farmers to work for their insurance premiums by engaging in community-identified disaster risk reduction products, such as soil management and improved irrigation (WFP, 2011), which makes insurance affordable to the most marginalized and resource-poor sectors of society.

_____ END BOX 22-1 HERE _____

The challenges associated with current risk reduction strategies include political and institutional challenges in translating early warning into early action (Bailey, 2013); communication challenges related to EWS: conveying useful information in local languages and communicating EWS in remote areas; national-level mistrust of locally collected data, which are perceived to be inflated to leverage more relief resources (Hellmuth *et al.*, 2007; Pantuliano and Wekesa, 2008; Cartwright *et al.*, 2008; FAO, 2011); the call for improved user-friendliness of early warning information, including at smaller spatial scales; the need for increased capacity in National Meteorological centres (22.4.2); and the need for better linkages between early warning, response, and prevention (Haan *et al.*, 2012).

Evidence is increasing that livelihood diversification, long used by African households to cope with climate shocks, can also assist with building resilience for longer term climate change by spreading risk. Over the past 20 years, households in the Sahel have reduced their vulnerability and increased their wealth through livelihood diversification, particularly when diversifying out of agriculture (Mertz *et al.*, 2011). Households may employ a range of strategies, including on-farm diversification or specialization (Sissoko *et al.*, 2011; Tacoli, 2011). Motsholapheko *et al.* (2011) show how livelihood diversification is used as an adaptation to flooding in the Okavango Delta, Botswana, and Badjeck *et al.* (2010) recommend private and public insurance schemes to help fishing communities rebuild after extreme events, and education and skills upgrading to enable broader choices when fishery activities can no longer be sustained. See Chapter 9 for a fuller discussion of the role of livelihood diversification in adaptation, particularly 9.3.3.1 and 9.3.5.2). Remittances are a longstanding and important means of reducing risk to climate variability and other household stressors, and of contributing to recovery from climatic shocks, as further discussed in Chapter 9 (9.3.3.3, 9.3.5.2).

While livelihood diversification is an important adaptation strategy, it may replace formerly sustainable practices with livelihood activities that have negative environmental impacts (22.4.5.8).

Rural finance and micro-credit can be enabling activities for adaptive response, which are also used by women for resilience-building activities (e.g., as documented in Sudan by Osman-Elasha *et al.*, 2008). Credit and storage systems are instrumental in supporting families during the lean period, to prevent the sale of assets to buy food when market prices are higher (Romero González *et al.*, 2011). Long seen as a fundamental process for most African families to incorporate choice into their risk profile and adapt to climate variability (Goldstone, 2002; Urdal, 2005; Reuveny, 2007; Fox and Hoelscher, 2010), there is evidence in some areas of the increased importance of migration (discussed in section 22.6.1, 8.2, 9.3.3.3, 12.4) and trade for livelihood strategies, as opposed to subsistence agriculture, as shown by Mertz *et al.* (2011) for the Sudano-Sahelian region of West Africa.

22.4.5.3. Adaptation as a Participatory Learning Process

Since AR4, there has been more focus on the importance of flexible and iterative learning approaches for effective adaptation (*medium evidence, high agreement*). Due to the variety of intersecting social, environmental, and economic factors that affect societal adaptation, governments, communities, and individuals (Jones *et al.*, 2010; Jones, 2012), adaptation is increasingly recognized as a complex process involving multiple linked steps at several scales, rather than a series of simple planned technical interventions (Moser and Ekstrom, 2010). Implementing adaptation as a participatory learning process enables people to adopt a proactive or anticipatory stance to avoid 'learning by shock' (Tschakert and Dietrich, 2010).

Iterative and experiential learning allows for flexible adaptation planning, appropriate considering the uncertainty inherent in climate projections that is compounded by other sources of flux affecting populations in Africa (Suarez *et al.*, 2008; Dodman and Carmin, 2011; Huq, 2011; Koelle and Annecke, 2011). Many studies have highlighted the utility of participatory action research, social and experiential learning, and creating enabling spaces for multi-stakeholder dialogue for managing uncertainty and unlocking the social and behavioral change required for adaptation (e.g., Tompkins and Adger, 2003; Ziervogel and Opere, 2010; Bizikova *et al.*, 2010; Tschakert and Dietrich 2010; CCAA, 2011; Ebi *et al.*, 2011; UNDP-UNEP Poverty-Environment Initiative, 2011b; Thorn, 2011; Faysse *et al.*, 2012). Transdisciplinary approaches, which hold promise for enhancing linkages between sectors and thus reducing maladaptation are also starting to be adopted, as for example in the urban context (Evans, 2011). Learning approaches for adaptation may involve co-production of knowledge – such as combining local and traditional knowledge with scientific knowledge (22.4.5.4).

Adaptive co-management[10] holds potential to develop capacity to deal with change (Watkiss *et al.*, 2010; Plummer, 2012); the implications of strategic adaptive management for adaptation in aquatic protected areas in South Africa are being explored (Kingsford *et al.*, 2011).

[FOOTNOTE 10: Adaptive co-management is understood as “a process by which institutional arrangements and ecological knowledge are tested and revised in a dynamic, ongoing, self-organized process of learning-by-doing” (Folke *et al.*, 2002).]

Caveats and constraints to viewing adaptation as a participatory learning process include the time and resources required from both local actors and external facilitators, the challenges of multidisciplinary research, the politics of stakeholder participation and the effects of power imbalances, and the need to consider not only the consensus approach but also the role of conflicts (Aylett, 2010; Tschakert and Dietrich, 2010; Beardon and Newman, 2011; Jobbins, 2011; Shankland and Chambote, 2011). Learning throughout the adaptation process necessitates additional emphasis on ways of sharing experiences between communities and other stakeholders, both horizontally and vertically (22.4.5.4). Information and communication technologies, including mobile phones, radio, and the internet, can play a role in facilitating participatory learning processes and helping to overcome some of the challenges (Harvey *et al.*, 2012).

The increased emphasis on the importance of innovation for successful adaptation, in both rural and urban contexts, relates to interventions that employ innovative methods, as well as the innovation role of institutions (Tschakert and Dietrich, 2010; Dodman and Carmin, 2011; Rodima-Taylor, 2012; Scheffran *et al.*, 2012). Scheffran *et al.* (2012) demonstrate how migrant social organizations in the western Sahel initiate innovations across regions by transferring technology and knowledge, as well as remittances and resources. While relevant, high-quality data is important as a basis for adaptation planning, innovative methods are being used to overcome data gaps, particularly local climatic data and analysis capability (Tschakert and Dietrich, 2010; GEF Evaluation Office, 2011).

22.4.5.4. Knowledge Development and Sharing

Recent literature has confirmed the positive role of local and traditional knowledge in building resilience and adaptive capacity, and shaping responses to climatic variability and change in Africa (Nyong *et al.*, 2007; Osbahr *et al.*, 2007; Goulden *et al.*, 2009b; Ifejika Speranza *et al.*, 2010; Jalloh *et al.*, 2011b; Newsham and Thomas, 2011). This is particularly so at the community scale, where there may be limited access to, quality of, or ability to use scientific information. The recent report on extreme events and disasters (IPCC, 2012) supports this view, finding *high agreement* and *robust evidence* of the positive impacts of integrating indigenous and scientific knowledge for adaptation. Concerns about the future adequacy of local knowledge to respond to climate impacts within the multi-stressor context include the decline in intergenerational transmission; a perceived decline in the reliability of local indicators for variability and change, as a result of socio-cultural, environmental, and climate changes (Hitchcock 2009; Jennings and Magrath 2009); and challenges of the emerging and anticipated climatic changes seeming to overrun indigenous knowledge and coping mechanisms of farmers (Berkes, 2009; Ifejika Speranza *et al.*, 2010; Jalloh *et al.*, 2011b; section 22.4.6). Based on analysis of the responses to the Sahel droughts during the 1970s and 1980s, Mortimore (2010) argues that local knowledge systems are more dynamic and robust than is often acknowledged. Linking indigenous and conventional climate observations can add value to climate change adaptation within different local communities in Africa (Roncoli *et al.*, 2002; Nyong *et al.*, 2007; Chang'a *et al.*, 2010; Guthiga and Newsham, 2011).

Choosing specific adaptation actions that are informed by users' perceptions and supported by accurate climate information, relevant to the scale where decisions are made, would be supportive of the largely autonomous adaptation taking place in Africa (Vogel and O'Brien, 2006; Ziervogel *et al.*, 2008; Bryan *et al.*, 2009; Godfrey *et al.*, 2010). Key problems regarding how science can inform decision making and policy are how best to match scientific information, for example about uncertainty of change, with decision needs; how to tailor information to different constituencies; and what criteria to use to assess whether or not information is legitimate to influence policy and decisionmaking (Vogel *et al.*, 2007; Hirsch Hadorn *et al.*, 2008). Institutional innovation is one solution: for example, Nigeria established the Science Committee on Climate Change to develop strategies to bridge the gap between increasing scientific knowledge and policy (Corsi *et al.*, 2012).

There is agreement that culture, or the shaping social norms, values, and rules including those related to ethnicity, class, gender, health, age, social status, cast, and hierarchy, is of crucial importance for adaptive capacity as a positive attribute but also as a barrier to successful local adaptation (22.4.6); further research is required in this field, not least because culture is highly heterogeneous within a society or locality (Adger *et al.*, 2007, 2009; Ensor and Berger, 2009; Nielsen and Reenberg, 2010; Jones, 2012). Studies show that while it is important to further develop the evidence base for the effectiveness of traditional knowledge, integrating cultural components such as stories, myths, and oral history into initiatives to document local and traditional knowledge on adaptive or coping mechanisms is a key to better understanding how climate vulnerability and adaptation are framed and experienced (Urquhart, 2009; Beardon and Newman, 2011; Ford *et al.*, 2012). Appropriate and equitable processes of participation and communication between scientists and local people have been found to prevent misuse or misappropriation of local and scientific knowledge (Nyong *et al.*, 2007; Orlove *et al.*, 2010; Crane, 2010).

While multi-stakeholder platforms promote collaborative adaptation responses (CARE, 2012), adaptation initiatives in Africa lack comprehensive, institutionalised and proactive systems for knowledge sharing (GEF Evaluation Office, 2011; AAP, 2012).

22.4.5.5. Communication, Education, and Capacity Development

Capacity development and awareness raising to enhance understanding of climate impacts and adaptation competencies and engender behavioural change have been undertaken through civil society-driven approaches or by institutions, such as regional and national research institutes, international and national programs and non-governmental organizations (UNFCCC, 2007; Reid *et al.*, 2010; CCAA, 2011; START, 2011; Figueiredo and Perkins, 2012). Promising examples include youth ambassadors in Lesotho and civil society organizations in Tanzania (Corsi *et al.*, 2012), and children as effective communicators and advocates for adaptation-related behavioral and policy change (22.4.3). Progress on inclusion of climate change into formal education is mixed, occurring within the relatively low priority given to environmental education in most countries (UNFCCC, 2007; Corsi *et al.*, 2012; Mukute *et al.*, 2012).

Innovative methods used to communicate climate change include participatory video, photo stories, oral history videos, vernacular drama, radio, television and festivals, with an emphasis on the important rle of the media (Suarez *et al.*, 2008; Harvey, 2011; Chikapa, 2012; Corsi *et al.*, 2012). Better evidence-based communication processes will enhance awareness raising of the diverse range of stakeholders at all levels on the different aspects of climate change (Niang, 2007; Simane *et al.*, 2012). A better understanding of the dimensions of the problem could be achieved by bringing together multiple users and producers of scientific and local knowledgein a trans-disciplinary process (Vogel *et al.*, 2007; Hirsch Hadorn *et al.*, 2008; Ziervogel *et al.*, 2008; Koné *et al.*, 2011)

22.4.5.6. Ecosystem Services, Biodiversity, and Natural Resource Management

Africa's longstanding experiences with natural resource management, biodiversity use, and ecosystem-based responses such as afforestation, rangeland regeneration, catchment rehabilitation and community-based natural resource management (CBNRM) can be harnessed to develop effective and ecologically sustainable local adaptation strategies (*high confidence*). Relevant specific experiences include using mobile grazing to deal with both spatial and temporal rainfall variability in the Sahel (Djoudi *et al.*, 2013); reducing the negative impacts of drought and floods on agricultural and livestock-based livelihoods through forest goods and services in Mali, Tanzania, and Zambia (Robledo *et al.*, 2012); and ensuring food security and improved livelihoods for indigenous and local communities in West and Central Africa through the rich diversity of plant and animal genetic resources (Jalloh *et al.*, 2011b).

Natural resource management (NRM) practices that improve ecosystem resilience can serve as proactive, low regrets adaptation strategies for vulnerable livelihoods (*high confidence*). Two relevant widespread dual-benefit practices, developed to address desertification, are natural regeneration of local trees (Box 22-2) and water harvesting. Water harvesting practices[11] have increased soil organic matter, improved soil structure, and increased agricultural yields at sites in Burkina Faso, Mali, Niger, and elsewhere, and are used by 60% of farmers in one area of Burkina Faso (Fatondji *et al.*, 2009; Vohland and Barry, 2009; Barbier *et al.*, 2009; Larwanou and Saadou, 2011). Although these and other practices serve as adaptations to climate change, revenue generation and other concerns may outweigh climate change as a motivating factor in their adoption (Mertz *et al.*, 2009; Nielsen and Reenberg, 2010). While destocking of livestock during drought periods may also address desertification and adaptation, the lack of individual incentives and marketing mechanisms to destock and other cultural barriers inhibit their widespread adoption in the Sahel (Hein *et al.*, 2009; Nielsen and Reenberg, 2010). Despite these provisos and other constraints (see for example Nelson and Agrawal, 2008; section 22.4.6 further highlights local-level institutional constraints), local stakeholder institutions for CBNRM do enable a more flexible response to changing climatic conditions; CBNRM is also a vehicle for improving links between ecosystem services and poverty reduction, to enable sustainable adaptation approaches (Shackleton *et al.*, 2010; Chishakwe *et al.*, 2012; Girot *et al.*, 2012). Based on lessons learned in Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia and Zimbabwe, Chishakwe *et al.* (2012) point out the synergies between CBNRM and adaptation at the community level, notwithstanding institutional and other constraints experienced with CBNRM.

[FOOTNOTE 11: Water harvesting refers to a collection of traditional practices in which farmers use small planting pits, half-moon berms, rock bunds along contours, and other structures to capture runoff from episodic rain events (Kandji *et al.*, 2006).]

_____ START BOX 22-2 HERE _____

Box 22-2. African Success Story: Integrating Trees into Annual Cropping Systems

Recent success stories from smallholder systems in Africa illustrate the potential for transforming degraded agricultural landscapes into more productive, sustainable and resilient systems by integrating trees into annual cropping systems. For example, in Zambia and Malawi, an integrated strategy for replenishing soil fertility on degraded lands, which combines planting of nitrogen-fixing *Faidherbia* trees with small doses of mineral fertilizers, has consistently more than doubled yields of maize leading to increased food security and greater income generation (Garrity *et al.*, 2010). In the Sahel, natural regeneration, or the traditional selection and protection of small trees to maturity by farmers and herders has, perhaps for centuries, produced extensive parks of *Acacia albida* (winter thorn) in Senegal (Lericollais, 1989), *Adansonia digitata* (baobab) in West and southern Africa (Sanchez *et al.*, 2011), and *Butyrospermum parkii* (Shea butter) in Burkina Faso (Gijsbers *et al.*, 1994). Recent natural regeneration efforts have increased tree density and species richness at locations in Burkina Faso (Ræbild *et al.*, 2012) and Niger (Larwanou and Saadou, 2011), though adoption and success is somewhat dependent on soil type (Haglund *et al.*, 2011; Larwanou and Saadou, 2011). In southern Niger, farmer-managed natural regeneration of *Faidherbia albida* and other field trees, which began in earnest in the late 1980s, has led to large-scale increase in tree cover across 4.8 million ha, and to decreased sensitivity to drought of the production systems, compared to other regions in Niger (Reij *et al.*, 2009; Tougiani *et al.*, 2009; Sendzimir *et al.*, 2011).

_____ END BOX 22-2 HERE _____

Differentiation in the literature is growing between 'hard path' and 'soft path' approaches to adaptation (Sovacool, 2011; Kundzewicz, 2011), with 'soft path', low-regrets approaches, such as using intact wetlands for flood risk management, often the first line of defence for poor people in Africa; as contrasted with 'hard path' approaches like embankments and dams for flood control (McCully, 2007; Kundzewicz, 2011). Intact ecosystem services and biodiversity are recognized as critical components of successful human adaptation to climate change that may be more effective and incur lower costs than 'hard' or engineered solutions (Abramovitz *et al.*, 2002; Petersen and Holness, 2011; UNDP-UNEP Poverty-Environment Initiative, 2011a; Girot et al, 2012; Pramova *et al*., 2012; Roberts *et al.*, 2012; Box 22-2). This provides a compelling reason for linking biodiversity, developmental, and social goals, as taken up, for example, in Djibouti's NAPA project on mangrove restoration to reduce salt water intrusion and coastal production losses due to climate hazards (Pramova *et al.*, 2012).

The emerging global concept of ecosystem-based adaptation (EbA) provides a system-oriented approach for Africa's longstanding local NRM practices. Despite the evidence from studies cited in this section, scaling-up to prioritize ecosystem responses and EbA in plans and policy has been slow; a broad understanding that EbA is an integral component of the developmental agenda, rather than a competing 'green' agenda, would promote this process. Adaptive environmental governance represents one of the future challenges for the implementation of EbA strategies in Africa, together with sustainable use of resources, secure access to meet needs under climate change, and strong local institutions to enable this (Robledo *et al.*, 2012). Ecosystem-based adaptation could be an important approach to consider for the globally significant Congo Basin forests, particularly given the predominance of REDD+ approaches for this region that risk neglecting adaptation responses, or may result in maladaptation (Somorin *et al.*, 2012; Sonwa *et al.*, 2012; sections 22.4.5.8, 22.6.2). Ecosystem-based approaches are further discussed in WGII Chapter 4, and Box CC-EA.

22.4.5.7. Technological and Infrastructural Adaptation Responses

Since AR4, experience has been gained on technological and infrastructural adaptation in agricultural and water management responses, for climate-proofing infrastructure, and for improved food storage and management to reduce post-harvest losses; this has been increasingly in conjunction with 'soft' measures.

There is increased evidence that farmers are changing their production practices in response to increased food security risks linked to climate change and variability, through both technical and behavioural means. Examples include planting cereal crop varieties that are better suited to shorter and more variable growing seasons (Akullo *et al.*, 2007; Thomas *et al.*, 2007; Yesuf *et al.*, 2008; Yaro, 2010; Laube *et al.*, 2012), constructing bunds to more effectively capture rainwater and reduce soil erosion (Nyssen *et al.*, 2007; Thomas *et al.*, 2007; Reij *et al.*, 2009), reduced tillage practices and crop residue management to more effectively bridge dry spells (Ngigi *et al*., 2006; Marongwe *et al.*, 2011), and adjusting planting dates to match shifts in the timing of rainfall (Abou-Hadid, 2006; Vincent *et al.*, 2011b).

Conservation agriculture has good potential to both bolster food production and enable better management of climate risks (*high confidence)* (Verchot *et al.*, 2007; Thomas, 2008; Syampungani *et al.*, 2010; Thierfelder and Wall, 2010; Kassam *et al.*, 2012). Such practices, which include conservation/zero tillage, soil incorporation of crop residues and green manures, building of stone bunds, agroforestry, and afforestation/reforestation of croplands, reduce runoff and protect soils from erosion, increase rainwater capture and soil water-holding capacity, replenish soil fertility, and increase carbon storage in agricultural landscapes. Conservation agriculture systems have potential to lower the costs of tillage and weed control with subsequent increase in net returns, as found in Malawi by Ngwira *et al.* (2012).

Expansion of irrigation in sub-Saharan Africa holds significant potential for spurring agricultural growth while also better managing water deficiency risks associated with climate change (Dillon, 2011; You *et al.*, 2011). Embedding irrigation expansion within systems-level planning that considers the multi-stressor context in which irrigation expansion is occurring can help to ensure that efforts to promote irrigation can be sustained and do not instead generate a new set of hurdles for producers or engender conflict (van de Giesen *et al.*, 2010; Burney and Naylor, 2012; Laube *et al.*, 2012). Suitable approaches to expand irrigation in Africa include using low-pressure drip irrigation technologies and construction of small reservoirs, both of which can help to foster diversification toward irrigated high-value horticultural crops (Karlberg *et al.*, 2007; Woltering *et al.*, 2011; Biazin *et al.*, 2012). If drought risk increases and rainfall patterns change, adaptation in agricultural water management would be enhanced through a strategic approach that encompasses overall water use efficiency for both rainfed and irrigated production (Weiβ *et al.*, 2009), embeds irrigation expansion efforts within a larger rural development context that includes increased access to agricultural inputs and markets (You *et al.*, 2011; Burney and Naylor, 2012), and that involves an integrated suite of options (e.g., plant breeding and improved pest and disease and soil fertility management, and *in situ* rainwater harvesting) to increase water productivity (Passioura, 2006; Biazin *et al.*, 2012).

Experience has been gained since the AR4 on adaptation of infrastructure (transportation, buildings, food storage, coastal), with evidence that this can sometimes be achieved at low cost, and additional implementation of soft measures such as building codes and zone planning (UNFCCC, 2007; Halsnæs and and Trarup, 2009; Urquhart, 2009; UN-Habitat and UNEP, 2010; AfDB, 2011; Mosha, 2011; Siegel, 2011; Corsi *et al.*, 2012). Examples of adaptation actions for road and transportation infrastructure include submersible roads in Madagascar and building dikes to avoid flooding in Djibouti (UNFCCC, 2007; Urquhart, 2009). Infrastructural climate change impact assessments and enhanced construction and infrastructural standards - such as raising foundations of buildings, strengthening roads, and increasing storm water drainage capacity - are steps to safeguard buildings in vulnerable locations or with inadequate construction (UN-Habitat and UNEP, 2010; Mosha, 2011; Corsi *et al.*, 2012). Mainstreaming adaptation into infrastructure development can be achieved at low cost, as has been shown for flood-prone roads in Mozambique (Halsnæs and and Trarup, 2009). Integrating climate change considerations into infrastructure at the design stage is preferable from a cost and feasibility perspective than trying to retrofit infrastructure (Chigwada, 2005; Siegel, 2011). Softer measures, such as building codes and zone planning are being implemented and are needed to complement and/or provide strategic guidance for hard infrastructural climate proofing, for example, the adoption of cyclone-resistant standards for public buildings in Madagascar (AfDB, 2011). Research in South Africa has recognized that the best option for adaptation in the coastal zone is not to combat coastal erosion in the long term, but rather to allow progression of the natural processes (Naidu *et al.*, 2006; Zitholele Consulting, 2009).

Reducing post-harvest losses through improved food storage, food preservation, greater access to processing facilities, and improved systems of transportation to markets are important means to enhance food security (Brown *et al.*, 2009; Godfray *et al.*, 2010; Codjoe and Owusu 2011). Low cost farm-level storage options, such as metal silos (Tefera *et al.*, 2011), and triple-sealed plastic bags (Baoua *et al.*, 2012) are effective for reducing post-harvest losses from pests and pathogens. Better storage allows farmers greater flexibility in when they sell their grain, with related income benefits (Brown *et al.*, 2009), and reduces post-harvest infection of grain by aflatoxins, which is widespread in Africa and increases with drought stress and high humidity during storage (Cotty and Jaime-Garcia, 2007; Shephard, 2008).

22.4.5.8. Maladaptation Risks

The literature increasingly highlights the need, when designing development or adaptation research, policies and initiatives, to adopt a longer-term view and to consider the multi-stressor context in which people live, in order to avoid maladaptation, or outcomes that may serve short-term goals but come with future costs to society (refer to Glossary). The short-term nature of policy and other interventions, especially if they favor economic growth and modernization over resilience and human security, may themselves act as stressors or allow people to only react to short-term climate variability (Bryan *et al.*, 2009; Brooks *et al.*, 2009; Bunce *et al.*, 2010a; Levine et al, 2011). The political context can also undermine autonomous adaptation and lead to maladaptation; for instance, Smucker and Wisner (2008) found that political and economic changes in Kenya meant that farmers could no longer use traditional strategies for coping with climatic shocks and stressors, with the poorest increasingly having to resort to coping strategies that undermined their long-term livelihood security, also known as erosive coping, such as more intensive grazing of livestock and shorter crop rotations (van der Geest and Dietz, 2004). In a case from the Simiyu wetlands in Tanzania, Hamisi *et al.* (2012) find that coping and reactive adaptation strategies may lead to maladaptation – for instance, through negative impacts on natural vegetation because of increased intensity of farming in wetter parts of the floodplain, where farmers have moved to exploit the higher soil water content.

Some diversification strategies, such as charcoal production and artisanal mining, may increase risk through promoting ecological change and the loss of ecosystem services to fall back on (Paavola, 2008; Adger et al, 2011; Shackleton and Shackleton, 2012). Studies also highlight risks that traditional adaptive pastoralism systems may be replaced by maladaptive activities. For example, charcoal production has become a major source of income for 70% of poor and middle-income pastoralists in some areas of Somaliland, with resultant deforestation (Hartmann and Sugulle, 2009).

Another example of maladaptation provided in the literature is the potential long-term hydro-dependency risks and threats to ecosystem health and community resilience as a result of increased dam building in Africa, which may be underpinned by policies of multi-lateral donors (Avery, 2012; Beilfuss, 2012; Jones *et al*., 2012). While increased rainwater storage will assist with buffering dry periods, and hydropower can play a key role in ending energy poverty, it is important that this is designed to promote environmental and social sustainability; that costs and benefits are equitably shared; and that water storage and energy generation infrastructure is itself climate proofed. Additional substantive review of such international development projects would assist in assuring that these do not result in maladaptation. See WGII Chapter 4 for a discussion of the unwanted consequences of building more and larger impoundments and increased water abstraction on terrestrial and freshwater ecosystems; health aspects of this are noted in sections 22.3.5.1 and 22.3.5.4. See section 22.6.2 on avoiding undesirable trade-offs between REDD+ approaches and adaptation that have the potential to result in significant maladaptation.

22.4.6. Barriers and Limits to Adaptation in Africa

A complex web of interacting barriers to local-level adaptation exists that manifests from national to local scales to constrain adaptation, which includes institutional, political, social, cultural, biophysical, cognitive and behavioral, and gender-related (*high confidence*). While relatively few studies from Africa have focused specifically on barriers and limits to adaptation, perceived and experienced constraints distilled from the literature encompass the resources needed for adaptation, the factors influencing adaptive capacity, the reasons for not employing particular adaptive strategies or not responding to climate change signals, and the reasons why some groups or individuals adapt but not others (Roncoli *et al.*, 2010; Bryan *et al.*, 2011; Nyanga *et al.*, 2011; Ludi *et al.*, 2012).

At the local level, institutional barriers hamper adaptation through elite capture and corruption; poor survival of institutions without social roots; and lack of attention to the institutional requirements of new technological interventions (Ludi *et al.*, 2012). Tenure security over land and vital assets is widely accepted as being crucial for enabling people to make longer-term and forward-looking decisions in the face of uncertainty, such as changing farming practices, farming systems, or even transforming livelihoods altogether (Bryan *et al.*, 2009; Brown *et al.*, 2010; Romero González *et al.*, 2011). In addition to unclear land tenure, legislation forbidding ecosystem use is one of the issues strengthening underlying conflicts over resources in Africa; resolving this would enable ecosystems to contribute to adaptation beyond short-term coping (Robledo *et al.*, 2012). There is also evidence that innovation may be suppressed if the dominant culture disapproves of departure from the ‘normal way of doing things’ (Ludi *et al.*, 2012; Jones 2012).

Characteristics such as wealth, gender, ethnicity, religion, class, caste, or profession can act as social barriers for some to adapt successfully or acquire the required adaptive capacities (Ziervogel *et al.*, 2008; Godfrey *et al.* 2010; Jones and Boyd, 2011). Based on field research conducted in the Borana area of southern Ethiopia, Debsu (2012) highlights the complex way in which external interventions may affect local and indigenous institutions by strengthening some coping and adaptive mechanisms and weakening others. Restrictive institutions can block attempts to enhance local adaptive capacity by maintaining structural inequities related to gender and ethnic minorities (Jones, 2012). Constraints faced by women, often through customs and legal barriers, include limited access to land and natural resources; lack of credit and input in decisionmaking, limited ability to take financial risk, lack of confidence, limited access to information and new ideas, and under-valuation of women’s opinions

(McFerson, 2010; Peach Brown, 2011, Djoudi and Brockhaus 2011; Jones 2012; Ludi *et al.*, 2012; Goh, 2012; Codjoe *et al.* 2012).

Few small-scale farmers across Africa are able to adapt to climatic changes, while others are restricted by a suite of overlapping barriers (*high agreement, robust evidence*). Constraints identified in Kenya, South Africa, Ethiopia, Malawi, Mozambique, Zimbabwe, Zambia and Ghana included poverty and a lack of cash or credit (financial barriers); limited access to water and land, poor soil quality, land fragmentation, poor roads, and pests and diseases (biophysical and infrastructural barriers); lack of access to inputs, shortage of labor, poor quality of seed and inputs attributed to a lack of quality controls by government and corrupt business practices by traders, insecure tenure, and poor market access (institutional, technological, and political barriers); and finally a lack of information on agroforestry/afforestation, different crop varieties, climate change predictions and weather, and adaptation strategies (informational barriers) (Bryan *et al.* 2009, 2011; Barbier *et al.*, 2009; Clover and Eriksen, 2009; Deressa *et al.*, 2009; Roncoli *et al.*, 2010; Mandleni and Anim, 2011; Nhemachena and Hassan, 2011; Nyanga *et al.*,2011; Vincent *et al.*, 2011a).

Recognition is increasing that understanding psychological factors such as mindsets and risk perceptions is crucial for supporting adaptation (Grothmann and Patt, 2005; Patt and Schröter, 2008; Jones, 2012). Cognitive barriers to adaptation include alternative explanations of extreme events and weather such as religion (God's will), the ancestors, and witchcraft, or seeing these changes as out of people's own control (Byran *et al.*, 2009; Roncoli *et al.*, 2010; Mandleni and Anim, 2011; Artur and Hilhorst, 2012; Jones, 2012; Mubaya *et al.* 2012).

Climate uncertainty, high levels of variability, lack of access to appropriate real-time and future climate information, and poor predictive capacity at a local scale are commonly cited barriers to adaptation from the individual to national level (Repetto, 2008; Dinku *et al.*, 2011; Jones, 2012; Mather and Stretch, 2012). Despite the cultural and psychological barriers noted above, several studies have shown that farmers with access to climate information are more predisposed to adjust their behaviour in response to perceived climate changes (Mubaya *et al.*, 2012).

At a policy level, studies have detected political, institutional and discursive barriers to adaptation. Adaptation options in southern Africa have been blocked by political and institutional inefficiencies, lack of prioritization of climate change, and the dominance of other discourses, such as the mitigation discourse in South Africa and short-term disaster-focused views of climate variability (Madzwamuse, 2010; Bele *et al.*, 2011; Berrang-Ford *et al.*, 2011; Conway and Schipper, 2011; Kalame *et al.*, 2011; Chevallier, 2012; Toteng, 2012; Leck *et al.*, 2012). Lack of local participation in policy formulation, the neglect of social and cultural context, and the inadvertent undermining of local coping and adaptive strategies have also been identified by several commentators as barriers to appropriate national policies and frameworks that would support local-level adaptation (e.g., Brockhaus and Djoudi, 2008; Bele *et al.*, 2011; Chevallier, 2012).

Many of these constraints to adaptation are well entrenched and will be far from easy to overcome; some may act as limits to adaptation for particular social groups (*high confidence)*. Biophysical barriers to adaptation in the arid areas could present as limits for more vulnerable groups if current climate change trends continue (Leary *et al.*, 2008b; Sallu *et al.*, 2010; Roncoli *et al.*, 2010). Traditional and autonomous adaptation strategies, particularly in the drylands, have been constrained by social-ecological change and drivers such as population growth, land privatization, land degradation, widespread poverty, HIV/AIDS, poorly conceived policies and modernization, obstacles to mobility and use of indigenous knowledge, as well as erosion of traditional knowledge, to the extent that it is difficult or no longer possible to respond to climate variability and risk in ways that people did in the past (Leary *et al.*, 2008b; Dabi *et al.*, 2008; Paavola, 2008; Smucker and Wisner, 2008; Clover and Eriksen, 2009; Conway, 2009; UNCCD *et al.*, 2009; Bunce *et al.*, 2010b; Quinn *et al.*, 2011; Jones, 2012; section 22.4.5.4). As a result of these multiple stressors working together, the number of response options has decreased and traditional coping strategies are no longer sufficient (Dube and Sekhwela, 2008). Studies have shown that most autonomous adaptation usually involves minor adjustments to current practices (e.g. changes in planting decisions); there are simply too many barriers to implementing substantial changes that require investment (e.g., agroforestry and irrigation) (Bryan *et al.*, 2011). Such adaptation strategies would be enhanced through government and private sector/NGO support, without which many poor groups in Africa may face real limits to adaptation (Vincent *et al.*, 2011a; Jones, 2012).

These findings highlight the benefits of transformational change in situations where high levels of vulnerability and low adaptive capacity detract from the possibility for systems to adapt sustainably. This is in agreement with the Special Report on Extreme Events, which additionally found *high agreement* and *robust evidence* for the importance of a spectrum of actions ranging from incremental steps to transformational changes in order to reduce climate risks (IPCC, 2012). In support of such solutions, Moench (2011) has called for distilling common principles for building adaptive capacity at different stages, and adaptive management and learning are seen as critical approaches for facilitating transformation (Section 22.4.5.3; IPCC, 2012). Chapter 16 provides further discussion on how encountering limits to adaptation may trigger transformational change, which can be a means of adapting to hard limits.

22.5. Key Risks for Africa

Table 22-6 highlights key risks for Africa (see also Table 19-4 and CC-KR), as identified through assessment of the literature and expert judgement of the author team, with supporting evaluation of evidence and agreement in the sections of this chapter, as referenced in the caption.

[INSERT TABLE 22-6 HERE
Table 22-6: Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Africa. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.]

As indicated in Table 22-6, seven of the nine key regional risks are assessed for the present as being either medium or high under current adaptation levels, reflecting both the severity of multiple relevant stressors and Africa's existing adaptation deficit. This is the case for risks relating to shifts in biome distribution (22.3.2.1), degradation of coral reefs (22.3.2.3), reduced crop productivity (22.3.4.1), adverse effects on livestock (22.3.4.2), vector- and water-borne diseases (22.3.5.2, 22.3.5.4), under nutrition (22.3.5.3), and migration (22.6.1.2). This assessment indicates that allowing current emissions levels to result in a +4°C world (above pre-industrial levels) by the 2080-2100 period would have negative impacts on Africa's food security, as even under high adaptation levels, risks of reduced crop productivity and adverse effects on livestock are assessed as remaining very high. Moreover, our assessment is that even if high levels of adaptation were achieved, risks of stress on water resources (22.3.3), degradation of coral reefs (22.3.2.3), and the destructive effects of sea level rise and extreme weather events (22.3.6) would remain high. However, even under a lower emissions scenario leading to a long-term 2°C warming, all nine key regional risks are assessed as remaining high or very high under current levels of adaptation. The assessment indicates that even under high adaptation, residual impacts in a 2°C world would be significant, with only risk associated with migration rated as being capable of reduction to low under high levels of adaptation. High adaptation would be enabled by concerted effort and substantial funding; even if this is realized, no risk is assessed as being capable of reduction to below medium status.

22.6. Emerging Issues

22.6.1. Human Security

Although the significance of human security cannot be overestimated, the evidence of the impact of climate change on human security in Africa is disputable (see Chapters 12 and 19). Adverse climate events potentially impact all aspects of human security, either directly or indirectly (on mapping climate security vulnerability in Africa see Busby *et al*., 2013). Food security, water stress, land use and, health security, violent conflict, changing migration patterns, and human settlements are interrelating issues of discussions between climate change and human security. Violent conflict and migration are discussed below (for further details see Chapter 12).

22.6.1.1 Violent Conflict

While there seems to be consensus that the environment is only one of several interconnected causes of conflict and is rarely considered to be the most decisive factor (Kolmannskog, 2010), it remains disputed whether, and if so, how, the changing climate directly increases the risk of violent conflict in Africa (for more details see also Chapters 12 and 19, in particular 12.5.1; 19.4; Gleditsch, 2012). However, views are emerging that there is a positive relationship between increases in temperature and increases in human conflict (Hsiang *et al*., 2013). Some of the factors which may increase the risk of violent conflict, such as low per capita incomes, economic contraction and inconsistent state institutions are sensitive to climate change (12.5.1). For the African Sahel States it has been argued that the propensity for communal conflict across ethnic groups within Africa is influenced by political and economic vulnerability to climate change (Raleigh, 2010). Evidence on the question of whether, and if so to what extent, climate change and variability increases the risk of civil war in Africa is contested (Burke *et al.*, 2009b; Buhaug, 2010; Devitt and Tol, 2012). It has been suggested that due to the depletion of natural resources in Africa as a result of overexploitation and the impact of climate change on environmental degradation, competition for scarce resources could increase and lead to violent conflict (Kumssa and Jones, 2010). For East Africa it has been suggested that increased levels of malnutrition are related to armed conflicts (Rowhani *et al.*, 2011). There is some agreement that rainfall variation has an inconsistent relationship to conflict: both higher and lower anomalous rainfall is associated with increased communal conflict levels; although dry conditions have a lesser effect (Raleigh and Kniveton, 2012; Hendrix and Salehyan 2012; Theisen 2012).

22.6.1.2 Migration

Human migration has social, political, demographic, economic and environmental drivers, which may operate independently or in combination (for more in-depth discussions see Chapters 12.4 and 19.4.2.1; Perch-Nielsen *et al.*, 2008; Piguet, 2010; Foresight, 2011; Piguet *et al.*, 2011; Black *et al.*, 2011a; Van der Geest, 2011). Many of these drivers are climate sensitive (Black *et al.*, 2011c; 12.4.1.). People migrate either temporarily or permanently, within their country or across borders (12.4.1.2; Figure 12-1; Table 12-3; Warner *et al.*, 2010; Kälin and Schrepfer, 2012). The evidence base in the field of migration in Africa is both varied and patchy. Evidence suggests that migration is a strategy to adapt to climate change (12.4.2). Mobility is indeed a strategy (not a reaction) to high levels of climatic variation that is characteristic of Africa (Tacoli, 2011) and the specifics of the response are determined by the economic context of the specific communities.

Besides low-lying islands and coastal and deltaic regions in general, sub-Saharan Africa is one of the regions that would particularly be affected by environmentally induced migration (Gemenne, 2011a). Case studies from Somalia and Burundi emphasize the interaction of climate change, disaster, conflict, displacement, and migration (Kolmannskog, 2010). In Ghana for example, an African country with few conflicts caused by political, ethnic, or religious tensions, and thus with migration drivers more likely related to economic and environmental motivators (Tschakert and Tutu, 2010), some different types of migration flows are considered to have different sensitivity to climate change (Black *et al.*, 2011a). The floods of the Zambezi River in Mozambique in 2008 have displaced 90,000 people, and it has been observed that along the Zambezi River Valley, with approximately 1 million people living in the flood-affected areas, temporary mass displacement is taking on permanent characteristics (Jäger *et al.*, 2009; Warner *et al.*, 2010).

Different assessments of future trends have recently produced contradictory conclusions (e.g., UN-OCAH and IDMC, 2009; Naude, 2010; ADB, 2011; Tacoli, 2011, IDMC, 2011). One approach in assessing future migration potentials, with considerable relevance to the African context, focused on capturing the net effect of environmental change on aggregate migration through analysis of both its interactions with other migration drivers and the role of migration within adaptation strategies, rather than identifying specific groups as potential 'environmental migrants' (Foresight, 2011). Even if Africa's population doubles by 2050 to 2 billion (Lutz and K.C., 2010) and the potential for displacement rises as a consequence of the impact of extreme weather events, recent analyses (Foresight, 2011; Black *et al.*, 2011b) show that the picture for future migration is much more complex than previous assessments of a rise in climate induced migration suggest, and relates to the intersection of multiple drivers with rates of global growth, levels of governance, and climate change.

The empirical base for major migration consequences is weak (Lilleør and Van den Broeck, 2011; Black *et al.*, 2011a; Gemenne, 2011b) and non-existent for international migration patterns (Marchiori *et al.*, 2011). Even across the same type of extreme weather event, the responses can vary (Findlay, 2011; Gray, 2011 for Kenya and Uganda; Raleigh, 2011 for the African Sahel States)).

22.6.2. Integrated Adaptation / Mitigation Approaches

Relevant experience gained in Africa since AR4 in implementing integrated adaptation–mitigation responses within a pro-poor orientation that leverages developmental benefits encompasses some participation of farmers and local communities in carbon offset systems, increasing the use of relevant technologies such as agroforestry and farmer-assisted tree regeneration (22.4.5.6), and emerging Green Economy policy responses. The recognition that adaptation and mitigation are complementary elements of the global response to climate change, and not trade-offs, is gaining traction in Africa (Goklany, 2007; Nyong *et al.*, 2007; UNCCD *et al.*, 2009; Woodfine, 2009; Jalloh *et al.*, 2011b; Milder *et al.*, 2011).

While the suitability of on- and off-farm techniques for an integrated adaptation-mitigation response depends on local physical conditions as well as political and institutional factors, sustainable land management techniques are particularly beneficial for an integrated response in Africa; these include agroforestry, including through farmer-managed natural regeneration; and conservation agriculture (Woodfine, 2009; Milder *et al.*, 2011; Mutonyi and Fungo, 2011; section 22.4.5.6; Box 22-2). An emerging area is multiple-benefit initiatives that aim to reduce poverty, promote adaptation through restoring local ecosystems, and deliver benefits from carbon markets. Brown *et al.*, (2011) note the example of a community-based project in Humbo, Ethiopia, which is facilitating adaptation and generating temporary certified emissions reductions under the Clean Development Mechanism, by restoration of degraded native forests (2,728 ha) through farmer-managed natural regeneration.

The key role of local communities in carbon offset systems through community forestry entails land use flexibility (Purdon, 2010), but can be constrained by the lack of supportive policy environments – for example, for conservation agriculture (Milder *et al.*, 2011).

The literature highlights the desirability of responding to climate change through integrated adaptation–mitigation approaches, including through spatial planning, in the implementation of REDD+ in Africa, especially given the significant contribution to food security and livelihoods of forest systems (Bwango *et al.*, 2000; Guariguata et al., 2008; Nkem *et al.*, 2007; Nasi *et al.*, 2008; Biesbroek *et al.*, 2009; Somorin *et al.*, 2012). However, forests are mainly used for reactive coping and not anticipatory adaptation; studies show that governments favour mitigation while local communities prioritise adaptation (Fisher *et al.*, 2010; Somorin *et al.*, 2012). Flexible REDD+ models that include agriculture and adaptation hold promise for generating co-benefits for poverty reduction, given food security and adaptation priorities, and help to avoid trade-offs between REDD+ implementation and adaptive capacities of communities, ecosystems, and nations (Nkem *et al.*, 2008; Thomson *et al.*, 2010; CIFOR, 2011; Richard *et al.*, 2011; Wertz-Kanounnikoff *et al.*, 2011).

Integrated adaptation–mitigation responses are being considered within the context of the emerging Green Economy discussions. African leaders agreed in 2011 to develop an African Green Growth Strategy, to build a shared vision for promoting sustainable low-carbon growth through a linked adaptation–mitigation approach, with adaptation seen as an urgent priority. A national example is the launch of Ethiopia's Climate Resilient Green Economy Facility in 2012 (Corsi *et al.*, 2012).

22.6.3. Biofuels and Land Use

The potential for first-generation biofuel production in Africa, derived from bioethanol from starch sources and biodiesel production from oilseeds, is significant given the continent's extensive arable lands, labor availability, and favorable climate for biofuel crop production (Amigun *et al.*, 2011; Arndt *et al.*, 2011; Hanff *et al.*, 2011). While biofuel production has positive energy security and economic growth implications, the prospect of wide-scale biofuel production in Africa carries with it significant risks related to about environmental and social sustainability. Among the concerns are competition for land and water between fuel and food crops, adverse impacts of biofuels on biodiversity and the environment, contractual and regulatory obligations that expose farmers to legal risks, changes in land tenure security, and reduced livelihood opportunities for women, pastoralists and migrant farmers who depend on access to the land resource base (Unruh, 2008; Amigun *et al.*, 2011; German *et al.*, 2011; Schoneveld *et al.*, 2011).

More research is needed to understand fully the socioeconomic and environmental tradeoffs associated with biofuel production in Africa. One critical knowledge gap concerns the effect of biofuel production, particularly large-scale schemes, on land use change and subsequent food and livelihood security. For example, the conversion of marginal lands to biofuel crop production would impact the ability of users of these lands (pastoralists and in some cases women who are allocated marginal land for food and medicinal production) to participate in land use and food production decisions (Amigun *et al.*, 2011; Schoneveld *et al.*, 2011). In addition, biofuel production could potentially lead to the extension of agriculture into forested areas, either directly through conversion of fallow vegetation or the opening of mature woodland, or indirectly through use of these lands to offset food crop displacement (German *et al.*, 2011). Such land use conversion would result in biofuel production reducing terrestrial carbon storage potential (Vang Rasmussen *et al.*, 2012a; Vang Rasmussen *et al.*, 2012b).

Better agronomic characterization of biofuel crops is another key knowledge gap. For example, little information exists with respect to the agronomic characteristics of the oilseed crop Jatropha (*Jatropha curcas*) under conditions of intensive cultivation across differing growing environments, despite the fact that Jatropha has been widely touted as an appropriate feedstock for biofuel production in Africa because of its ability to grow in a wide range of climates and soils. Oilseed yields of Jatropha can be highly variable, and even basic information about yield potential and water and fertilizer requirements for producing economically significant oilseed yields is scanty (Achten *et al.*, 2008; Peters and Thielmann, 2008; Hanff *et al.*, 2011). Such knowledge would not only provide a basis for better crop management but would also help to gain better estimates of the extent of water consumption for biofuel production in the context of non-biofuel water-use needs across landscapes. Assessments of Jatropha's potential as an invasive species and its potential allelopathic effects on native vegetation are also needed, in light of the fact that some countries have designated Jatropha as an invasive species (Achten *et al.*, 2008).

22.6.4. Climate Finance and Management

Recent analyses emphasise the significant financial resources and technological support needed to both address Africa's current adaptation deficit and to protect rural and urban livelihoods, societies and economies from climate change impacts at different local scales, with estimates of adaptation costs between US$20-30 billion per annum over the next couple of decades, up to US$60 billion per annum by 2030 (for example see figure 22.6), although these figures are *likely* to be under-estimates, as studies upon which these estimates are based do not always include the costs of overcoming Africa's current adaptation deficit, may be run for one scenario at a time, and do not factor in a range of uncertainties in the planning environment (Parry et al, 2009b; Fankhauser and Schmidt-Traub, 2010; Watkiss et al, 2010; AfDB, 2011; Dodman and Carmin, 2011; LDC Expert Group, 2011; Smith et al, 2011).

Damages related to climate change may affect economic growth and the ability to trade (Lecocq and Shalizi, 2007; Ruppel and Ruppel-Schlichting, 2012). Costs of adaptation and negative economic impacts of climate change have been referred to in sections 22.3.4.4 and 22.3.6; Warner *et al*. (2012) have highlighted the residual impacts of climate change that would occur after adaptation, for case studies in Kenya and The Gambia. The following examples are illustrative of the move to discuss financial implications in the literature.

Scenarios for Tanzania, where agriculture accounts for about half of gross production and employs about 80% of the labor force (Thurlow and Wobst, 2003), project that changes in the mean and extremes of climate variables, could increase poverty vulnerability (Ahmed *et al*., 2011). Scenarios for Namibia based on a computable general equilibrium model project that annual losses to the economy ascribed to the impacts of climate change on the country's natural resources could range between 1.0% and 4.8% of GDP (Reid *et al.*, 2008). Ghana's agricultural and economic sector with cocoa being the single most important export product is particularly vulnerable, since cocoa is prone to the effects of a changing climate (Black *et al.*, 2011c), which has been central to the country's debates on development and poverty alleviation strategies (WTO Trade Policy Review, 2008).

The potential for adaptation to reduce the risks associated with sea level rise is substantial for cumulative land loss and for numbers of people flooded or forced to migrate, with adaptation costs lower than the economic and social damages expected if nothing is done (Kebede *et al.*, 2010).See Figure 22-6.

[INSERT FIGURE 22-6 HERE
Figure 22-6: Total additional costs of adaptation per year from 2000 to 2100 for Tanzania (including beach nourishment and sea and river dikes). The values do not consider the existing adaptation deficit (values in $US 2005, without discounting Source: Kebede *et al.*, 2010.]

The Dynamic Interactive Vulnerability Assessment (DIVA) model was used to assess the monetary and non-monetary impacts of sea level rise on the entire coast (3,461 km) of Tanzania. Under the B1 low-range sea level rise scenario it was estimated that by 2030, a total area of 3,579 to 7,624 km^2 would be lost, mainly through inundation; with around 234,000 to 1.6 million people per year who could potentially experience flooding. Without adaptation, residual damages have been estimated at between US$ 26 and 55 million per year (Kebede *et al*., 2010). Table 22-7 shows the economic impacts of land inundated in Cape Town based on different sea level rise scenarios.

[INSERT TABLE 22-7 HERE
Table 22-7: Land inundated and economic impacts in Cape Town based on a risk assessment (Cartwright, 2008).]

In line with increasing international impetus for adaptation (Persson *et al.*, 2009) the Parties to the UNFCCC agreed on providing "adequate, predictable and sustainable financial resources" for adaptation in developing countries, and, within this context, paid special attention to Africa which is "particularly vulnerable" to the adverse effects of climate change (UNFCCC, 2009; UNFCCC, 2011; Berenter, 2012). Doubts remain about how private sector financing can be effectively mobilized and channeled toward adaptation in developing countries (Atteridge, 2011; Naidoo *et al.*, 2012). The 2012 Landscape of Climate Finance Report (Buchner *et al.*, 2012) stated that mitigation activities attracted US$ 350 billion, mostly related to renewable energy and energy efficiency, while adaptation activities attracted US$ 14 billion. Approximately 30% of the global distributed adaptation finance went to Africa (Nakhooda *et al.*, 2011) and seems to prioritize the continent (Naidoo *et al.*, 2012). However, it is being questioned, whether the adaptation funding that is currently delivered does fulfill demonstrated needs (Flåm and Skjærseth, 2009; Denton, 2010 for sub-Saharan Africa Nakhooda *et al.*, 2011).

Effective adaptation requires more than sufficient levels of funding. It requires developing country 'readiness,' which includes abilities to plan and access finances; the capacity to deliver adaptation projects and programs, and to monitor, report, and evaluate their effectiveness (Vandeweerd *et al.*, 2012); and also a regulatory framework, which guarantees e.g. property rights (IPCC AR5 WGIII Draft 2 Chapter 16 p.:27; line 30-33). Particularly serious challenges are associated with directing finance to the sectors and people most vulnerable to climate change

(Denton, 2010; Nakhooda *et al.*, 2011; Pauw *et al.*, 2012). The risk of fund mismanagement with regard to climate finance and adaptation funds needs to be borne in mind. Suggestions to address adequately the level of complexity, uncertainty, and novelty that surrounds many climate finance issues *inter alia* include longer-term and integrated programs rather than isolated projects; building capacity and institutions in African countries (Nakhooda *et al.*, 2011; Pauw *et al.*, 2012); identifying priorities, processes, and knowledge needs at the local level (Haites, 2011; Pauw, 2013); and, accordingly, developing grassroots projects (Fankhauser and Burton, 2011).

22.7. Research Gaps

Research has a key role to play in providing information for informed decisionmaking at local to national levels (Fankhauser, 1997; Ziervogel *et al.*, 2008; Arendse and Crane, 2010). While there is significant activity in African research institutions, much African research capacity is spent on foreign-led research that may necessarily prioritize addressing national knowledge gaps about climate change (Madzwamuse, 2010), and African research may lack merited policy uptake or global recognition as it is often not published in peer-reviewed literature (Denton *et al.*, 2011).

The following overarching data and research gaps have been identified also see Table 22.8:

- Data management and monitoring of climate and hydroclimate parameters and development of climate change scenarios as well as monitoring systems to address climate change impacts in the different sectors (for example the impacts of pests and diseases on crops and livestock) and systems;
- Research and improved methodologies to assess and quantify the impact of climate change on different sectors and systems.
- Socio-economic consequences of the loss of ecosystems and also of economic activities as well as of certain choices in terms of mitigation (biofuels and their links with food and livelihood security for example) and adaptation to climate change;
- The links influence of climate change in emerging issues such as migration and urban food security;
- Developing tools allowing decision makers to make their decisions based on the complexity of the world under climate change, taking into consideration gender, age and all regarding the contribution of local communities.

[INSERT TABLE 22-8 HERE
Table 22-8: Research gaps in different sectors.]

Frequently Asked Questions

FAQ 22.1: How could climate change impact food security in Africa? *[to be inserted in Section 22.3.4.5]*
Food security is comprised of availability (is enough food produced), access (can people get it, and afford it), utilization (how local conditions bear on peoples nutritional uptake from food), and stability (is the supply and access ensured). Strong consensus exists that climate change will have a significantly negative impact on all these aspects of food security in Africa.

Food availability could be threatened through direct climate impacts on crops and livestock from increased flooding, drought, shifts in the timing and amount of rainfall, and high temperatures, or indirectly through increased soil erosion from more frequent heavy storms or through increased pest and disease pressure on crops and livestock caused by warmer temperatures and other changes in climatic conditions. Food access could be threatened by climate change impacts on productivity in important cereal-producing regions of the world which, along with other factors, could raise food prices and erode the ability of the poor in Africa to afford purchased food. Access is also threatened by extreme events that impair food transport and other food system infrastructure. Climate change could impact food utilization through increased disease burden that reduces the ability of the human body to absorb nutrients from food. Warmer and more humid conditions caused by climate change could impact food availability and utilization through increased risk of spoilage of fresh food and pest and pathogen damage to stored foods (cereals, pulses, tubers) that reduces both food availability and quality. Stability could be affected by changes in availability and access that are linked to climatic and other factors.

FAQ 22.2: What role does climate change play with regard to violent conflict in Africa?
[to be inserted in Section 22.6.1.1]
Wide consensus exists that violent conflicts are based on a variety of interconnected causes, of which the environment is considered to be one, but rarely the most decisive factor. Whether the changing climate increases the risk of civil war in Africa remains disputed and little robust research is available to resolve this question. Climate change impacts that intensify competition for increasingly scarce resources like freshwater and arable land, especially in the context of population growth, are areas of concern. The degradation of natural resources as a result of both overexploitation and climate change will contribute to increased conflicts over the distribution of these resources. In addition to these stressors, however, the outbreak of armed conflict depends on many country-specific sociopolitical, economic and cultural factors.

Cross-Chapter Boxes

Box CC-GC. Gender and Climate Change

[Jon Barnett (Australia), Marta G. Rivera Ferre (Spain), Petra Tschakert (U.S.A.), Katharine Vincent (South Africa), Alistair Woodward (New Zealand)]

Gender, along with socio-demographic factors of age, wealth and class, is critical to the ways in which climate change is experienced. There are significant gender dimensions to impacts, adaptation and vulnerability. This issue was raised in WGII AR4 and SREX reports (Adger *et al.*, 2007; IPCC, 2012), but for the AR5 there are significant new findings, based on multiple lines of evidence on how climate change is differentiated by gender, and how climate change contributes to perpetuating existing gender inequalities. This new research has been undertaken in every region of the world (e.g. Brouwer *et al.*, 2007; Nightingale, 2009; Buechler, 2009; Nelson and Stathers, 2009; Dankelman, 2010; MacGregor, 2010; Alston, 2011; Arora-Jonsson, 2011; Resureccion, 2011; Omolo, 2011).

Gender dimensions of vulnerability derive from differential access to the social and environmental resources required for adaptation. In many rural economies and resource-based livelihood systems, it is well established that women have poorer access than men to financial resources, land, education, health and other basic rights. Further drivers of gender inequality stem from social exclusion from decision-making processes and labour markets, making women in particular less able to cope with and adapt to climate change impacts (Rijkers and Costa, 2012; Djoudi and Brockhaus, 2011; Paavola, 2008). These gender inequalities manifest themselves in gendered livelihood impacts and feminisation of responsibilities: whilst both men and women experience increases in productive roles, only women experience increased reproductive roles (Resureccion, 2011; 9.3.5.1.5, Box 13-1). A study in Australia, for example, showed how more regular occurrence of drought has put women under increasing pressure to earn off-farm income, and contribute to more on-farm labor (Alston, 2011). Studies in Tanzania and Malawi demonstrate how women experience food and nutrition insecurity since food is preferentially distributed among other family members (Nelson and Stathers, 2009; Kakota *et al.*, 2011).

AR4 assessed a body of literature that focused on women’s relatively higher vulnerability to weather-related disasters in terms of number of deaths (Adger *et al.*, 2007). Additional literature published since that time adds nuances by showing how socially-constructed gender differences affect exposure to extreme events, leading to differential patterns of mortality for both men and women (*high confidence*) [11.3.3, Table 12-3]. Statistical evidence of patterns of male and female mortality from recorded extreme events in 141 countries between 1981-2002 found that disasters kill women at an earlier age than men (Neumayer and Plümper, 2007) [Box 13-1]. Reasons for gendered differences in mortality include various socially- and culturally-determined gender roles. Studies in Bangladesh, for example, show that women do not learn to swim and so are vulnerable when exposed to flooding (Röhr, 2006) and that, in Nicaragua, the construction of gender roles means that middle-class women are expected to stay in the house, even during floods and in risk-prone areas (Bradshaw, 2010). While the differential vulnerability of women to extreme events has long been understood, there is now increasing evidence to show how gender roles for men can affect their vulnerability. In particular, men are often expected to be brave and heroic, and engage in risky life-saving behaviors that increase their likelihood of mortality [Box 13-1]. In Hai Lang district, Vietnam, for example, more men died than women due to their involvement in search and rescue and protection of fields during flooding (Campbell *et al.*, 2009). Women and girls are more likely to become victims of domestic violence after a disaster, particularly when they are living in emergency accommodation, which has been documented in the U.S. and Australia (Jenkins and Phillips, 2008; Anastario *et al.*, 2009; Alston, 2011; Whittenbury, 2013; Box 13-1).

Heat stress exhibits gendered differences, reflecting both physiological and social factors (11.3.3). The majority of studies in European countries show women to be more at risk, but their usually higher physiological vulnerability can be offset in some circumstances by relatively lower social vulnerability (if they are well connected in supportive social networks, for example). During the Paris heat wave, unmarried men were at greater risk than unmarried women, and in Chicago elderly men were at greatest risk, thought to reflect their lack of connectedness in social support networks which led to higher social vulnerability (Kovats and Hajat, 2008). A multi-city study showed geographical variations in the relationship between sex and mortality due to heat stress: in Mexico City, women had a higher risk of mortality than men, although the reverse was true in Santiago and Sao Paulo (Bell *et al.*, 2008).

Recognizing gender differences in vulnerability and adaptation can enable gender-sensitive responses that reduce the vulnerability of women and men (Alston, 2013). Evaluations of adaptation investments demonstrate that those approaches that are not sensitive to gender dimensions and other drivers of social inequalities risk reinforcing existing vulnerabilities (Figueiredo and Perkins, 2012; Arora-Jonsson, 2011; Vincent *et al.*, 2010). Government-supported interventions to improve production through cash-cropping and non-farm enterprises in rural economies, for example, typically advantage men over women since cash generation is seen as a male activity in rural areas (Gladwin *et al.*, 2001;13.3.1). In contrast, rainwater and conservation-based adaptation initiatives may require additional labor which women cannot necessarily afford to provide (Baiphethi *et al.*, 2008). Encouraging gender-equitable access to education and strengthening of social capital are among the best means of improving adaptation of rural women farmers (Below *et al.*, 2012; Goulden *et al.*, 2009; Vincent *et al.*, 2010) and could be used to complement existing initiatives mentioned above that benefit men. Rights-based approaches to development can inform adaptation efforts as they focus on addressing the ways in which institutional practices shape access to resources and control over decision-making processes, including through the social construction of gender and its intersection with other factors that shape inequalities and vulnerabilities (Tschakert, 2013; Bee *et al.*, 2013; Tschakert and Machado, 2012; see also 22.4.3 and Table 22-5).

Box CC-GC References

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Box CC-UP. Uncertain Trends in Major Upwelling Ecosystems

[Salvador E. Lluch-Cota (Mexico), Ove Hoegh-Guldberg (Australia), David Karl (USA), Hans O. Pörtner (Germany), Svein Sundby (Norway), Jean-Pierre Gatusso (France)]

Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These waters trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the Planet, the Equatorial Upwelling System (EUS, 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE, 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25 % to global fish production (Figure 30.1B, Table S30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of 'bottom-up' trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds and marine mammals.

There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI 3.2, 3.4.4, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, due to the uncertainty in wind speed trends (WGI, 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the early 1990s (WGI, 9.4.1.3.4). Observations and modelling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the the difference in heat gaining rates between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping, and the upwelling of nutrient rich, cold waters (Figure CC-UP). Some regional records support this hypothesis, others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems making it difficult to predict changes in the intensity of all Eastern Boundary Upwelling Ecosystems (30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts are highly relevant since these are the most biologically active systems in the ocean. Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO_2 enrichment in deeper water layers. Once this water returns to the surface through upwelling benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (high confidence, 6.3.2, 6.3.3; 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller *et al.*, 2010), reduce the fisheries catch potential and impact aquaculture in coastal areas (5.4.3.3, 6.3.7, 30.5.1.1.2, 30.5.5.1.3, Barton *et al.*, 2012). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulphide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor . This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia's most valuable fishery (Hamukuaya *et al*., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (6.4.1, Chp 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean , upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N_2-fixing microorganisms (Deutsch *et al*., 2007; Deutsch and Weber, 2012), but field observations of N2 fixation in these regions have not supported these predictions (Fernandez *et al*., 2011; Franz *et al*., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O_2 and CO_2 inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO_2 concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending upon pCO_2 of the upwelled water, and potentially increasingly impact the biota of Eastern Boundary Upwelling Ecosystems.

[INSERT FIGURE UP-1 HERE
Figure UP-1: Upper panel: Schematic hypothetic mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decreased coastal fisheries due to an augmented exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.]

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Box CC-WE: The Water-Energy-Food/Feed/Fiber Nexus as Linked to Climate Change

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Water, energy, and food/feed/fiber are linked through numerous interactive pathways and subject to a changing climate, as depicted in Figure WE-1. The depth and intensity of those linkages vary enormously between countries, regions and production systems. Energy technologies (e.g. biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops and forages) may require significant amounts of water (Sections 3.7.2, 7.3.2, 10.2, 10.3.4, 22.3.3, 25.7.2; Allan, 2003; King and Weber 2008; McMahon and Price, 2011; Macknick *et al*., 2012a). In irrigated agriculture, climate, irrigating procedure, crop choice and yields determine water requirements per unit of produced crop. In areas where water (and wastewater) must be pumped and/or treated, energy must be provided (Asano et al., 2006; Khan and Hanjra, 2009; USEPA, 2010; Gerten et al., 2011). While food production, refrigeration, transport and processing require large amounts of energy (Pelletier et al., 2011), a major link between food and energy as related to climate change is the competition of bioenergy and food production for land and water (Section 7.3.2, Box 25-10; Diffenbaugh et al., 2012; Skaggs et al., 2012) *(robust evidence, high agreement)*. Food and crop wastes, and wastewater, may be used as sources of energy, saving not only the consumption of conventional non-renewable fuels used in their traditional processes, but also the consumption of the water and energy employed for processing or treatment and disposal (Schievano et al., 2009; Sung et al., 2010; Olson, 2012). Examples of this can be found in several countries across all income ranges. For example, sugar cane by-products are increasingly used to produce electricity or for cogeneration (McKendry, 2002; Kim and Dale 2004) for economic benefits, and increasingly as an option for greenhouse gas mitigation.

[INSERT FIGURE WE-1 HERE
Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.]

Most energy production methods require significant amounts of water, either directly (e.g., crop-based energy sources and hydropower) or indirectly (e.g., cooling for thermal energy sources or other operations) (Sections 10.2.2 10.3.4, 25.7.4; van Vliet et al., 2012; Davies et al., 2013) *(robust evidence, high agreement).* Water for biofuels, for example, under the IEA Alternative Policy Scenario, which has biofuels production increasing to 71 EJ in 2030, has been reported by Gerbens-Leenes et al. (2012) to drive global consumptive irrigation water use from 0.5% of global renewable water resources in 2005 to 5.5% in 2030, resulting in increased pressure on freshwater resources, with potential negative impacts on freshwater ecosystems. Water is also required for mining (Section 25.7.3), processing, and residue disposal of fossil and nuclear fuels or their byproducts. Water for energy currently ranges from a few percent in most developing countries to more than 50% of freshwater withdrawals in some developed countries, depending on the country (Kenny et al., 2009; WEC, 2010). Future water requirements will depend on electricity demand growth, the portfolio of generation technologies and water management options employed (WEC, 2010; Sattler et al., 2012) *(medium evidence, high agreement)*. Future water availability for energy production will change due to climate change (Sections 3.4, 3.5.1, 3.5.2.2) *(robust evidence, high agreement).*

Water may require significant amounts of energy for lifting, transport and distribution and for its treatment either to use it or to depollute it. Wastewater and even excess rainfall in cities requires energy to be treated or disposed. Some non-conventional water sources (wastewater or seawater) are often highly energy intensive. Energy intensities per m^3 of water vary by about a factor of 10 between different sources, e.g. locally produced potable water from ground/surface water sources vs. desalinated seawater (Box 25-2, Tables 25-6 and 25-7; Macknick et al., 2012b; Plappally and Lienhard, 2012). Groundwater (35% of total global water withdrawals, with irrigated food production being the largest user; Döll et al., 2012) is generally more energy intensive than surface water. In India, for example, 19% of total electricity use in 2012 was for agricultural purposes (Central Statistics Office, 2013), with a large share for groundwater pumping. Pumping from greater depth increases energy demand significantly– electricity use (kWhr/m^3 of water) increases by a factor of 3 when going from 35 to 120 m depth (Plappally and Lienhard, 2012). The reuse of appropriate wastewater for irrigation (reclaiming both water and energy-intense nutrients) may increase agricultural yields, save energy, and prevent soil erosion (Smit and Nasr, 1992; Jimenez, 1996; Wichelns et al., 2007; Raschid-Sally and Jayakody, 2008) *(medium confidence)*. More energy efficient treatment methods enable poor quality ("black") wastewater to be treated to quality levels suitable for discharge into water courses, avoiding additional fresh water and associated energy demands (Keraita et al, 2008). If properly treated to retain nutrients, such treated water may increase soil productivity, contributing to increased crop yields/food security in regions unable to afford high power bills or expensive fertilizer (Oron, 1996; Lazarova and Bahri, 2005; Redwood and Huibers, 2008; Jimenez, 2009) *(high confidence)*.

Linkages among water, energy, food/feed/fiber and climate are also strongly related to land use and management (Section 4.4.4, Box 25-10) *(robust evidence, high agreement)*. Land degradation often reduces efficiency of water and energy use (e.g. resulting in higher fertilizer demand and surface runoff), and compromises food security (Sections 3.7.2, 4.4.4). On the other hand, afforestation activities to sequester carbon have important co-benefits of reducing soil erosion and providing additional (even if only temporary) habitat (see Box 25-10) but may reduce renewable water resources. Water abstraction for energy, food or biofuel production or carbon sequestration can also compete with minimal environmental flows needed to maintain riverine habitats and wetlands, implying a potential conflict between economic and other valuations and uses of water (Sections 25.4.3 and 25.6.2, Box 25-10) *(medium evidence, high agreement)*. Only a few reports have begun to evaluate the multiple interactions among energy, food, land, and water and climate (McCornick et al., 2008; Bazilian et al., 2011; Bierbaum and Matson, 2013), addressing the issues from a security standpoint and describing early integrated modeling approaches. The interaction among each of these factors is influenced by the changing climate, which in turn impacts energy and water demand, bioproductivity and other factors (see Figure WE-1 and Wise et al., 2009), and has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction as well as the implications for health and economic impacts as described throughout this report.

The interconnectivity of food/fiber, water, land use, energy and climate change, including the perhaps not yet well understood cross-sector impacts, are increasingly important in assessing the implications for adaptation/mitigation policy decisions. Fuel-food-land use-water-GHG mitigation strategy interactions, particularly related to bioresources for food/feed, power, or fuel, suggest that combined assessment of water, land type and use requirements, energy requirements and potential uses and GHG impacts often epitomize the interlinkages. For example, mitigation scenarios described in the IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (IPCC, 2011) indicate up to 300EJ of biomass primary energy by 2050 under increasingly stringent mitigation scenarios. Such high levels of biomass production, in the absence of technology and process/management/operations change, would have significant implications for land use, water and energy, as well as food production and pricing. Consideration of the interlinkages of energy, food/feed/fiber, water, land use and climate change is increasingly recognized as critical to effective climate resilient pathway decision making *(medium evidence, high agreement)*, although tools to support local- and regional-scale assessments and decision-support remain very limited.

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Table 22-1: Major conclusions from previous IPCC assessments.

Report	Major conclusions	Reference
IPCC special report on regional climate change	• Sensitivity of **water resources and coastal zones** to climatic parameters • Identification of climate change as an **additional burden** on an already stressful situation • **Major challenges for Africa**: Lack of data on energy sources; uncertainties linked to climate change scenarios (mainly for precipitation); need for integrated studies; and the necessary links between science and decision makers	Zinyowera *et al.*, 1997
Third Assessment Report (TAR)	• **Impacts of climate change on and vulnerability of six sectors**: water resources; food security; natural resources and biodiversity management; health; human settlements and infrastructure; desertification • **Adaptation strategies** for each of the sectors • Threats of **desertification** and **droughts** to the economy of the continent • **Suggestion of adaptation options**: mainly linked with better resource management • **Identification of research gaps and needs**: capacity building; data needs; development of integrated analysis; consideration of literature in other languages	Desanker *et al.*, 2001
Fourth Assessment Report (AR4)	• Vulnerability of Africa mainly due to its **low adaptive capacity** • **Sources of vulnerability** mainly socioeconomic causes (demographic growth, governance, conflicts, etc.) • **Impacts of climate change on various sectors**: energy, tourism and coastal zones considered separately • Potential impacts of extreme weather events (droughts and floods) • Adaptation costs • Need for mainstreaming climate change adaptation into national development policies • Two case studies: ***1.*** Food security: climate change could affect the three main components of food security ***2.*** Traditional Knowledge: African communities have prior experience with climate variability, although this knowledge will not be sufficient to face climate change impacts. • **Research needs**: better knowledge of climate variability; more studies on the impacts of climate change on water resources, energy, biodiversity, tourism, and health; the links between different sectors (e.g., between agriculture, land availability, and biofuels); developing links with the disaster reduction community; increasing interdisciplinary analysis of climate change; and strengthening institutional capacities	Boko *et al.*, 2007

Table 22-2: Under-nourishment in Africa, by number and % of total population.

Undernourished	1990 – 1992	1999 – 2001	2004 – 2006	2007 – 2009	2010 – 2012
Million	175	205	210	220	239
(%) of total population	27.3%	25.3%	23.1%	22.6%	22.9%

Source: IFAD *et al.*, 2012

Table 22-3: Examples of detected changes in species, natural ecosystems, and managed ecosystems in Africa that are both consistent with a climate change signal and published since the AR4. Confidence in detection of change is based on the length of study, and the type, amount and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate being a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change.

Type of change and nature of evidence	**Examples**	**Time scale of observations**	**Confidence in the detection of change**	**Potential climate change driver(s)**	**Confidence in the role of climate vs. other drivers**
Changes in ecosystem types *Robust evidence*	Across sub-Saharan Africa, 57% increase in agricultural areas and 15% increase in barren (largely desert) areas was accompanied by 16% decrease in total forest cover and 5% decrease in total non-forest cover (Brink and Eva, 2009)	~ 25 years (1975-2000)	**medium**	Increasing CO_2, changing precipitation patterns, increasing temperatures	**low**
	On Mt. Kilimanjaro, increased vulnerability to anthropogenic fires has driven 9% decreases in montane forest and 83% decreases in subalpine forest (Hemp, 2009)	~ 25 years (1976-2000)	**high**	Increasing temperatures, decreasing precipitation	**Low**
	In the Democratic Republic of the Congo, total forest cover declined by 2.3%, with most losses in secondary humid forest (Potapov *et al*., 2012)	~ 10 years (2000-2010)	**high**	None proposed	**low**
	Dieback of seaward edge of mangroves in Cameroon at rates up to 3 m $year^{-1}$ (Ellison and Zhou, 2012)	~ 35 years (1975-2010)	**high**	Sea level rise	**medium**
	Across western Africa, central Africa and Madagascar, net deforestation was 0.28% $year^{-1}$ for 1990-2000 and 0.14% $year^{-1}$ for 2000-2010 (Mayaux *et al*., 2013)	~ 20 years (1990-2010)	**high**	None proposed	**low**

Changes in ecosystem structure *Robust evidence*	Surveys of coral reefs in northern Tanzania indicate relative stability in the abundance and diversity of species, despite climate and non-climate stressors (McClanahan *et al*., 2009)	~ 9 years (1996-2005)	**high**	None proposed	**low**
	Analysis of sediment cores from Lake Victoria indicates current community structure (i.e., dominated by cyanobacteria and invasive fish) was established rapidly, during the 1980s (Hecky *et al*., 2010)	~ 100 years (1900-2000)	**high**	Increasing temperatures	**Low**
	Long-term declines in density of trees and shrubs in the Sahel zone of Senegal (Vincke *et al*., 2010) and Mali (Ruelland *et al*., 2011)	~ 20-50 years (Senegal, 1976-1995; Mali, 1952-2003)	**high**	Drought stress induced by decreasing precipitation	**low**
	Southward shift in the Sahel, Sudan, and Guinean savanna vegetation zones inferred from declines in tree density in Senegal and declines in tree species richness and changes in species composition in Mauritania, Mali, Burkina Faso, Niger, and Chad (Gonzales *et al*., 2012)	~ 40-50 years (density,1954-2002; diversity, 1960-2000)	**medium**	Increasing temperatures, decreasing precipitation	**medium**
	Long-term increase in shrub and tree cover across mesic savanna sites (700-1000 mm MAP) with contrasting land-use histories in South Africa (Wigley *et al*., 2009; Wigley *et al*., 2010)	~67 years (1937-2004)	**high**	Increasing CO_2	**low**
	In long-term field experiments in South Africa where disturbance from fire and herbivory was controlled, density of trees and shrubs increased in mesic savannas (600 and 750 mm MAP) but showed no change in a semi-arid savanna (550 mm MAP) (Buitenwerf *et al*., 2012)	~ 30 – 50 years (1980-2010 for 600 mm MAP site; 1954-2004 for 550 & 750 mm MAP sites)	**high**	In mesic site, increasing CO_2; but lack of response in semiarid site surprising and unexplained	**Medium**
Changes in ecosystem physiology *Moderate evidence*	A reconstruction of drought history in Tunisia and Algeria based on tree ring records from *Cedrus atlantica* and *Pinus halepensis* indicates that a 1999-2002 drought was the most severe since the 15th century (Touchan *et al*., 2008)	~ 550 years (1456–2002)	**high**	Increasing temperatures, decreasing precipitation	**low**
	Across 79 African tropical forest plots, above-ground carbon storage in live trees increased by 0.63 Mg C ha^{-1} yr^{-1} (Lewis *et al*., 2009)	~ 40 years (1968-2007)	**high**	Increasing CO_2	**Medium**
	Increased stratification and reduced nutrient fluxes and primary productivity in Lake Tanganyika (Verburg and Hecky, 2009)	~ 90 years (1913-2000)	**high**	Increasing temperatures	**High**
	Recent increases in surface temperatures and decreases in productivity of Lake Tanganyika exceed the range of natural variability (Tierney *et al*., 2010)	~ 1,500 years (500-2000)	**high**	Increasing temperatures	**High**

Changes in species distributions, physiology, or behavior *Moderate evidence*	The range of *Aloe dichotoma*, a Namib Desert tree, is shifting poleward, but extinction along trailing edge exceeds colonization along leading edge (Foden *et al*., 2007)	~ 100 years (1904-2002)	**high**	Increasing temperatures, decreasing precipitation	**Medium**
	On Tsaratanana Massif, the highest mountain in Madagascar, reptiles and amphibians are moving upslope (Raxworthy *et al.*, 2008)	~ 10 years (1993-2003)	**high**	Increasing temperatures	**Medium**
	Pomacentrus damselfish species vary in avoidance of predation-related mortality under elevated CO_2 (Ferrari *et al*., 2011)	minutes to days (Nov.-Dec. 2009)	**high**	Increasing CO_2	**low**
	In greenhouse experiments, growth of seedlings of woody savanna species (*Acacia karoo* and *Terminalia sericea*) was enhanced at elevated CO_2 (Bond and Midgley, 2012)	~1-2 years	**high**	Increasing CO_2	**medium**

Table 22-4: Projected changes in agro-climatic suitability for perennial crops in Africa by mid-century under an A2 scenario.

Crop	**Suitability change**	**Country**	**Source**
Coffee	Increased suitability at high latitudes; decreased suitability at low latitudes	Kenya	Läderach et al., 2010
Tea	Decreased suitability	Uganda	Eitzinger et al., 2011a,b
	Increased suitability at high latitudes; decreased suitability at low latitudes	Kenya	
Cocoa	Constant or increased suitability at high latitudes; decreased suitability at low latitudes	Ghana, Côte d'Ivoire	Läderach et al., 2011c
Cashew	Increased suitability	Ghana, Côte d'Ivoire	Läderach et al., 2011a
Cotton	Decreased suitability	Ghana, Côte d'Ivoire	Läderach et al., 2011b

Table 22-5: Cross-cutting approaches for equity and social justice in adaptation.

Equitable adaptation approach	Key issues to address for adaptation	Factors that could cause maladaptation	Opportunities	Lessons learned
Gender mainstreamed adaptation in Africa	Lack of empowerment and participation in decision-making (Patt *et al*., 2009) Climate impacts increase women's household roles, with risk of girls missing school to assist (Raworth, 2008; Romero González *et al*., 2011; UNDP, 2011b) Male adaptation strategies e.g. migration risk increasing women's vulnerability (Djoudi and Brockhaus, 2011)	Employment opportunities not sufficiently extended to women in adaptation initiatives (Madzwamuse, 2010) Failure to incorporate power relations in adaptation responses (Djoudi and Brockhaus, 2011; Romero González *et al*., 2011)	Women's aptitude for long-term thinking, trusting and integrating scientific knowledge, and taking decisions under uncertainty (Patt *et al.*, 2009) Potential long-term increase in women's empowerment and social and economic status (Djoudi and Brockhaus, 2011) Women opportunistically using development projects for adaptation (Nielsen, 2010)	Security of tenure over land and resource access is critical for enabling enhanced adaptive capacity of women (ADF, 2010) Research on understanding different adaptive strategies of benefit for women and men is needed
Child-centered approaches to adaptation	Children and youth represent over 60% of Africa's population, yet their issues are largely absent from adaptation policy (ADF, 2010) Children's differential vulnerability to projected climate impacts is high, particularly to hunger, malnutrition and disasters (UNICEF, 2007)	Limits to children's agency related to power imbalances between children and adults, and different cultural contexts (Seballos *et al*., 2011)	Using approaches that stress agency and empowerment, and 'innovative energies' of youth; build on targeted adaptation initiatives, such as child-centred disaster risk reduction and adaptation (ADF, 2010; Seballos *et al*., 2011)	Positive role of children and youth as change agents for climate adaptation, within appropriate enabling environment Child-sensitive programmes and policies can reduce risks children face from disasters (Seballos et al, 2011) Funding for climate resilience programmes will protect children's basic rights (UNICEF, 2010; UNICEF, 2011)
Human rights-based approaches (HRBA)	Common critical rights issues for local communities are land/resource rights, gender equality, and political voice and fair adjudication of grievances for the poor and excluded (Castro *et al.*, 2012)	Lack of recognition and promotion of their human rights blocks indigenous peoples' coping and adaptation capacities (UNPFII, 2008)	Using the HRBA lens to understand climate risk necessitates risk analysis to probe the root causes of differential disaster risk vulnerabilities, to enable structural, sustainable responses (Urquhart, 2014)	Applying HRBA presents a framework for addressing conflicting rights and interests, necessary for building resilience and equitable adaptation responses (Nilsson and Schnell, 2010)

Table 22-6: Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Africa. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Shifts in biome distribution, and severe impacts on wildlife due to diseases and species extinction (*high confidence*)	Very few adaptation options; migration corridors; protected areas; better management of natural resources		22.3.2.1, 22.3.2.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Stress on water resources currently facing significant strain from overexploitation and degradation, and increased future demand, will be compounded by temperature rise and changes in precipitation (*high confidence*)	Reducing nonclimate stressors on water resources is critical for realizing adaptation co-benefits. Strengthening institutional capacities for demand management, groundwater assessment, integrated water-wastewater planning and integrated land and water governance would advance adaptation planning.		22.3.2.2, 22.3.3, 22.4.2, 22.4.4, 22.4.5	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Degradation of coral reefs results in loss of protective ecosystems and fishery stocks (*medium confidence*)	Few adaptation options; marine protected areas; conservation and protection; better management of natural resources.		22.3.2.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Reduced crop productivity with strong adverse effects on regional, national and household food security, linked to temperature rise and precipitation changes, and secondary (indirect) impacts, such as those linked to increased pest and disease damage and flood risks to food system infrastructure (*high confidence*)	Adaptation can be made more effective where technologic adaptation responses (e.g. stress tolerant crop varieties, irrigation, etc.) are embedded within efforts to enhance smallholder access to credit and other critical production resources, livelihoods diversification, institutional strengthening at local to regional levels to support agriculture and strong gender oriented policy support.		22.3.4.1, 22.4.5.2, 22.4.5.4, 22.4.5.6, 22.4.5.7, 22.4.6	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Adverse effects on livestock linked to temperature rise and precipitation changes that lead to increased heat and water stress, and shifts in the range of pests and diseases, with adverse impacts on pastoral livelihoods and rural poverty (*medium confidence*)	Addressing nonclimate stressors facing pastoralists, including policy and governance features that perpetuate their marginalization, is critical for reducing vulnerability. Natural resource-based strategies such as reducing drought risk to pastoral livelihoods through use of forest goods and services hold potential, provided sufficient attention is paid to forest conservation and sustainable management.		22.3.4.2, 22.4.5.2, 22.4.5.6, 22.4.5.8	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Changes in the incidence and geographic range of vector- and water-borne diseases due to changes in the mean and variability of temperature and precipitation, particularly along the edges of their distribution (*medium confidence*)	Achieving development goals, particularly improvement in access to safe water and improved sanitation, along with enhancement of public health functions, such as surveillance. Specific adaptation options include vulnerability mapping and early warning systems. Coordination activities with other sectors.		22.3.5, 22.3.5.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Undernutrition, with its potential for life-long impacts on health and development and its associated increase in vulnerability to malaria and diarrheal diseases, can result from changing crop yields, migration due to weather and climate extremes, and other factors (*medium confidence*)	Early warning systems and vulnerability mapping (for targeted interventions); diet diversification; coordination with food and Agriculture sectors; improved public health functions to address underlying diseases.		22.3.5.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high

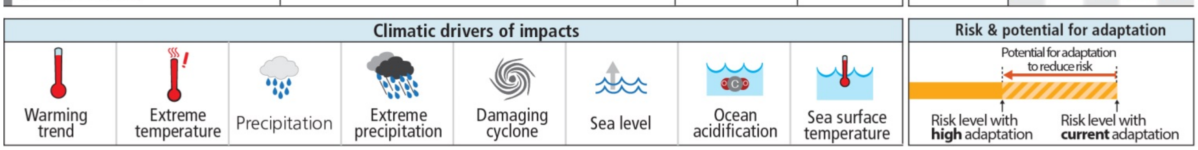


Table 22-7: Land inundated and economic impacts in Cape Town based on a risk assessment (Cartwright, 2008).

Sea level rise scenarios	Land inundated	Economic impacts (for 25 years)
Scenario 1 (+ 2.5 to 6.5 m depending on the exposure) 95%	25.1 km^2 (1% of the total CT area)	5.2 billion R (794 million US$)
Scenario 2 (+ 4.5 m) 85%	60.9 km^2 (2% of the total CT area)	23.7 billion R (30.3 billion US$)
Scenario 3 (+6.5 m) 20%	95 km^2 (4% of the total CT area)	54.8 billion R

Note: The economic impacts are determined based on the value of properties, losses of touristic revenues and the cost of infrastructure replacement. The total geographical gross product for Cape Town in 2008 was 165 billion of Rands.

Table 22-8: Research gaps in different sectors.

Key Sectors	Gaps observed
Climate Science	•Research in climate and climate impacts would be greatly enhanced if data custodians and researchers worked together to use observed station data in scientific studies. Research into regional climate change and climate impacts relies on observed climate and hydrological data as an evaluative base. These data are most often recorded by meteorological institutions in each country and sold to support data collection efforts. However, African researchers are generally excluded from access to these critical data due to the high costs involved which hinders both climate and climate impacts research. •Downscaling GCM data to the regional scale captures the influence of topography on the regional climate. Regional climate information is essential for understanding regional climate processes, regional impacts and potential future changes in these. Additionally, impacts models such as hydrology and crop models generally require input data at a resolution higher than what GCMs can provide. Regional downscaling, either statistically or through using regional climate models, can provide information at these scales and can also change the sign of GCM-projected rainfall change over topographically complex areas [22.2.2.2].
Ecosystems	•Monitoring networks for assessing long-term changes to critical ecosystems such as coastal ecosystems, lakes, mountains, grasslands, forests, wetlands, deserts, and savannas to enhance understanding of long-term ecological dynamics, feedbacks between climate and ecosystems, the effects of natural climate variability on ecosystems, the limits of natural climate variability, and the marginal additional effects of global climate forcing. •Develop the status of protected areas to include climate change effects
Food Systems	•Socioeconomic and environmental tradeoffs of biofuel production, especially the effect on land use change and food and livelihood security; better agronomic characterization of biofuel crops to avoid maladaptive decisions with respect to biofuel production •Vulnerability to and impacts of climate change on food systems (production, transport, processing, storage, marketing and consumption) •Impacts of climate change on urban food security, and dynamic of rural-urban linkages in vulnerability and adaptive capacity •Impacts of climate change on food safety and quality
Water resources	•Characterization of Africa's groundwater resource potential; understanding interactions between non-climate and climate drivers as related to future groundwater resources. •Impacts of climate change on water quality, and how this links to food and health security •Decision making under uncertainty with respect to water resources given limitations of climate models for adequately capturing future rainfall projections

Human security and urban areas	•Research to explore and monitor the links between climate change and migration and its potential negative effects on environmental degradation; the potential positive role of migration in climate change adaptation. •Improved methods and research to analyse the relation between climate change and violent conflict.
Livelihoods and poverty	•Methodologies for cyclical learning and decision-support to enable anticipatory adaptation in contexts of high poverty and vulnerability (Tschakert and Dietrich, 2010) •Frameworks to integrate differentiated views of poverty into adaptation and disaster risk reduction, and to better link these with social protection in different contexts •Ethical and political dimensions of engaging with local and traditional knowledge on climate change
Health	Research and improved methodologies (including longitudinal studies) to assess and quantify the impact of climate change on vector borne, foodborne, waterborne, nutrition, heatstress and indirect impacts on HIV. Research to quantify the direct and indirect health impacts of extreme weather events in Africa; injuries, mental illness; health infrastructure Frameworks and research platforms to be developed with other sectors to determine how underlying risks (for example food security) will be addressed to improve health outcomes.
Adaptation	Research to develop home-grown and to localize global adaptation technologies to build resilience Equitable adaptation frameworks to deal with high uncertainty levels and integrate marginalized groups; and that identify and eliminate multi-level constraints to women's adaptive ability Multi--tiered approach to building institutional and community capacity to respond to climate risk Potential changes in economic and social systems under different climate scenarios, to understand the implications of adaptation and planning choices (Clements *et al.*, 2011) Principles/determining factors for effective adaptation, including community-based adaptation Understanding synergies and trade-offs between different adaptation and mitigation approaches (Chambwera and Anderson, 2011) Additional national and sub-natinal modeling and analysis of the economic costs of impacts and adaptation, including of the 'soft' costs of impacts and adaptation Monitoring adaptation
Other	Methods in vulnerability analysis for capturing the complex interactions in systems across scales Understanding compound impacts from concomitant temperature and precipitation stress, e.g. effect on a particular threshold of a heatwave occurring during a period of below normal precipitation.

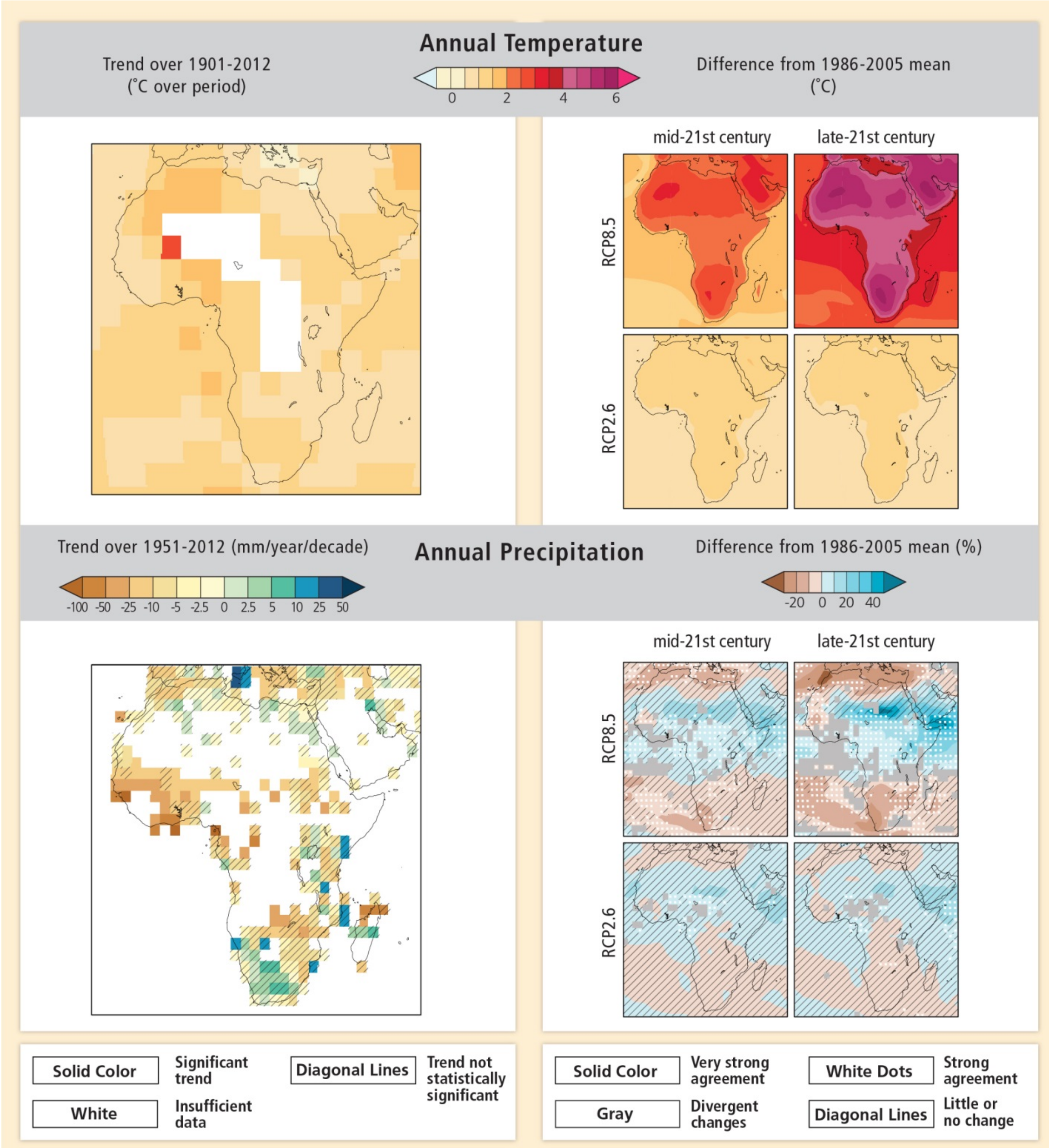


Figure 22-1: Observed and simulated variations in past and projected future annual average precipitation and temperature. Observed differences in the Climate Research Unit, University of East Anglia data (CRU) are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through 1925. For CMIP5, white indicates areas where <66% of models exhibit a change greater than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Grey indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. Colors with circles indicate the ensemble-mean change in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. Colors without circles indicate areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on the sign of change. The realizations from each model are first averaged to create baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated. The baseline period is 1986-2005. The late-21st Century period is 2081-2100. The mid-21st century period is 2046-2065.

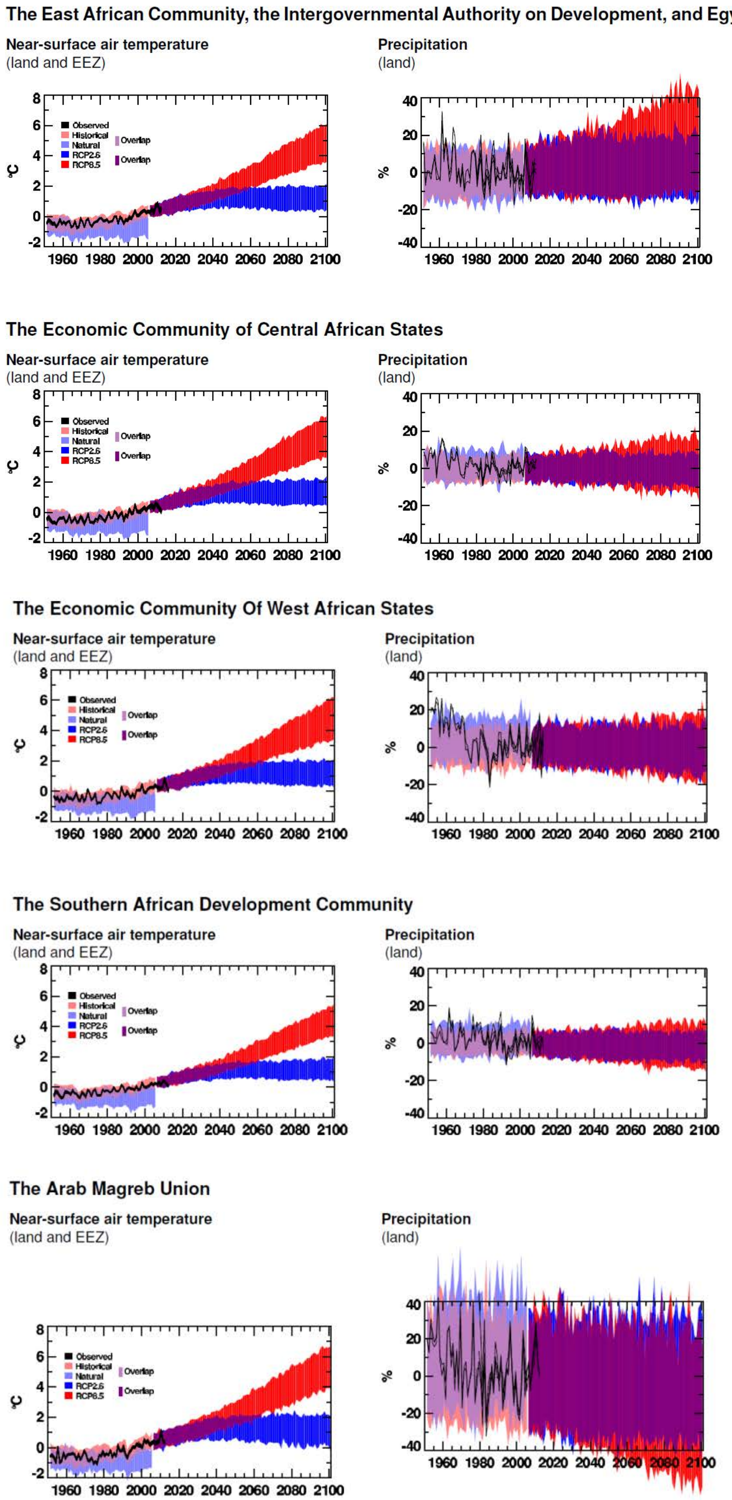
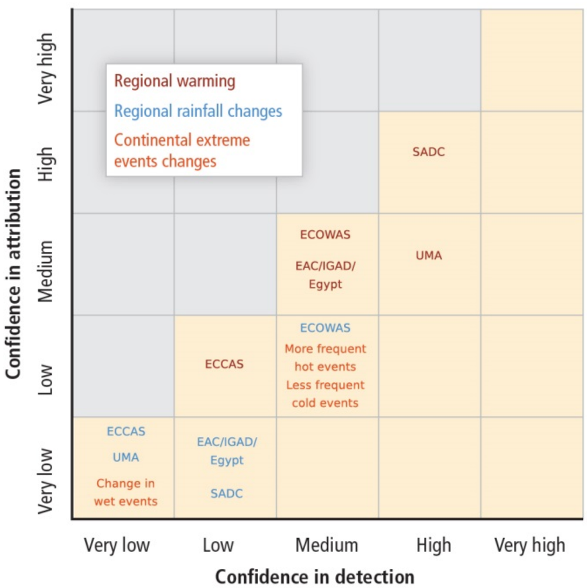

The East African Community, the Intergovernmental Authority on Development, and Egypt
Near-surface air temperature
(land and EEZ)
Precipitation
(land)
The Economic Community of Central African States
Near-surface air temperature
(land and EEZ)
Precipitation
(land)
The Economic Community Of West African States
Near-surface air temperature
(land and EEZ)
Precipitation
(land)
The Southern African Development Community
Near-surface air temperature
(land and EEZ)
Precipitation
(land)
The Arab Magreb Union
Near-surface air temperature
(land and EEZ)
Precipitation
(land)
Observed
Historical
Natural
RCP2.6
RCP8.5
Overlap
Overlap
°C
%
1960 1980 2000 2020 2040 2060 2080 2100

Figure 22-2: Observed and simulated variations in past and projected future annual average temperature over EAC-IGAD-Egypt, ECCAS, ECOWAS, SADC and UMA. Black lines show various estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the "RCP2.6" emissions scenario (63), and the "RCP8.5" (63). Data are anomalies from the 1986-2005 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.
[Illustration to be redrawn to conform to IPCC publication specifications.]



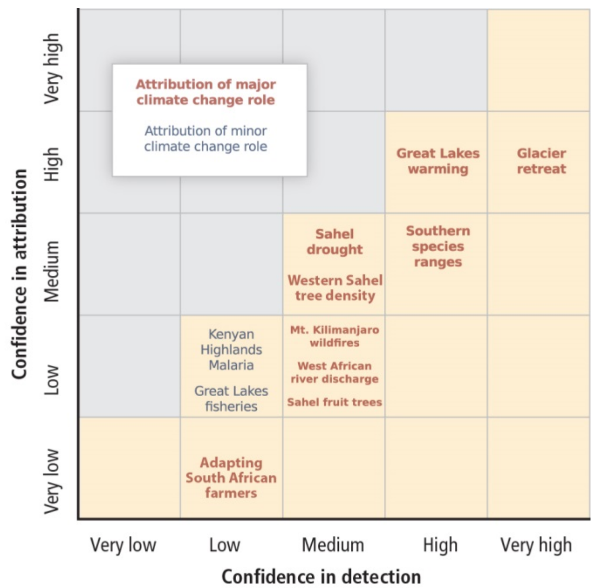


Figure 22-3: Left: Confidence in detection and in attribution of observed climate change over Africa to anthropogenic emissions. All detection assessments are against a reference of no change, while all attribution assessments concern a major role of anthropogenic emissions in the observed changes. See 22.2, and SREX-3, and WGI AR5 10 for details. Right: Confidence in detection and in attribution of the impacts of observed regional climate change on various African systems. All detection assessments are against a reference of no change, except "Kenyan Highlands malaria" (changes due to vaccination, drug resistance, demography, and livelihoods), "Great Lakes fisheries" (changes due to fisheries management and land use) and “Adapting South African farmers” (economic changes). Attribution is to a major role or a minor role of observed climate change, as indicated. See 22.2.2, 22.3.2.1, 22.3.2.2, 2.3.3, 22.4.2, 22.3.4.4, 22.3.5.4, 22.4.5.7 and Tables 18-5, 18-6, 18-7, and 18-9 for details. Assessments follow the methods outlined in 18.2.

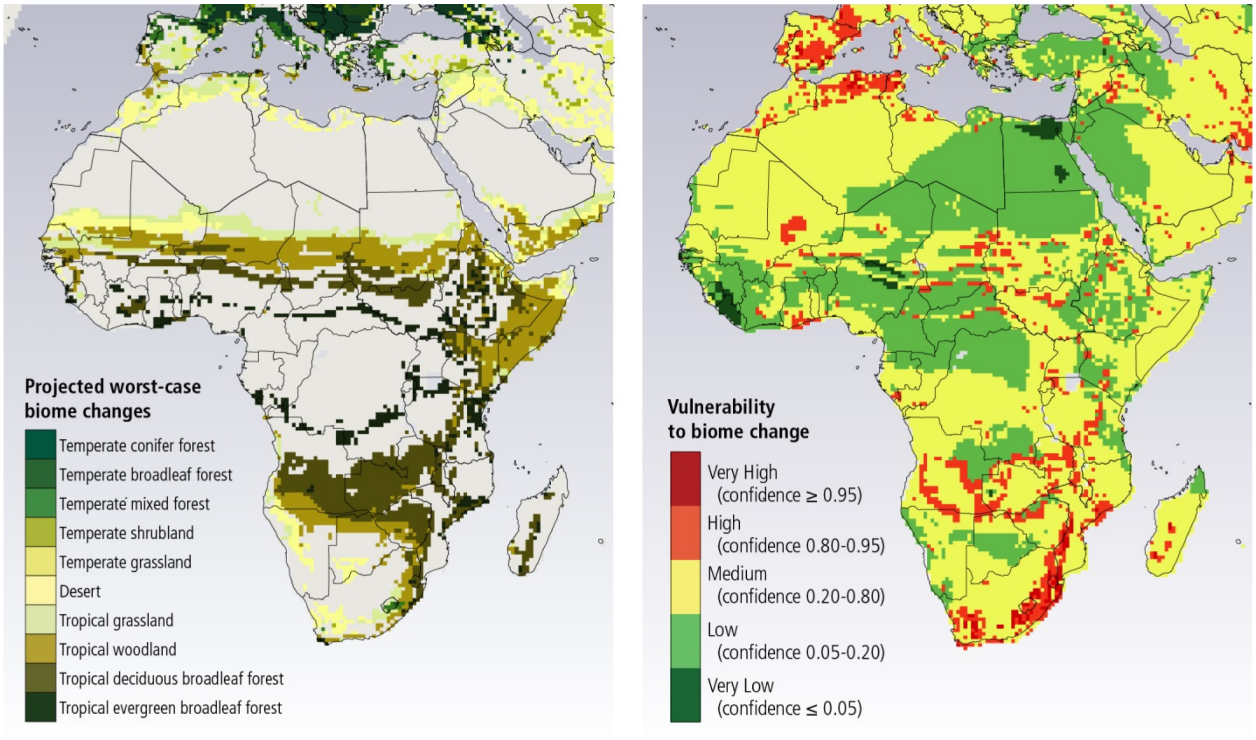


Figure 22-4: Left – Projected biome change from the periods 1961-1990 to 2071-2100 using the MC1 Dynamic Vegetation Model. Change is indicated if any of nine combinations of three GCMs (CSIRO Mk3, HadCM3, MIROC 3.2 medres) and three emissions scenarios (B1, A1B, A2) project change and is thus a worst-case scenario. Colours represent the future biome predicted. Right – Vulnerability of ecosystems to biome shifts based on historical climate (1901-2002) and projected vegetation (2071-2100), where all nine GCM-emissions scenario combinations agree on the projected biome change. Source: Gonzalez et al. (2010).

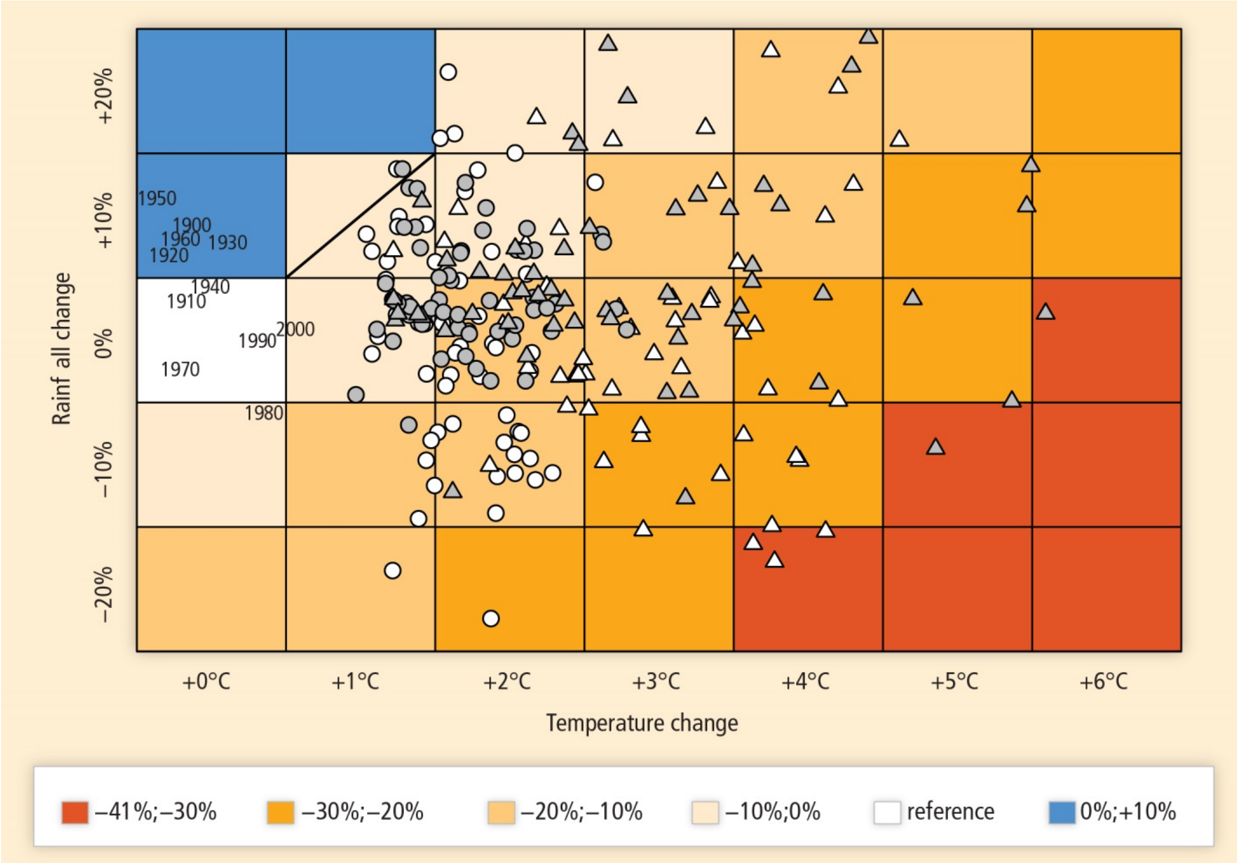


Figure 22-5: The effect of rainfall and temperature changes on mean crop yield. Mean crop yield change (%) relative to the 1961–90 baseline for 7 temperatures (x-axis) and 5 rainfall (y-axis) scenarios. Results are shown as the average over the 35 stations across West Africa and the 6 cultivars of sorghum and millet. White triangles and circles are the projected anomalies computed by several CMIP3 GCMs and three IPCC emission scenarios (B1, A1B, A2) for 2071–90 and 2031–50, respectively. Projections from CMIP5 GCMs and three RCPs (4.5, 6.0 and 8.5) are represented by grey triangles and circles. Models and scenarios names are displayed in figure S2 (available at stacks.iop.org/ERL/8/014040/mmedia). Past observed climate anomalies from CRU data are also projected by computing 10-year averages (e.g. '1940' is for 1941–50). All mean yield changes are significant at a 5% level except boxes with a diagonal line. Source: Sultan et al., 2013.

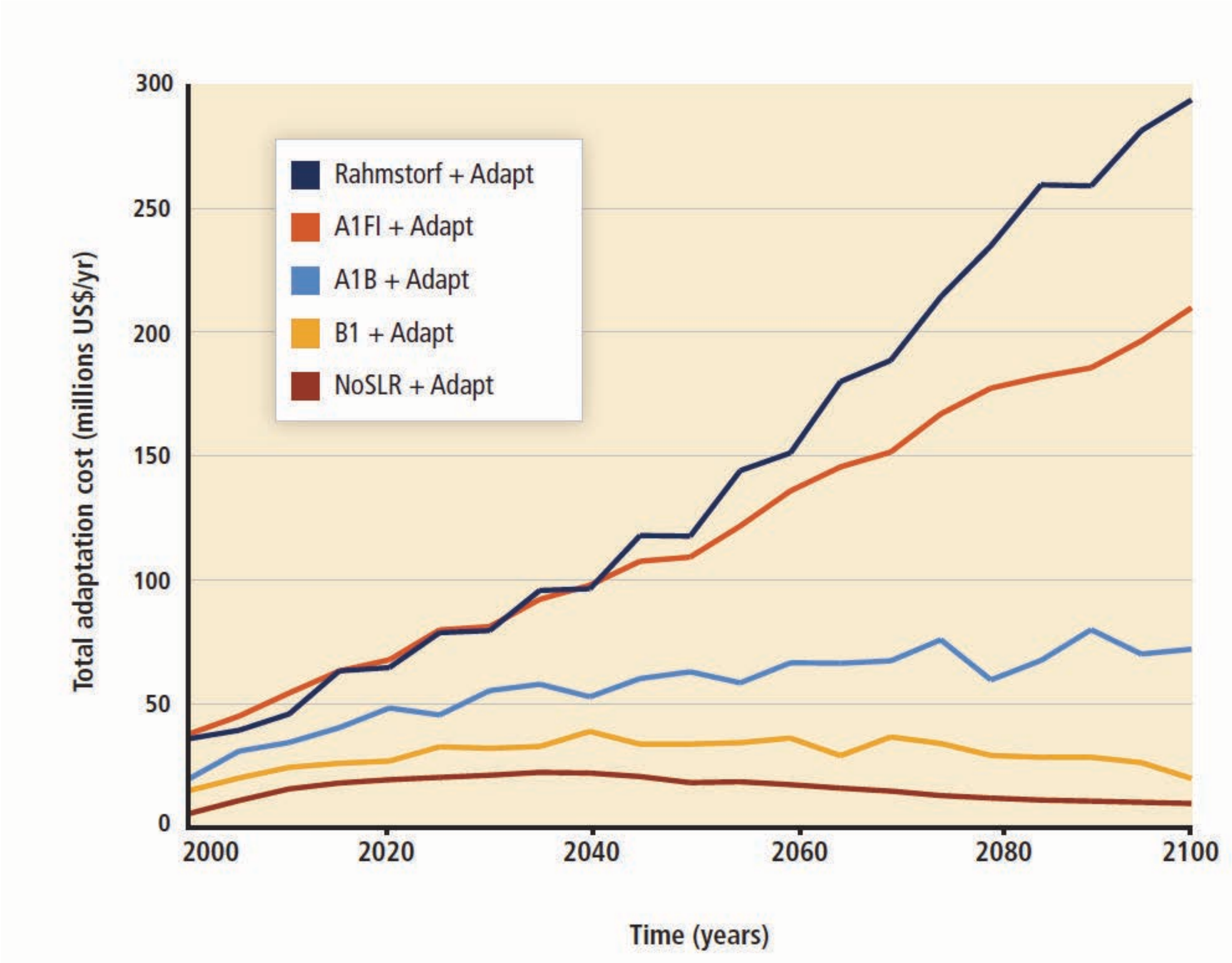


Figure 22-6: Total additional costs of adaptation per year from 2000 to 2100 for Tanzania (including beach nourishment and sea and river dikes). The values do not consider the existing adaptation deficit (values in $US2005), without discounting. Source: Kebede *et al.*, 2010.

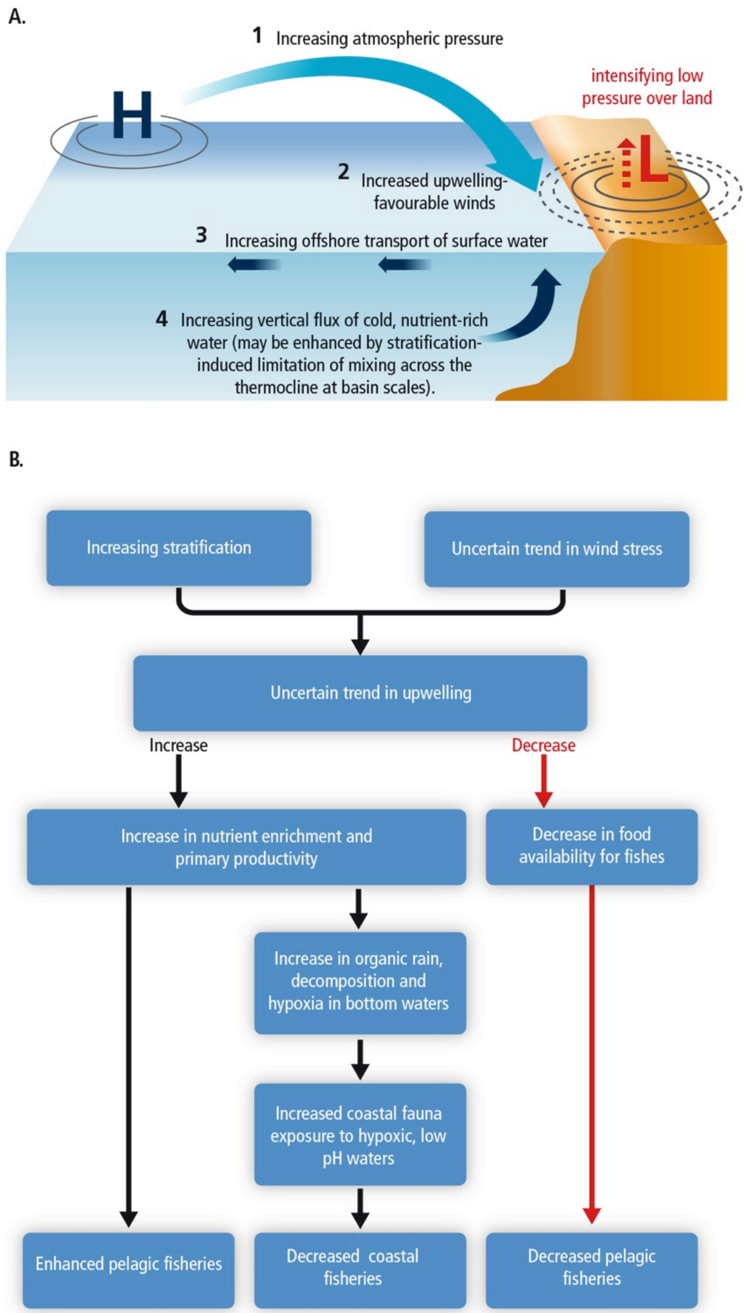


Figure UP-1: Upper panel: Schematic hypothetic mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decreased coastal fisheries due to an augmented exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.

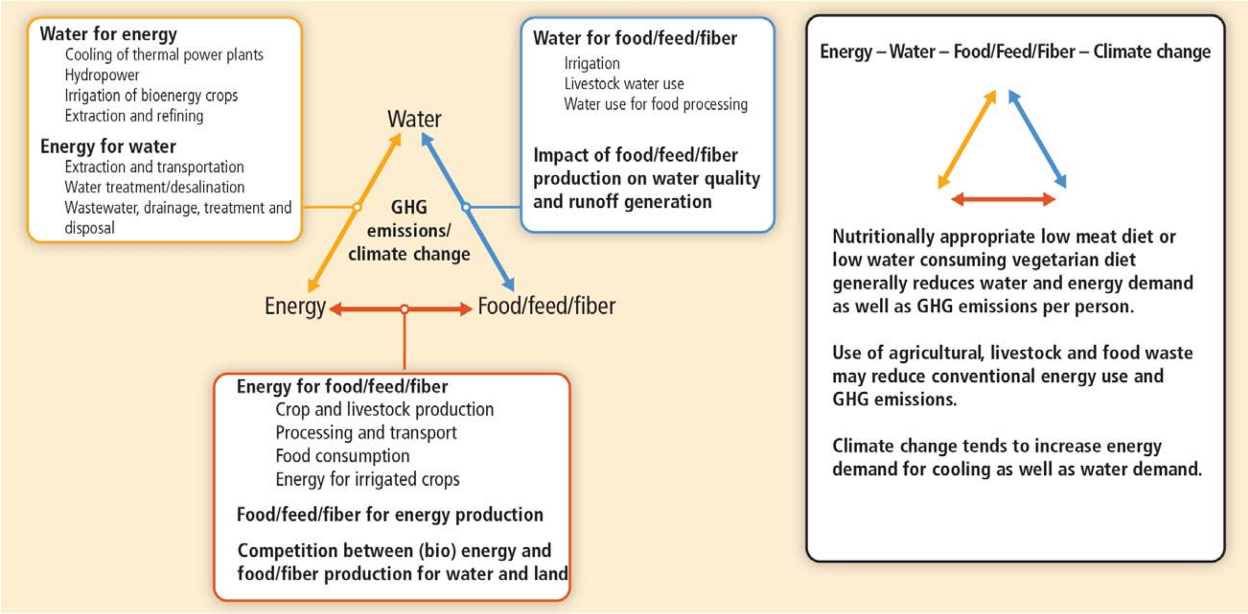


Figure WE-1: The water-energy-food nexus as related to climate change. The interlinkages of supply/demand, quality and quantity of water, energy and food/feed/fiber with changing climatic conditions have implications for both adaptation and mitigation strategies.

Chapter 23. Europe

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Contents

Executive Summary

Observed climate trends and future climate projections show regionally varying changes in temperature and rainfall in Europe [***high confidence***] [23.2.2], in agreement with AR4 findings, with projected increases in temperature throughout Europe and increasing precipitation in Northern Europe and decreasing precipitation in Southern Europe [23.2.2.2]. Climate projections show a marked increase in high temperature extremes [*high confidence*], meteorological droughts [*medium confidence*] [23.2.3] and heavy precipitation events [*high confidence*] [23.2.2.3] with variations across Europe, and small or no changes in wind speed extremes [*low confidence*] except increases in winter wind speed extremes over Central and Northern Europe [*medium confidence*] [23.2.2.3].

Observed climate change in Europe has had wide ranging effects throughout the European region including: the distribution, phenology, and abundance of animal, fish and plant species [*high confidence*] [23.6.4, Table 23.6]; stagnating wheat yields in some sub-regions [*medium confidence, limited evidence*] [23.4.1]; and forest decline in some sub-regions [*medium confidence*] [23.4.4]. Climate change has affected both human health (from increased heat waves) [*medium confidence*] [23.5.1] and animal health (changes in infectious diseases) [*high confidence*] 23.4.5]. There is less evidence of impacts on social systems attributable to observed climate change, except in pastoralist populations [*low confidence*].

Climate change will increase the likelihood of systemic failures across European countries caused by extreme climate events affecting multiple sectors [*medium confidence*] [23.2.2.3, 23.2.3, 23.3, 23.4, 23.5, 23.6, 23.9.1]. Extreme weather events currently have significant impacts in Europe in multiple economic sectors as well as adverse social and health effects [*high confidence*] [Table 23.1]. There is limited evidence that resilience to heat waves and fires has improved in Europe [*medium confidence*] [23.9.2, 23.5.], while some countries have improved their flood protection following major flood events [23.9.2, 23.7.3]. Climate change is very likely to increase the frequency and intensity of heat waves, particularly in Southern Europe [*high confidence*] [23.2.2] with mostly adverse implications for health, agriculture, forestry, energy production and use, transport, tourism, labour productivity, and the built environment [Table 23-1, 23.3.2, 23.3.3, 23.3.4, 23.3.6, 23.4.1, 23.4.2, 23.4.3, 23.4.4, 23.5.1].

The provision of ecosystem services is projected to decline across all service categories in response to climate change in Southern Europe and Alpine sub-regions [*high confidence*] [23.9.1, Box 23-1]. Both gains and losses in the provision of ecosystem services are projected for the other European sub-regions [*high confidence*], but the provision of cultural services is projected to decline in the Continental, Northern and Southern sub-regions [*low confidence*] [Box 23-1].

Climate change is expected to impede economic activity in Southern Europe more than in other sub-regions [*medium confidence*] [Table 23.4, 23.9.3], and may increase future intra-regional disparity [*low confidence*] [23.9.3]. There are also important differences in vulnerability within sub-regions, for example, plant species and some economic sectors are most vulnerable in high mountain areas due to lack of adaptation options [*medium confidence]*[23.9.1.]. Southern Europe is particularly vulnerable to climate change [*high confidence*] as multiple sectors will be adversely affected (tourism, agriculture, forestry, infrastructure, energy, population health) [*high confidence*] [23.9] [Box 23-3].

The impacts of sea level rise on populations and infrastructure in coastal regions can be reduced by adaptation [*medium confidence]* [23.3.1, 23.5.3]. Populations in urban areas are particularly vulnerable to climate change impacts due to the high density of people and built infrastructure [*medium confidence*] [23.3, 23.5.1].

Synthesis of evidence across sectors and sub-regions confirm that there are limits to adaptation from physical, social, economic and technological factors [*high confidence*] [23.5]. Adaptation is further impeded because climate change affects multiple sectors [23.10]. The majority of published assessments are based on climate projections in the range 1-4 degrees global mean temperature per century. Limited evidence exists regarding the potential impacts in Europe under high rates of warming (>4 degrees global mean temperature per century) [23.9.1].

Impacts by Sector

Sea level rise and increases in extreme rainfall are projected to further increase coastal and river flood risk in Europe and, without adaptive measures, will substantially increase flood damages (people affected and economic losses) [*high confidence*] [23.3.1, 23.5.1]. Adaptation can prevent most of the projected damages [*high confidence – based on medium evidence, high agreement*] but there may be constraints to building flood defences in some areas [23.3.1, 23.7.1, 23.8.3]. Direct economic river flood damages in Europe have increased over recent decades [*high confidence*] but this increase is due to development in flood zones and not due to observed climate change [23.3.1.2, SREX 4.5]. Some areas in Europe show changes in river flood occurrence related to observed changes in extreme river discharge [*medium confidence*] [23.2.3].

Climate change is projected to affect the impacts of hot and cold weather extremes on transport leading to economic damage and/or adaptation costs, as well as some benefits (e.g. reduction of maintenance costs) during winter [*medium confidence*] [23.3.3]. Climate change is projected to reduce severe accidents in road transport [*medium confidence*] and adversely affect inland water transport in summer in some rivers (e.g. the Rhine) after 2050 [*medium confidence*]. Damages to rail infrastructure from high temperatures may also increase *[medium confidence*]. Adaptation through maintenance and operational measures can reduce adverse impacts to some extent.

Climate change is expected to affect future energy production and transmission [23.3.4]. Hydropower production is likely to decrease in all sub-regions except Scandinavia [*high confidence*] [23.3.4]. Climate change is unlikely to affect wind energy production before 2050 [*medium confidence*] but will have a negative impact in summer and a varied impact in winter after 2050 [*medium confidence*]. Climate change is likely to decrease thermal power production during summer [*high confidence*] [23.3.4]. Climate change will increase the problems associated with overheating in buildings [*medium confidence*] [23.3.2]. Although climate change is very likely to decrease space heating demand [*high confidence*], cooling demand will increase [*very high confidence*] although income growth mostly drives projected cooling demand up to 2050 [*medium confidence*] [23.3.4]. More energy efficient buildings and cooling systems as well as demand-side management will reduce future energy demands [23.3.4].

After 2050, tourism activity is projected to decrease in southern Europe [*low confidence*] and increase in Northern and Continental Europe [*medium confidence*]. No significant impacts on the tourism sector are projected before 2050 in winter or summer tourism except for ski tourism in low altitude sites and under limited adaptation [*medium confidence*] [23.3.6]. Artificial snowmaking may prolong the activity of some ski resorts [*medium confidence*] [23.3.6].

Climate change is likely to increase cereal yields in Northern Europe [*medium confidence, disagreement*] but decrease yields in Southern Europe [*high confidence*] [23.4.1]. In Northern Europe, climate change is very likely to extend the seasonal activity of pests and plant diseases [*high confidence*] [23.4.1]. Yields of some arable crop species like wheat have been negatively affected by observed warming in some European countries since 1980s [*medium confidence, limited evidence*] [23.4.1] Compared to AR4, new evidence regarding future yields in Northern Europe, is less consistent regarding the magnitude and sign of change. Climate change may adversely affect dairy production in Southern Europe because of heat stress in lactating cows [*medium confidence*] [23.4.2]. Climate change has contributed to vector-borne disease in ruminants in Europe [*high confidence*] [23.4.2] and northward expansion of tick disease vectors [*medium confidence*] [23.4.2, 23.5.1].

Climate change will increase irrigation needs [*high confidence*] but future irrigation will be constrained by reduced runoff, demand from other sectors, and by economic costs [23.4.1, 23.4.3]. By 2050s, irrigation will not be sufficient to prevent damage from heat waves to crops in some sub-regions [*medium confidence*]. System costs will increase under all climate scenarios [*high confidence*] [23.4.3]. Integrated management of water, also across countries' boundaries, is needed to address future competing demands between agriculture, energy, conservation and human settlements [23.7.2].

As a result of increased evaporative demand, climate change is likely to significantly reduce water availability from river abstraction and from groundwater resources [*medium confidence*], in the context of increased demand (from agriculture, energy and industry, and domestic use) and cross-sectoral implications which are not fully understood [23.4.3, 23.9.1]. Some adaptation is possible through uptake of more water efficient technologies and water saving strategies [23.4.3, 23.7.2, 23.9.1].

Climate change will change the geographic distribution of wine grape varieties [*high confidence*] and this will reduce the value of wine products and the livelihoods of local wine communities in Southern and Continental Europe [*medium confidence*] and increase production in Northern Europe [*low confidence*] [23.4.1, 23.3.5, 23.5.4, Box 23-2]. Some adaptation is possible through technologies and good practice [Box 23-2].

Climate warming will increase forest productivity in northern Europe [*medium confidence*] [23.4.4], although damage from pests and diseases in all sub-regions will increase due to climate change [*high confidence*] [23.4.4]. Wildfire risk in Southern Europe [*high confidence*] and damages from storms in central Europe [*low confidence*] may also increase due to climate change [23.4.4]. Climate change is likely to cause ecological and socio-economic damages from shifts in forest tree species range (from south-west to north-east) [*medium confidence*], and in pest species distributions [*low confidence*] [23.4.4]. Forest management measures can enhance ecosystem resilience [*medium confidence*] [23.4.4].

Observed warming has shifted marine fish species ranges to higher latitudes [*high confidence*] and reduced body size in species [*medium confidence*] [23.4.6]. There is limited and diverging evidence on climate change impacts on net fisheries economic turnover. Local economic impacts attributable to climate change will depend on the market value of (high temperature tolerant) invasive species [23.4.6]. Climate change is unlikely to entail relocation of fishing fleets [*high confidence*] [23.4.6]. Observed higher water temperatures have adversely affected both wild and farmed freshwater salmon production in the southern part of their distribution [*high confidence*] [23.4.6]. High temperatures may increase the frequency of harmful algal blooms [*low confidence*] [23.4.6].

Climate change will affect bioenergy cultivation patterns in Europe by shifting northward their potential area of production [medium confidence] [23.4.5]. Elevated atmospheric CO_2 can improve drought tolerance of bioenergy crop species due to improved plant water use, maintaining high yields in future climate scenarios in temperate regions [*low confidence*] [23.4.5].

Climate change is likely to affect human health in Europe. Heat-related deaths and injuries are likely to increase, particularly in Southern Europe [*medium confidence*] [23.5.1]. Climate change may change the distribution and seasonal pattern of some human infections, including those transmitted by arthropods [*medium confidence*], and increase the risk of introduction of new infectious diseases [*low confidence*] [23.5.1].

Climate change and sea level rise may damage European cultural heritage, including buildings, local industries, landscapes, archaeological sites, and iconic places [*medium confidence*] and some cultural landscapes may be lost forever [*low confidence*] [23.5.4] [Table 23.3].

Climate change may adversely affect background levels of tropospheric ozone [*low confidence, limited evidence, low agreement*], assuming no change in emissions, but the implications for future particulate pollution (which is more health-damaging) are very uncertain [23.6.1]. Higher temperatures may have affected trends in ground level tropospheric ozone [*low confidence*] [23.6.1.]. Climate change is likely to decrease surface water quality due to higher temperatures and changes in precipitation patterns [*medium confidence*] [23.6.3], and is likely to increase soil salinity in coastal regions *[low confidence]* [23.6.2]. Climate change may also increase soil erosion (from increased extreme events) and reduce soil fertility [*low confidence, limited evidence*] [23.6.2].

Observed climate change is affecting a wide range of flora and fauna, including plant pests and diseases [*high confidence*] [23.4.1, 23.4.4] and the disease vectors and hosts [*medium confidence*] [23.4.3]. Climate change is *very likely* to cause changes in habitats and species, with local extinctions [*high confidence*] and continental scale shifts in species distributions [*medium confidence]* [23.6.4]. The habitat of alpine plants is very likely to be significantly reduced [*high confidence*] [23.6.4]. Phenological mismatch will constrain both terrestrial and marine ecosystem functioning under climate change [*high confidence*] [23.6.4, 23.6.5], with a reduction in some ecosystem services [*low confidence*] [23.6.4, Box 23-1]. The introduction and expansion of invasive species, especially those with high migration rates, from outside Europe is likely to increase with climate change [*medium confidence*]

[23.6.4]. Climate change is likely to entail the loss or displacement of coastal wetlands [*high confidence*] [23.6.5]. Climate change threatens the effectiveness of European conservation areas [*low confidence*] [23.6.4], and stresses the need for habitat connectivity through specific conservation policies [23.6.4].

Adaptation

The capacity to adapt in Europe is high compared to other world regions, but there are important differences in impacts and in the capacity to respond between and within the European sub-regions. In Europe, adaptation policy has been developed at international (European Union), national and local government level [23.7], including the prioritisation of adaptation options. There is limited systematic information on current implementation or effectiveness of adaptation measures or policies [Box 23-3]. Some adaptation planning has been integrated into coastal and water management, as well as disaster risk management [23.7.1, 23.7.2, 23.7.3]. There is limited evidence of adaptation planning in rural development or land-use planning [23.7.4, 23.7.5].

Adaptation will incur a cost, estimated from detailed bottom-up sector-specific studies for coastal defences, energy production, energy use, and agriculture [23.7.6]. The costs of adapting buildings (houses, schools, hospitals) and upgrading flood defences increase under all scenarios relative to no climate change [*high confidence*] [23.3.2]. Some impacts will be unavoidable due to limits (physical, technological, social, economic or political) [Table 23-3, 23.7.7].

There is also emerging evidence regarding opportunities and unintended consequences of policies, strategies and measures that address adaptation and/or mitigation goals [23.8]. Some agricultural practices can reduce GHG emissions and also increase resilience of crops to temperature and rainfall variability [23.8.2]. There is evidence for unintended consequences of mitigation policies in the built environment (especially dwellings) and energy sector [*medium confidence*] [23.8.1]. Low carbon policies in the transport and energy sectors to reduce emissions are associated with large benefits to human health [23.8.3] [*high confidence*].

23.1. Introduction

This chapter reviews the scientific evidence published since AR4 on observed and projected impacts of anthropogenic climate change in Europe and adaptation responses. The geographical scope of this chapter is the same as in AR4 with the inclusion of Turkey. Thus, the European region includes all countries from Iceland in the west to Russia (west of the Urals) and the Caspian Sea in the east, and from the northern shores of the Mediterranean and Black Seas and the Caucasus in the south to the Arctic Ocean in the north. Impacts above the Arctic Circle are addressed in the Polar Regions Chapter 28 and impacts in the Baltic and Mediterranean Seas are addressed in the Open Oceans Chapter 30. Impacts in Malta, Cyprus, and other island states in Europe are discussed in the Small Island Chapter 29.

The European region has been divided into 5 sub-regions (see Figure 23-1): Atlantic, Alpine, Southern, Northern, and Continental. The sub-regions are derived by aggregating the climate zones developed by (Metzger *et al.*, 2005) and therefore represent geographical and ecological zones rather than political boundaries. The scientific evidence has been evaluated to compare impacts across (rather than within) sub-regions, although this is not always possible, depending on the scientific information available.

[INSERT FIGURE 23-1 HERE
Figure 23-1: Sub-regional classification of the IPCC Europe region. Based on Metzger et al., 2005.]

23.1.1. Scope and Route Map of Chapter

The chapter is structured around key policy areas. Sections 23.3 to 23.6 summarise the latest scientific evidence on sensitivity climate, observed impacts and attribution, projected impacts and adaptation options, with respect to four main categories of impacts:

- Production systems and physical infrastructure
- Agriculture, fisheries, forestry and bioenergy production
- Health protection and social welfare
- Protection of environmental quality and biological conservation.

The benefit of assessing evidence in a regional chapter is that impacts across sectors can be described, and interactions between impacts can be identified. Further, the cross-sectoral decision making required to address climate change can be reviewed. The chapter also includes sections that were not in AR4. As adaptation and mitigation policy develops, the evidence for potential co-benefits and unintended consequences of such strategies is reviewed (Section 23.8). The final section synthesise the key findings with respect to: observed impacts of climate change, key vulnerabilities and research and knowledge gaps.

The chapter evaluates the scientific evidence in relation to the five sub-regions discussed above. The majority of the research in the Europe region is for impacts in countries in the European Union due to targeted research funding through the European Commission and national governments which means that countries in eastern Europe and Russia are less well represented in this chapter. Further, regional assessments may be reported for the EU15, EU27 or EEA (32) group of countries [Table SM23-1].

23.1.2. Policy Frameworks

Since AR4, there have been significant changes in Europe in responses to climate change. More countries now have adaptation and mitigation policies in place. An important force for climate policy development in the region is the European Union (EU). EU Member States have mitigation targets, as well as the overall EU target, with both sectoral and regional aspects to the commitments.

Adaptation policies and practices have been developed at the international, national and local levels although research on implementation of such policies is limited. Due to the vast range of policies, strategies and measures it is not possible to describe them extensively here. However, adaptation in related to cross-sectoral decision-making is discussed in section 23.7 (see also Box 23-3 on national adaptation policies). The European Climate Adaptation Platform (Climate-ADAPT) catalogues adaptation actions reported by EU Member States (EC, 2013b). The EU Adaptation Strategy was adopted in 2013 (EC, 2013a). See Chapter 15 for a more extensive discussion of institutions and governance in relation to adaptation planning and implementation.

23.1.3. Conclusions from Previous Assessments

AR4 documented a wide range of impacts of observed climate change in Europe (AR4 WG2 Chapter 12). The SREX confirmed increases in warm days, warm nights and decreases in cold days and cold nights since 1950 (*high confidence*, SREX-3.3.1). Extreme precipitation increased in part of the continent, mainly in winter over western-central Europe and European Russia (*medium confidence*, SREX-3.3.2). Dryness has increased mainly in Southern Europe (*medium confidence*, SREX-3.3.2). Climate change is expected to magnify regional differences within Europe for agriculture and forestry because water stress was projected to increase over central and southern Europe (AR4-12.4.1, SREX-3.3.2, SREX-3.5.1). Many climate-related hazard were projected to increase in frequency and intensity, but with significant variations within the region (AR4-12.4).

The AR4 identified that climate changes would pose challenges to many economic sectors and was expected to alter the distribution of economic activity within Europe (*high confidence*). Adaptation measures were evolving from reactive disaster response to more proactive risk management. A prominent example was the implementation of heat health warning systems following the 2003 heat wave event (AR4 WG2 12.6.1, SREX 9.2.1). National adaptation plans were developed and specific plans were incorporated in European and national policies (AR4 WG2 12.2.3, 12.5) but these were not yet evaluated (AR4 WG2 12.8).

23.2. Current and Future Trends

23.2.1 Non- Climate Trends

European countries are diverse in both demographic and economic trends. Population health and social welfare has improved everywhere in Europe, with reductions in adult and child mortality rates, but social inequalities both within and between countries persist (Marmot *et al.*, 2012). Population has increased in most EU27 countries, primarily due to net immigration (Eurostat, 2011a), although population growth is slow (total and working age population) (Rees *et al.*, 2012). Ageing of the population is a significant trend in Europe, as in all high income populations. This will have both economic and social implications, with many regions experiencing a decline in the labour force (Rees *et al.*, 2012). Since AR4, economic growth has slowed or become negative in many countries, leading to a reduction in social protection measures and increased unemployment (Eurostat, 2011b). The longer term implications of the financial crisis in Europe are unclear, although it may lead to a modification of the economic outlook and affect future social protection policies with implications for adaptation.

Europe is one of the world's largest and most productive suppliers of food and fibre (Easterling *et al.*, 2007) and agriculture is the most important European land use by area (45% of the total area) (Rounsevell *et al.*, 2006). After 1945, an unprecedented increase in agricultural productivity occurred, but also declines in agricultural land use areas. This intensification had several negative impacts on the ecological properties of agricultural systems, such as carbon sequestration, nutrient cycling, soil structure and functioning, water purification and pollination. Pollution from agriculture has led to eutrophication and declines in water quality in some areas (ELME, 2007). Most scenario studies suggest that agricultural land areas will continue to decrease in the future (see also (Busch, 2006) for a discussion). Agriculture accounts for 24 % of total national freshwater abstraction in Europe and more than 80 % in some southern European countries (EEA, 2009). Economic restructuring in some eastern European countries has led to a decrease in water abstraction for irrigation, suggesting the potential for future increases in irrigated agriculture and water use efficiency (EEA, 2009).

Forest in Europe covers approximately 35% of the land area (Eurostat, 2009). The majority of forests now grow faster than in the early 20th century due to advances in forest management practices, genetic improvement and in central Europe, the cessation of site-degrading practices such as litter collection for fuel. Increasing temperatures and CO_2 concentrations, nitrogen deposition, and the reduction of air pollution (SO_2) have also had a positive effect on forest growth. Scenario studies suggest that forested areas will increase in Europe in the future on land formerly used for agriculture (Rounsevell *et al.*, 2006). Soil degradation is already intense in parts of the Mediterranean and central-eastern Europe and, together with prolonged drought periods and fires, is already contributing to an increased risk of desertification. Projected risks for future desertification are the highest in these areas (EEA, 2012).

Urban development is projected to increase all over Europe (Reginster and Rounsevell, 2006), but especially rapidly in Eastern Europe, with the magnitude of these increases depending on population growth, economic growth and land use planning policy. Although changes in urban land use will be relatively small in area terms, urban development has major impacts locally on environmental quality. Outdoor air quality has, however, been improving (ELME, 2007). Peri-urbanisation is an increasing trend in which residents move out of cities to locations with a rural character, but retain a functional link to cities by commuting to work (Reginster and Rounsevell, 2006)(Rounsevell and Reay, 2009).

Several European scenario studies have been undertaken to describe European future trends with respect to: socio-economic development (Mooij de and Tang, 2003), land use change (Letourneau *et al.*, 2012; Verburg *et al.*, 2010)(Haines-Young *et al.*, 2012), land use and biodiversity (Spangenberg *et al.*, 2011), crop production (Hermans *et al.*, 2010), demographic change (Davoudi *et al.*, 2010), economic development (Dammers, 2010) and European policy (Helming *et al.*, 2011)(Lennert and Robert, 2010). Many of these scenarios also account for the effects of future climate change (see (Rounsevell and Metzger, 2010) for a review). Long term projections (to the end of the century) are described under the new Shared Socio-economic Pathway scenarios (SSPs) (Kriegler *et al.*, 2010). Detailed country and regional scale socio-economic scenarios have also been produced for the Netherlands (WLO, 2006), the UK (UK National Ecosystem Assessment, 2011) and Scotland (Harrison *et al.*, 2013). The probabilistic representation of socio-economic futures has also been developed for agricultural land use change (Hardacre *et al.*, 2012). There is little evidence to suggest, however, that probabilistic futures or scenarios more generally are being used in policy making (Bryson *et al.*, 2010).

23.2.2. Observed and Projected Climate Change

23.2.2.1. Observed Climate Change

The average temperature in Europe has continued to increase with regionally and seasonally different rates of warming, being greatest in high latitudes in Northern Europe (AR5 WG2 Chapter 28). Since the 1980s, warming has been strongest over Scandinavia, especially in winter, whereas the Iberian Peninsula warmed mostly in summer (EEA, 2012; Haylock *et al.*, 2008). The decadal average temperature over land area for 2002-2011 is 1.3°C+/-0.11°C above the 1850-1899 average, based on HadCRUT3 (Brohan *et al.*, 2006), MLOST (Smith *et al.*, 2008) and GISS Temp (Hansen *et al.*, 2010). See AR5 WG1 Section 2.4 for a discussion of data and uncertainties and AR5 WG2 Chapter 21for observed regional climate change.

Since 1950, high-temperature extremes (hot days, tropical nights, and heat waves) have become more frequent, while low-temperature extremes (cold spells, frost days) have become less frequent (AR5 WG1 Chapter 2.6, SREX-3)(EEA, 2012). The recent cold winters in Northern and Atlantic Europe reflect the high natural variability in the region (Peterson *et al.*, 2012)(AR5 WG1 section 2.7), and do not contradict the general warming trend. In Eastern Europe, including the European part of Russia, summer 2010 was exceptionally hot, with an amplitude and spatial extent that exceeded the previous 2003 heat wave (Barriopedro *et al.*, 2011). Table 23-1 describes the impacts of major extreme events in Europe in the last decade.

Since 1950, annual precipitation has increased in Northern Europe (up to +70 mm/decade) based on Haylock *et al.* (2008), and decreased in parts of Southern Europe (EEA, 2012). Winter snow cover extent has a high inter-annual variability and a non-significant negative trend over the period 1967-2007 (Henderson and Leathers, 2010). Regional observed changes in temperature and precipitation extremes are also described in Table 3-2 of SREX and in Berg *et al.* (2013). Mean wind speeds have declined over Europe over recent decades (Vautard *et al.*, 2010) with *low confidence* due to problematic anemometer data and climate variability (SREX Section 3.3). Bett *et al* (2013) did not find any trend in windspeed using the Twentieth Century Reanalysis.

Europe is marked by increasing mean sea level with regional variations, except in the northern Baltic Sea where the relative sea level decreased due to vertical crustal motion (Albrecht *et al.*, 2011; EEA, 2012; Haigh *et al.*, 2010; Menendez and WoodWorth, 2010). Extreme sea levels have increased due to mean sea level rise (*medium confidence*, SREX Section 3.5, Haigh *et al.*, 2010; Menendez and WoodWorth, 2010). Variability in waves is related to internal climate variability rather than climate trends (SREX Section 3.5, Charles *et al.*, 2012).

23.2.2.2. Projected Climate Changes

For Europe, sub-regional information from global (AR5 WG1 Chapter 14.8.6; AR5 WG1 Annex 1; AR5 WG2 Chapter 21 supplement) and regional high resolution climate model output (AR5 WG1 Chapter 14.8.6; WG2 Chapter 21, 23) provide more knowledge about the range of possible future climates under the SRES and RCP emission scenarios. Within the recognized limitations of climate projections (AR5 WG1 Chapter 9; WG2 Chapter 21), new research on inter-model comparisons has provided a more robust range of future climates to assess future impacts. Since AR4, climate impact assessments are more likely to use a range for the projected changes in temperature and rainfall. Access to comprehensive and detailed sets of climate projections for decision making exist in Europe (SREX Section 3.2.1, (Mitchell *et al.*, 2004)(Fronzek *et al.*, 2012; Jacob *et al.*, 2013).

Climate models show significant agreement for all emission scenarios in warming (magnitude and rate) all over Europe, with strongest warming projected in Southern Europe in summer, and in Northern Europe in winter (Kjellström *et al.*, 2011)(Goodess *et al.*, 2009). Even under an average global temperature increase limited to 2°C compared to pre-industrial times, the climate of Europe is simulated to depart significantly in the next decades from today's climate (Jacob and Podzun, 2010);(Van der Linden and Mitchell, 2009).

Precipitation signals vary regionally and seasonally. Trends are less clear in Continental Europe, with agreement in increase in Northern Europe and decrease in Southern Europe (*medium confidence*) (Kjellström *et al.*, 2011). Precipitation is projected to decrease in the summer months up to Southern Sweden and increase in winter (Schmidli *et al.*, 2007) with more rain than snow in mountainous regions (Steger *et al.*, 2013). In Northern Europe, a decrease of long term mean snow pack (although snow-rich winters will remain) towards the end of the century (Räisänen and Eklund, 2012) is projected. There is lack of information about past and future changes in hail occurrence in Europe. Changes in future circulation patterns (Kreienkamp *et al.*, 2010; Ulbrich *et al.*, 2009) and mean wind speed trends are uncertain in sign (Kjellström *et al.*, 2011)(McInnes *et al.*, 2011).

Regional coupled simulations over the Mediterranean region provide a more realistic characterization of impact parameters (e.g. snow cover, aridity index, river discharge), which were not revealed by CMIP3 global simulations (Dell'Aquila *et al.*, 2012).

For 2081-2100 compared to 1986-2005, projected global mean sea level rises (metres) are in the range 0.29-0.55 for RCP2.6, 0.36-0.63 for RCP4.5, 0.37-0.64 for RCP6.0 and 0.48-0.82 for RCP8.5 (*medium confidence*, AR5 WG3 Chapter 5). There is a *low confidenc*e on projected regional changes (Slangen *et al.*, 2012)(AR5 WG1 13.6). Low probability/high impact estimates of extreme mean sea-level rise projections derived from the A1FI SRES scenario for the Netherlands (Katsman *et al.*, 2011) indicate that the mean sea-level could rise globally between 0.55 and 1.15 m, and locally (the Netherlands) by 0.40 to 1.05 m, by 2100. Extreme (very unlikely) scenarios for the UK vary from 0.9 to 1.9 m by 2100 (Lowe *et al.*, 2009).

23.2.2.3. Projected Changes in Climate Extremes

There will be a marked increase in extremes in Europe, in particular, in heat waves, droughts and heavy precipitation events (Beniston *et al.*, 2007)(Lenderink and Van Meijgaard, 2008) and AR5 WG2 Chapter 21 Supplement. There is a general *high confidence* concerning changes in temperature extremes (toward increased number of warm days, warm nights and heat waves, SREX Table 3-3). Figure 23-2 (upper panels) shows projected changes in the mean number of heat waves in May to September for 2071-2100 compared to 1971-2000 for RCP4.5 and RCP8.5 with large differences depending on the emission scenario. The increase in likelihood of some individual events due to anthropogenic change has been quantified for the 2003 heat wave (Schär and Jendritzky, 2004), the warm winter of 2006/2007 and warm spring of 2007 (Beniston, 2007).

Changes in extreme precipitation depend on the region, with a *high confidence* of increased extreme precipitation in Northern Europe (all seasons) and Continental Europe (except summer). Future projections are regionally and seasonally different in Southern Europe (SREX Table 3-3). Figure 23-2 (middle panels) shows projected seasonal changes of heavy precipitation events for 2071-2100 compared to 1971-2000 for RCP4.5 and RCP8.5.

[INSERT FIGURE 23-2 HERE
Figure 23-2: First row: Projected changes in the mean number of heat waves occurring in the months May to September for the period 2071-2100 compared to 1971-2000 (number per 30 years). Heat waves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season of the control period (1971-2000) by at least 5°C. Second and third rows: Projected seasonal changes in heavy precipitation defined as the 95th percentile of daily precipitation (only days with precipitation > 1mm/day are considered) for the period 2071-2100 compared to 1971-2000 (in %) in the months December to January (DJF) and June to August (JJA). Fourth row: Projected changes in the 95th percentile of the length of dry spells for the period 2071-2100 compared to 1971-2000 (in days). Dry spells are defined as

periods of at least 5 consecutive days with daily precipitation below 1mm. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test). For the eastern parts of Black Sea, Eastern Anatolia and Southeast Anatolia (Turkey), no regional climate model projections are available. Changes represent the mean over 8 (RCP4.5, left side) and 9 (RCP8.5, right side) regional model simulations compiled within the EURO-CORDEX initiative. Adapted from Jacob et al. (2013).]

Projected changes of spatially averaged indices over the European sub-regions (Figure 23-1) are described in the supplemental information (Table SM23-2).

In winter, small increases in extreme wind speed are projected for Central and Northern Europe [*medium confidence*] (AR5 WG2 21.3.3.1.6; SREX Figure 3-8) (Beniston *et al.*, 2007; Haugen and Iversen, 2008; Rauthe *et al.*, 2010; Rockel and Woth, 2007; Schwierz *et al.*, 2010), connected to changes in storm tracks [*medium confidence*] (Pinto *et al.*, 2007a; Pinto *et al.*, 2007b)(Donat *et al.*, 2010)(Pinto *et al.*, 2010). Other parts of Europe and seasons are less clear in sign with a small decreasing trend in southern Europe [*low confidence*] (Donat *et al.*, 2011; McInnes *et al.*, 2011).

Extreme sea level events will increase (*high confidence*, AR5 WG1 13.7, SREX 3.5.3), mainly dominated by the global mean sea level increase. Storm surges are expected to vary along the European coasts. Significant increases are projected in the eastern North Sea (increase of 6-8% of the 99th percentile of the storm surge residual, 2071-2100 compared to 1961-1990, based on the B2, A1B and A2 SRES scenarios) (Debernard and Rÿed, 2008) and west of UK and Ireland (Debernard and Rÿed, 2008)(Wang *et al.*, 2008), except South of Ireland (Wang *et al.*, 2008). There is a *medium agreement* for the South of North Sea and Dutch coast where trends vary from increasing (Debernard and Rÿed, 2008) to stable (Sterl *et al.*, 2009). There is a *low agreement* on the trends in storm surge in the Adriatic sea (Jordà *et al.*, 2012; Lionello *et al.*, 2012; Troccoli *et al.*, 2012b)(Planton *et al.*, 2011).

23.2.3. Observed and Projected Trends in the Riverflow and Drought

Streamflows have decreased in the south and east of Europe and increased in Northern Europe (Stahl *et al.*, 2010)(Wilson *et al.*, 2010) (AR5 WG2 3.2.3). In general, few changes in flood trends can be attributed to climate change, partly due to the lack of sufficiently long records (Kundzewicz *et al.*, 2013). European mean and peak discharges are highly variable (Bouwer *et al.*, 2008); for instance in France, upward trends in low flows were observed over 1948-1988 and downward trends over 1968-2008 (Giuntoli *et al.*, 2013). Alpine glacier retreat during the last two decades caused a 13% increase in glacier contribution to August runoff of the four main rivers originating in the Alps, compared to the long-term average (Huss, 2011). Increases in extreme river discharge (peak flows) over the past 30-50 years have been observed in parts of Germany (Petrow *et al.*, 2009)(Petrow *et al.*, 2007), the Meuse river basin (Tu *et al.*, 2005), parts of Central Europe (Villarini *et al.*, 2011), Russia (Semenov, 2011), and Northeastern France (Renard *et al.*, 2008). Decreases in extreme river discharge have been observed in the Czech Republic (Yiou *et al.*, 2006), and no change observed in Switzerland (Schmocker-Fackel and Naef, 2010), Germany (Bormann *et al.*, 2011), and the Nordic countries (Wilson *et al.*, 2010). River regulation possibly partly masks increasing peak flows in the Rhine (Vorogushyn *et al.*, 2012). One study (Pall *et al.*, 2011) suggested that the UK 2000 flood was partly due to anthropogenic forcing, although another showed a weaker effect (Kay *et al.*, 2011).

Climate change is projected to affect the hydrology of river basins (SREX Chapter 3; AR5 WG2 Chapter 4). The occurrence of current 100-year return period discharges is projected to increase in Continental Europe, but decrease in some parts of Northern and Southern Europe by 2100 (Dankers and Feyen, 2008)(Rojas *et al.*, 2012). In contrast, studies for individual catchments indicate increases in extreme discharges, to varying degrees, in Finland (Veijalainen *et al.*, 2010), Denmark (Thodsen, 2007), Ireland (Wang *et al.*, 2006)(Steele-Dunne *et al.*, 2008)(Bastola *et al.*, 2011), the Rhine basin (Görgen *et al.*, 2010; Te Linde *et al.*, 2010a), Meuse basin (Leander *et al.*, 2008)(Ward *et al.*, 2011), the Danube basin (Dankers *et al.*, 2007), and France (Chauveau *et al.*, 2013; Quintana-Segui *et al.*, 2011). Although snowmelt floods may decrease, increased autumn and winter rainfall could lead to higher peak discharges in northern Europe (Lawrence and Hisdal, 2011). Declines in low flows are projected for the UK

(Christierson *et al.*, 2012), Turkey (Fujihara *et al.*, 2008), France (Chauveau *et al.*, 2013), and rivers fed by Alpine glaciers (Huss, 2011).

The analysis of trends in droughts is made complex by the different categories or definitions of drought (meteorological, agricultural, and hydrological) and the lack of long-term observational data (SREX Box 3-3). Southern Europe shows trends towards more intense and longer meteorological droughts, but they are still inconsistent (Sousa *et al.*, 2011). Drought trends in all other sub-regions are not statistically significant (SREX 3.5.1). Regional and global climate simulations project (*medium confidence*) an increase in duration and intensity of droughts in central and southern Europe and the Mediterranean up until the UK for different definitions of drought (Feyen and Dankers, 2009; Gao and Giorgi, 2008; Vidal and Wade, 2009)(Koutroulis *et al.*, 2010; Tsanis *et al.*, 2011) (AR5 WG2 Chapter 21). Even in regions where summer precipitation is expected to increase, soil moisture and hydrological droughts may become more severe due to increasing evapotranspiration (Wong *et al.*, 2011). Projected changes in the length of meteorological dry spells show that the increase is large in Southern Europe (Figure 23-2 fourth row).

23.3. Implications of Climate Change for Production Systems and Physical Infrastructure

23.3.1. Settlements

23.3.1.1. Coastal Flooding

As the risk of extreme sea level events increases with climate change [23.2.3, AR5 WG2 Chapter 5], coastal flood risk will remain a key challenge for several European cities, port facilities and other infrastructure (Nicholls *et al.*, 2008)(Hallegatte *et al.*, 2008)(Hallegatte *et al.*, 2011). With no adaptation, coastal flooding in the 2080s is projected to affect an additional 775,000 and 5.5 million people per year in the EU27 (B2 and A2 scenarios) (Ciscar *et al.*, 2011). The Atlantic, Northern and Southern European regions are projected to be most affected. Direct costs from sea level rise in the EU27 without adaptation could reach 17 billion Euros per year by 2100 (Hinkel *et al.*, 2010), with indirect costs also estimated for land-locked countries (Bosello *et al.*, 2012). Countries with high absolute damage costs include the Netherlands, Germany, France, Belgium, Denmark, Spain and Italy (Hinkel *et al.*, 2010). Upgrading coastal defences would substantially reduce impacts and damage costs (Hinkel *et al.*, 2010). However, the amount of assets and populations that need to protected by coastal defences is increasing, thus, the magnitude of losses when floods do occur will also increase in the futre (Hallegatte et al. 2013), entailing the need to prepare for very large flood disasters in the future.

An increase in future flood losses due to climate change have been estimated for Copenhagen (Hallegatte *et al.*, 2011), the UK coast (Mokrech *et al.*, 2008)(Purvis *et al.*, 2008)(Dawson *et al.*, 2011), the North Sea coast (Gaslikova *et al.*, 2011), cities including Amsterdam and Rotterdam (Hanson *et al.*, 2011), and the Netherlands (Aerts *et al.*, 2008). A 1m sea-level rise in Turkey could affect 3 million additional people and put 12 billion USD capital value at risk, with around 20 billion USD adaptation costs (10% of GNP) (Karaca and Nicholls, 2008). In Poland, up to 240,000 people would be affected by increasing flood risk on the Baltic coast (Pruszak and Zawadzka, 2008). The increasing cost of insurance and unwillingness of investors to place assets in affected areas is a potential growth impediment to coastal and island economies (Day *et al.*, 2008).

23.3.1.2. River and Pluvial Flooding

Recent major flood events in Europe include the 2007 floods in the UK (Table 23-1) (Chatterton *et al.*, 2010) and the 2013 floods in Germany. The observed increase in river flood events and damages in Europe is well documented (see AR5 WG2 18.4.2.1), however, the main cause is increased exposure of persons and property in flood risk areas (Barredo, 2009). Since AR4, new studies provide a wider range of estimates of future economic losses from river flooding attributable to climate change, depending on the modelling approach and climate scenario (Bubeck *et al.*, 2011). Studies now also quantify risk under changes in population and economic growth, generally indicating this contribution to be about equal or larger than climate change per se (Feyen *et al.*, 2009; Maaskant *et al.*, 2009; Rojas *et al.*, 2013)(Bouwer *et al.*, 2010)(Te Linde *et al.*, 2011). Some regions may see increasing risks, but others may see decreases or little to no change (Bubeck *et al.*, 2011)(ABI, 2009)(Feyen *et al.*, 2009)(Lugeri *et al.*, 2010)(Mechler *et al.*, 2010)(Feyen *et al.*, 2012)(Lung *et al.*, 2012). In the EU15, river flooding could affect 250,000-400,000 additional people by the 2080s (SRES A2 and B2 scenarios) and more than doubling annual average damages, with Central and Northern Europe and the UK most affected (Ciscar, 2009)(Ciscar *et al.*, 2011). When economic growth is included, economic flood losses in Europe could increase 17-fold under the A1B climate scenario (Rojas *et al.*, 2013).

Few studies have estimated future damages from inundation in response to an increase in intense rainfall (Hoes, 2006; Willems *et al.*, 2012). Processes that influence flash flood risk include increasing exposure from urban expansion, and forest fires that lead to erosion and increased surface runoff (Lasda *et al.*, 2010). Some studies have costed adaptation measures but these may only partly offset anticipated impacts (Zhou *et al.*, 2012).

[INSERT Table 23-1 HERE
Table 23-1: Impacts of climate extremes in the last decade in Europe.]

23.3.1.3. Windstorms

Several studies project an overall increase storm hazard in northwest Europe [23.2.2.3] and in economic and insured losses [AR5 WG2 Chapter 17.7.3], but natural variations in frequencies are large. There is no evidence that the observed increase in European storm losses is due to anthropogenic climate change (Barredo, 2010). There is a lack of information for other storm types, such as tornadoes and thunderstorms.

23.3.1.4. Mass Movements and Avalanches

In the European Alps, the frequency of rock avalanches and large rock slides has apparently increased over the period 1900-2007 (Fischer *et al.*, 2012). The frequency of landslides may also have increased in some locations (Lopez Saez *et al.*, 2013). Mass movements are projected to become more frequent with climate change (Huggel *et al.*, 2010; Stoffel and Huggel, 2012), although several studies indicate a more complex or stabilising response of mass movements to climate change (Dixon and Brook, 2007; Huggel *et al.*, 2012; Jomelli *et al.*, 2007; Jomelli *et al.*, 2009; Melchiorre and Frattini, 2012). Some land-use practices have led to conditions favourable to increased landslide risk, despite climate trends that would result in a decrease of landslide frequency, as reported in Calabria (Polemio and Petrucci, 2010) and in the Apennines (Wasowski *et al.*, 2010). Snow avalanche frequency changes in Europe are dominated by climate variability; studies based on avalanche observations (Eckert *et al.*, 2010) or favourable meteorological conditions (Castebrunet *et al.*, 2012; Teich *et al.*, 2012) show contrasting variations, depending on the region, elevation, season and orientation.

23.3.2. Built Environment

Built infrastructure in Europe is vulnerable to extreme weather events, including overheating of buildings (houses, hospitals, schools) during hot weather (Crump *et al.*, 2009; DCLG, 2012). Buildings that were originally designed for certain thermal conditions will need to function in warmer climates in the future (WHO, 2008). Climate change in Europe is expected to increase cooling energy demand (23.3.4) (Dolinar *et al.*, 2010), with implications for mitigation and adaptation policies (23.8.1). A range of adaptive strategies for buildings are available, including effective thermal mass and solar shading (ARUP, 2008). Climate change may also increase the frequency and intensity of drought-induced soil subsidence and associated damage to dwellings (Corti *et al.*, 2009).

With respect to the outdoor built environment, there is limited evidence regarding the potential for differential rates of radiatively-forced climate change in urban compared to rural areas (McCarthy *et al.*, 2010). Climate change may exacerbate London's nocturnal urban heat island (UHI) (Wilby, 2008), however, the response of different cities may vary. For example, a study of Paris (Lemonsu *et al.*, 2013) indicated a future reduction in strong urban heat island events when increased soil dryness was taken into effect. Modification of the built environment, via enhanced urban greening, for example, can reduce temperatures in urban areas, with co-benefits for health and wellbeing (23.7.4, 23.8.1).

23.3.3. Transport

Systematic and detailed knowledge on climate change impacts on transport in Europe remains limited (Koetse and Rietveld, 2009).

On *road transport*, in line with AR4, more frequent but less severe collisions due to reduced speed are expected in case of increased precipitation (Brijs *et al.*, 2008)(Kilpeläinen and Summala, 2007). However, lower traffic speed may cause welfare losses due to additional time spent driving (Sabir *et al.*, 2010). Severe snow and ice-related accidents will also decrease, but the effect of fewer frost days on total accidents is unclear (Andersson and Chapman, 2011a)(Andersson and Chapman, 2011b). Severe accidents caused by extreme weather are projected to decrease by 63-70% in 2040-2070 compared to 2007 as a result of modified climate and expected developments in vehicle technology and emergency systems (Nokkala *et al.*, 2012).

For *rail*, consistent with AR4, increased buckling in summer, as occurred in 2003 in the UK, is expected to increase the average annual cost of heat-related delays in some regions, while the opposite is expected for ice and snow-related delays (Dobney *et al.*, 2010; Lindgren *et al.*, 2009; Palin *et al.*, 2013). Effects from extreme precipitation, as well as the net overall regional impact of climate change remain unclear. Efficient adaptation comprises proper maintenance of track and track bed.

Regarding *inland waterways*, the case of Rhine shows that for 1-2 °C increases by 2050 more frequent high water levels are expected in winter, while after 2050 days with low water levels in summer will also increase (Jonkeren *et al.*, 2011)(Te Linde *et al.*, 2011)(Te Linde, 2007)(Hurkmans *et al.*, 2010). Low water levels will reduce the load factor of inland ships and consequently increase transport prices, as in the Rhine and Moselle in 2003 (Jonkeren, 2009)(Jonkeren *et al.*, 2007). Adaptation includes modal shifts, increase navigational hours per day under low water levels, and infrastructure modifications (e.g. canalization of river parts) (Jonkeren *et al.*, 2011; Krekt *et al.*, 2011).

For *long range ocean routes*, the economic attractiveness of the Northwest Passage and the Northern Sea Route depends also on passage fees, bunker prices and cost of alternative sea routes (Verny and Grigentin, 2009)(Liu and Kronbak, 2010)(Lasserre and Pelletier, 2011). Regarding *air transport*, for Heathrow airport in the UK, future temperature and wind changes were estimated to cause a small net annual increase but much larger seasonal changes on the occurrence of delays (Pejovic *et al.*, 2009).

23.3.4. Energy Production, Transmission, and Use

On *wind energy*, no significant changes are expected before 2050, at least in Northern Europe (Pryor and Schoof, 2010)(Pryor and Barthelmie, 2010)(Seljom *et al.*, 2011)(Barstad *et al.*, 2012; Hueging *et al.*, 2013). After 2050, in line with AR4, the wind energy potential in Northern, Continental and most of Atlantic Europe may increase during winter and decrease in summer (Harrison *et al.*, 2008; Hueging *et al.*, 2013)(Nolan *et al.*, 2012; Rockel and Woth, 2007). For Southern Europe, a decrease in both seasons is expected, except for the Aegean Sea and Adriatic coast where a significant increase during summer is possible (Bloom *et al.*, 2008; Hueging *et al.*, 2013; Najac *et al.*, 2011; Pašičko *et al.*, 2012).

For *hydropower*, electricity production in Scandinavia is expected to increase by 5-14% during 2071-2100 compared to historic or present levels (Golombek *et al.*, 2012) (Haddeland *et al.*, 2011); for 2021-2050, increases by 1-20% were estimated (Haddeland *et al.*, 2011)(Hamududu and Killingtveit, 2012; Seljom *et al.*, 2011). In Continental, and part of Alpine Europe, reductions in electricity production by 6-36% were estimated (Schaefli *et al.*, 2007) (Paiva *et al.*, 2011; Pašičko *et al.*, 2012)(Hendrickx and Sauquet, 2013; Stanzel and Nachtnebel, 2010). For Southern Europe, production is expected to decrease by 5-15% in 2050 compared to 2005 (Bangash *et al.*, 2013; Hamududu and

Killingtveit, 2012). Adaptation consists in improved water management, including pump storage if appropriate (Schaefli *et al.*, 2007)(García-Ruiz *et al.*, 2011).

Biofuel production is discussed in section 23.4.5. There are few studies of impacts on solar energy production. Crook et al. (2011) estimated an increase of the energy output from photovoltaic panels and especially from concentrated solar power plants in most of Europe under the A1B scenario.

On *thermal power*, in line with AR4, van Vliet et al. (2012) estimated a 6-19% decrease of the summer average usable capacity of power plants by 2031–2060 compared to 1971-2000, while smaller decreases have been also estimated (Linnerud *et al.*, 2011)(Förster and Lilliestam, 2010). Closed-cooling circuits are efficient adaptation choices for new plants (Koch and Vögele, 2009). In *power transmission*, increasing lightning and decreasing snow-sleet-and blizzard faults for 2050-2080 were estimated for the UK (McColl *et al.*, 2012).

By considering both heating and cooling, under a +3.7 ^{o}C scenario by 2100 a decrease of *total annual energy demand* in Europe as a whole during 2000-2100 was estimated (Isaac and van Vuuren, 2009). Seasonal changes will be prominent, especially for electricity (see Figure 23-3), with summer peaks arising also in countries with moderate summer temperatures (Hekkenberg *et al.*, 2009). Heating degree days are expected to decrease by 11-20% between 2000 and 2050 due solely to climate change (Isaac and van Vuuren, 2009). For cooling, very large percentage increases up to 2050 are estimated by the same authors for most of Europe as the current penetration of cooling devices is low; then, increases by 74-118% in 2100 (depending on the region) from 2050 are expected under the combined effect of climatic and non-climatic drivers. In Southern Europe, cooling degree days by 2060 will increase, while heating degree days will decrease but with substantial spatial variations (Giannakopoulos *et al.*, 2009). Consequently, net annual electricity generation cost will increase in most of the Mediterranean and decrease in the rest of Europe (Eskeland and Mideksa, 2010)(Mirasgedis *et al.*, 2007)(Pilli-Sihlova *et al.*, 2010; Zachariadis, 2010). Future building stock changes and retrofit rates are critical for impact assessment and adaptation (Olonscheck *et al.*, 2011). Energy efficient buildings and cooling systems, and demand-side management are effective adaptation options (Artmann *et al.*, 2008; Breesch and Janssens, 2010; Chow and Levermore, 2010; Day *et al.*, 2009; Jenkins *et al.*, 2008).

[INSERT FIGURE 23-3 HERE
Figure 23-3: Percentage change in electricity demand in Greece attributable to climate change, under a range of climate scenarios and economic assumptions. Source: Mirasgedis et al., 2007.]

23.3.5. Industry and Manufacturing

Research on the potential effects of climate change in industry is limited. Modifications in future consumption of food and beverage products have been estimated on the basis of current sensitivity to seasonal temperature (Mirasgedis *et al.*, 2013). Higher temperatures may favour the growth of food borne pathogens or contaminants (Jacxsens *et al.*, 2010; Popov Janevska *et al.*, 2010) (see also 23.5.1). The quality of some products, such as wine (23.4.1, Box 23-2), is also likely to be affected. In other sectors, the cumulative cost of direct climate change impacts in the Greek mining sector for 2021-2050 has been estimated at 0.245 billion Euros, in 2010 prices (Damigos, 2012). Adaptation to buildings or work practices are likely to be needed in order to maintain labour productivity during hot weather (Kjellstrom *et al.*, 2009)(11.6.2.2).

23.3.6. Tourism

In line with AR4, the climate for general tourist activities especially after 2070 is expected to improve significantly during summer and less during autumn and spring in northern Continental Europe, Finland, southern Scandinavia and southern England (Amelung and Moreno, 2012)(Amelung *et al.*, 2007)(Nicholls and Amelung, 2008). For the Mediterranean, climatic conditions for light outdoor tourist activities are expected to deteriorate in summer mainly after 2050, but improve during spring and autumn (Amelung and Moreno, 2009)(Hein *et al.*, 2009)(Perch-Nielsen *et al.*, 2010)(Amelung *et al.*, 2007)(Giannakopoulos *et al.*, 2011). Others concluded that before 2030 (or even 2060) this region as a whole will not become too hot for beach or urban tourism (Moreno and Amelung, 2009)(Rutty and Scott, 2010), while surveys showed that beach tourists are deterred mostly by rain (De Freitas *et al.*, 2008; Moreno, 2010).

Thus, from 2050, domestic tourism and tourist arrivals at locations in Northern and parts of Continental Europe may be enhanced at the expense of Southern locations (Amelung and Moreno, 2012; Bujosa and Roselló, 2012; Hamilton and Tol, 2007; Hein *et al.*, 2009). The age of tourists, the climate in their home country, local economic and environmental conditions (e.g. water stress, tourist development) are also critical (Hamilton and Tol, 2007)(Moreno and Amelung, 2009; Perch-Nielsen *et al.*, 2010)(Eugenio-Martin and Campos-Soria, 2010; Lyons *et al.*, 2009)(Rico-Amoros *et al.*, 2009).

Tourism in mountainous areas may benefit from improved climatic conditions in summer (Endler *et al.*, 2010; Endler and Matzarakis, 2011b; Perch-Nielsen *et al.*, 2010; Serquet and Rebetez, 2011). However, in agreement with AR4, natural snow reliability and thus ski season length will be adversely affected, especially where artificial snowmaking is limited (OECD, 2007; Steiger, 2011)(Moen and Fredman, 2007). Low-lying areas will be the most vulnerable (Endler *et al.*, 2010; Endler and Matzarakis, 2011a; Serquet and Rebetez, 2011; Steiger, 2011; Uhlmann *et al.*, 2009). Tourist response to marginal snow conditions remains largely unknown, while changes in weather extremes may also be critical (Tervo, 2008). Up to 2050, demographic changes (e.g. population declines in source countries, ageing populations) may have a higher impact than climate change (Steiger, 2012). Artificial snowmaking has physical and economic limitations, especially in small sized and low-altitude ski stations (Sauter *et al.*, 2010; Steiger and Mayer, 2008; Steiger, 2010; Steiger, 2011), and increases water and energy consumption. Shifts to higher altitudes, operational/ technical measures and year-round tourist activities may not fully compensate for adverse impacts.

23.3.7. Insurance and Banking

Insurance and banking face problems related to accurate pricing of risks, shortage of capital after large loss events, and by an increasing burden of losses that can affect markets and insurability, within but also outside the European region (Botzen *et al.*, 2010a; Botzen *et al.*, 2010b; CEA, 2007)(AR5 WG2 Section 10.7). However, risk transfer including insurance also holds potential for adaptation by providing incentives to reduce losses (Botzen and van den Bergh, 2008; CEA, 2009)(Herweijer *et al.*, 2009).

Banking is potentially affected through physical impacts on assets and investments, as well as through regulation and/or mitigation actions by changing demands regarding sustainability of investments and lending portfolios. Few banks have adopted climate strategies that also address adaptation (Furrer *et al.*, 2009)(Cogan, 2008).

Windstorm losses are well covered in Europe by building and motor policies, and thus create a large exposure to the insurance sector. Flood losses in the UK in 2000, 2007 and 2009 have put the insurance market under further pressure, with increasing need for the government to reduce risk (Ward *et al.*, 2008)(Lamond *et al.*, 2009). Other risks of concern to the European insurance industry is building subsidence related to drought (Corti *et al.*, 2009), and hail damage to buildings and agriculture (Kunz *et al.*, 2009; Botzen *et al.*, 2010b; GIA, 2011).

The financial sector can adapt through adjustment of premiums, restricting or reduction of coverage, further risk spreading, and importantly incentivising risk reduction (Botzen *et al.*, 2010a; Clemo, 2008)(Crichton, 2007)(Crichton, 2006)(Wamsler and Lawson, 2011)(Surminski and Philp, 2010). Public attitudes in Scotland and the Netherlands would support insurance of private property and public infrastructure damages in the case of increasing flood risk (Botzen *et al.*, 2009)(Glenk and Fisher, 2010). Government intervention is however often needed to provide compensation and back-stopping in the event of major losses (Aakre and Rübbelke, 2010; Aakre *et al.*, 2010). Hochrainer *et al.* (2010) analysed the performance of the EU Solidarity Fund that supports European governments in large events, and argue there is a need to increase its focus on risk reduction. Current insurance approaches present in Europe are likely to remain, as they are tailored to local situations and preferences (Schwarze *et al.*, 2011).

23.4. Implications of Climate Change for Agriculture, Fisheries, Forestry, and Bioenergy Production

23.4.1. Plant (Food) Production

In AR4, Alcamo et al. (2007) reported that crop suitability is likely to change throughout Europe. During the 2003 and 2010 summer heat waves, grain-harvest losses reached 20 and 30% in affected regions of Europe and Russia, respectively (Barriopedro *et al.*, 2011; Ciais *et al.*, 2005) (Table 23-1). Cereals production fell on average by 40% in the Iberian Peninsula during the intense 2004/2005 drought (EEA, 2010a). Climate-induced variability in wheat production has increased in recent decades in Southern and Central Europe (Brisson *et al.*, 2010)(Hawkins *et al.*, 2013)(Ladanyi, 2008), but no consistent reduction has been recorded in the northernmost areas of Europe (Peltonen-sainio *et al.*, 2010). Country-scale rainfed cereals yields are below agro-climatic potentials (Supit *et al.*, 2010) and wheat yield increases have levelled off in several countries over 1961-2009 (Olesen *et al.*, 2011). High temperatures and droughts during grain filling has contributed to the lack of yield increase of winter wheat in France despite improvements in crop breeding (Brisson *et al.*, 2010; Kristensen *et al.*, 2011). In contrast, in eastern Scotland, warming has favoured an increase in potato yields since 1960 (Gregory and Marshall, 2012). In north-east Spain, grape yield was reduced by an increased water deficit in the reproductive stage since the 1960s (Camps and Ramos, 2012).

Insight into the potential effect of climate change on crops requires the combination of a wide range of emission scenarios, global circulation models (GCM) and impact studies (Trnka *et al.*, 2007)(Soussana *et al.*, 2010). In the EU27, a 2.5 °C regional temperature increase in the 2080s under the B2 scenario could lead to small changes (on average +3%) in crop yields, whereas a 5.4 °C regional warming under the A2 scenario could reduce mean yields by 10% according to a study based on regional climate models (Ciscar *et al.*, 2011). An initial benefit from the increasing CO_2 concentration for rainfed crop yields would contrast by the end of the century with yield declines in most European subregions, although wheat yield could increase under the A2 scenario (Supit *et al.*, 2012, three GCMs, B1, A2 scenarios). Disease-limited yields of rain fed wheat and maize in the 2030s does not show consistent trends across two GCMs (Donatelli *et al.*, 2012). For a global temperature increase of 5° C, agroclimatic indices show an increasing frequency of extremely unfavourable years in European cropping areas (Trnka *et al.*, 2011). Under the A2 and B2 scenarios, crop production shortfalls, defined as years with production below 50% of its average climate normal production would double by 2020 and triple by 2070 as compared to a current frequency of 1-3 years per decade in the currently most productive southern European regions of Russia (Alcamo *et al.*, 2007).

The regional distribution of climate change impacts on agricultural production is likely to vary widely (Iglesias *et al.*, 2012) (Donatelli *et al.*, 2012) (Figure 23-4). Southern Europe would experience the largest yield losses (-25 % by 2080 under a 5.4 °C warming, (Ciscar *et al.*, 2011) with increased risks of rain fed summer crop failure (Bindi and Olesen, 2011)(Ferrara *et al.*, 2010)(Ruiz-Ramos *et al.*, 2011). Warmer and drier conditions by 2050 (Trnka *et al.*, 2010; Trnka *et al.*, 2011) would cause moderate declines in crop yields in Central Europe regions (Ciscar *et al.*, 2011). In Western Europe, increased heat stress around flowering could cause considerable yield losses in wheat (Semenov, 2009). For Northern Europe, there is diverging evidence concerning future impacts. Positive yield changes combined with the expansion of climatically suitable areas could lead to crop production increases (between 2.5 and 5.4°C regional warming) (Bindi and Olesen, 2011)(Bindi and Olesen, 2011). However, increased climatic variability would limit winter crops expansion (Peltonen-Sainio *et al.*, 2010) and cause at high latitudes high risk of marked cereal yield loss (Rötter *et al.*, 2011). Spring crops from tropical origin like maize for silage could become cultivated in Finland by the end of the century (Peltonen-Sainio *et al.*, 2009). Cereal yield reduction from ozone (Fuhrer, 2009) could reach 6 and 10 % in 2030 for the European Union with the B1 and A2 scenarios, respectively (Avnery *et al.*, 2011a; Avnery *et al.*, 2011b). Because of limited land availability and soil fertility outside of Chernozem (black earth) areas, the shift of agriculture to the boreal forest zone would not compensate for crop losses due to increasing aridity in South European regions of Russia with the best soils (Dronin and Kirilenko, 2011).

[INSERT FIGURE 23-4 HERE
Figure 23-4: Percentage change in simulated water-limited yield for winter wheat in 2030 with respect to the 2000 baseline for the A1B scenario using ECHAM5 (left column) and HadCM3 (right) GCMs. Upper maps to do not take adaptation into account. Bottom maps include adaptation. Source: Donatelli et al., 2012.]

With generally warmer and drier conditions, deep rooted weeds (Gilgen *et al.*, 2010b) and weeds with contrasting physiology, such as C_4 species, could pose a more serious threat (Bradley *et al.*, 2010) to crops than shallow rooted C_3 weeds (Stratonovitch, 2012). Arthropod-borne diseases (viruses and phytoplasmas), winter infection root and stem diseases (phoma stem canker of oilseed rape and eyespot of wheat) (Butterworth *et al.*, 2010)(West *et al.*, 2012), *Fusarium* blight (Madgwick *et al.*, 2011), grapevine moth (Caffarra *et al.*, 2012) and a black rot fungus in fruit trees (Weber, 2009) could create increasing damages in Europe under climate change. However, other pathogens like cereal stem rots (e.g. *Puccinia striiformis*) (Luck *et al.*, 2011) and grapevine powdery mildew (Caffarra *et al.*, 2012) could be limited by increasing temperatures. Increased damages from plant pathogens and insect pests are projected by 2050 in Nordic countries which have hitherto been protected by cold winters and geographic isolation (Hakala *et al.*, 2011; Roos *et al.*, 2011). Some pests, like the European corn borer (Trnka *et al.*, 2007), could also extend their climate niche in Central Europe. Pests and disease management will be affected with regard to timing, preference and efficacy of chemical and biological measures of control (Kersebaum *et al.*, 2008).

Autonomous adaptation by farmers, through the advancement of sowing and harvesting dates and the use of longer cycle varieties (Howden *et al.*, 2007; Moriondo *et al.*, 2011; Moriondo *et al.*, 2010; Olesen *et al.*, 2011) could result in a general improvement of European wheat yields in the 2030s compared to the 2000s (Donatelli *et al.*, 2012) (Figure 23-4). However, farmer sowing dates seem to advance slower than crop phenology (Menzel *et al.*, 2006)(Siebert and Ewert, 2012), possibly because earlier sowing is often prevented by lack of soil workability and frost-induced soil crumbling (Oort *et al.*, 2012). Simulation studies which anticipate on earlier sowing in Europe may thus be overly optimistic. Further adaptation options include: changes in crop species, fertilization, irrigation, drainage, land allocation and farming system (Bindi and Olesen, 2011). At the high range of the projected temperature changes, only plant breeding aimed at increasing yield potential jointly with drought resistance and adjusted agronomic practices may reduce risks of yield shortfall (Olesen *et al.*, 2011)(Rötter *et al.*, 2011)(Ventrella *et al.*, 2012). Crop breeding is, however, challenged by temperature and rainfall variability, since: i) breeding has not yet succeeded in altering crop plant development responses to short-term changes in temperature (Parent and Tardieu, 2012) and ii) distinct crop drought tolerance traits are required for mild and severe water deficit scenarios (Tardieu, 2012). Adaptation to increased climatic variability may require an increased use of between and within species genetic diversity in farming systems (Smith and Olesen, 2010) and the development of insurance products against weather-related yield variations (Musshoff *et al.*, 2011). Adaptive capacity and long term economic viability of farming systems may vary given farm structural change induced by climate change (Mandryk *et al.*, 2012); (Moriondo *et al.*, 2010b). In Southern Europe, the regional welfare loss caused by changes in the agriculture sector under a high warming scenario (+5.4°C) was estimated at 1% of GDP. Northern Europe was the single sub-region with welfare gains (+0.7%) from agriculture in this scenario (Ciscar *et al.*, 2011).

23.4.2. Livestock Production

Livestock production is adversely affected by heat (Tubiello *et al.*, 2007)(AR5 WG2 7.2.1.3). With intensive systems, heat stress reduced dairy production and growth performance of large finishing pigs at daily mean air temperatures above 18 and 21°C, respectively (André *et al.*, 2011; Renaudeau *et al.*, 2011). High temperature and air humidity during breeding increased cattle mortality risk by 60% in Italy (Crescio *et al.*, 2010). Adaptation requires changes in diets and in farm buildings (Renaudeau *et al.*, 2012) as well as targeted genetic improvement programmes (Hoffmann, 2010).

With grass based livestock systems, model simulations (A1B scenario, ensemble of downscaled GCMs) show by end of century increases in potential dairy production in Ireland and France, however with higher risks of summer-autumn production failures in Central Europe and at French sites (Graux *et al.*, 2012; Trnka *et al.*, 2009). Climate conditions projected for the 2070s in central France (A2 scenario) reduced significantly grassland production in a four years experiment under elevated CO_2 (Cantarel *et al.*, 2013). At the same site, a single experimental summer drought altered production during the next two years (Zwicke *et al.*, 2013). Resilience of grassland vegetation structure was observed to prolonged experimental heating and water manipulation (Grime *et al.*, 2008). However, weed pressure from tap-rooted forbs was increased after severe experimental summer droughts (Gilgen *et al.*, 2010a). Mediterranean populations could be used to breed more resilient and better adapted forage plant material for livestock production (Poirier *et al.*, 2012).

Climate change has affected animal health in Europe [*high confidence*]. The spread of bluetongue virus in sheep across Europe has been partly attributed to climate change (Arzt *et al.*, 2010)(Guis *et al.*, 2012) through increased seasonal activity of the *Culicoides* vector (Wilson and Mellor, 2009). The distribution of this vector is unlikely to expand but its abundance could increase in Southern Europe (Acevedo *et al.*, 2010). Ticks, the primary arthropod vectors of zoonotic diseases in Europe (e.g. Lyme disease and tick-borne encephalitis), have changed distributions towards higher altitudes and latitudes with climate change (van Dijk *et al.*, 2010)(Petney *et al.*, 2012; Randolph and Rogers, 2010)(AR5 WG2 23.5). Exposure to fly strike could increase in a warmer climate but adaptation in husbandry practices would limit impacts on livestock (Wall and Ellse, 2011). The overall risk of incursion of Crimean-Congo haemorrhagic fever virus in livestock through infected ticks introduced by migratory bird species would not be increased by climate change (Gale *et al.*, 2012). The probability of introduction and large-scale spread of Rift Valley Fever in Europe is also very low (Chevalier *et al.*, 2010). Epidemiological surveillance and increased coordinated regional monitoring and control programmes have the potential to reduce the incidence of vector-borne animal diseases (Chevalier *et al.*, 2010) (Wilson and Mellor, 2009).

23.4.3. Water Resources and Agriculture

Future projected trends confirm the widening of water resource differences between Northern and Southern Europe reported in AR4 (Alcamo *et al.*, 2007). In Southern Europe, soil water content will decline, saturation conditions and drainage will be increasingly rare and restricted to periods in winter and spring, and snow accumulation and melting will change, especially in the mid-mountain areas (García-Ruiz *et al.*, 2011). Across most of Northern and Continental Europe, an increase in flood hazards (Falloon and Betts, 2010)(23.3.1) could increase damages to crops and plant growth, complicate soil workability, and increase yield variability (Olesen *et al.*, 2011). Groundwater recharge and/or water table level would be significantly reduced by the end of the century under A2 scenario for river basins located in Southern Italy, Spain, Northern France and Belgium (Ducharne *et al.*, 2010; Goderniaux *et al.*, 2011; Guardiola-Albert and Jackson, 2011; Senatore *et al.*, 2011). However, non-significant impacts were found for aquifers in Switzerland and in England (Stoll *et al.*, 2011)(Jackson *et al.*, 2011). Less precipitation in summer and higher rainfall during winter could increase nitrate leaching (Kersebaum *et al.*, 2008) with negative impacts on water quality (Bindi and Olesen, 2011). Even with reduced N fertilizer application, groundwater nitrate concentrations would increase by the end of the century in the Seine river basin (Ducharne *et al.*, 2007). More robust water management, pricing and recycling policies, in order to secure adequate future water supply and prevent tensions among users could be required in Southern Europe (García-Ruiz *et al.*, 2011).

Reduced suitability for rainfed agricultural production (Daccache and Lamaddalena, 2010; Daccache *et al.*, 2012; Henriques *et al.*, 2008; Trnka *et al.*, 2011) will increase water demand for crop irrigation (Savé *et al.*, 2012). However, increased irrigation may not be a viable option, especially in the Mediterranean area, because of projected declines in total runoff and groundwater resources (Olesen *et al.*, 2011). In a number of catchments water resources are already over-licensed and/or over-abstracted (Daccache *et al.*, 2012) and their reliability is threatened by climate change induced decline in groundwater recharge and to a lesser extent by the increase in potential demand for irrigation (Ducharne *et al.*, 2010; Majone *et al.*, 2012). To match this demand, irrigation system costs could increase by 20-27% in Southern Italy (Daccache and Lamaddalena, 2010) and new irrigation infrastructures would be required in some regions (van der Velde *et al.*, 2010) However, since the economic benefits are expected to be small, the adoption of irrigation would require changes in institutional and market conditions (Finger *et al.*, 2011). Moreover, since aquatic and terrestrial ecosystems are affected by agricultural water use (Kløve *et al.*, 2011), irrigation demand restrictions are projected in environmentally focussed future regional scenarios (Henriques *et al.*, 2008). Earlier sowing dates, increased soil organic matter content, low-energy systems, deficit irrigation and improved water use efficiency of irrigation systems and crops can be used as adaptation pathways (Daccache and Lamaddalena, 2010; Gonzalez-Camacho *et al.*, 2008; Lee *et al.*, 2008; Schutze and Schmitz, 2010) especially in

Southern and south-eastern regions of Europe (Trnka *et al.*, 2009);(Falloon and Betts, 2010). Improved water management in upstream agricultural areas could mitigate adverse impacts downstream (Kløve *et al.*, 2011) and groundwater recharge could be targeted in areas with poor water-holding soils (Wessolek and Asseng, 2006).

23.4.4. Forestry

Observed and future responses of forests to climate change include changes in growth rates, phenology, composition of animal and plant communities, increased fire and storm damage, and increased insect and pathogen damage. Tree mortality and forest decline due to severe drought events were observed in forest populations in Southern Europe (Affolter *et al.*, 2010; Bigler *et al.*, 2006; Raftoyannis *et al.*, 2008), including Italy (Bertini *et al.*, 2011)(Giuggiola *et al.*, 2010), Cyprus (ECHOES Country report, 2009), and Greece (Raftoyannis *et al.*, 2008) as well as in Belgium (Kint *et al.*, 2012), Switzerland (Rigling *et al.*, 2013) and the pre-Alps in France (Allen *et al.*, 2010; Charru *et al.*, 2010; Rouault *et al.*, 2006). Declines have also been observed in wet forests not normally considered at risk of drought (Choat *et al.*, 2012). An increase in forest productivity has been observed in Russia (Sirotenko and Abashina, 2008).

Future projections show that in Northern and Atlantic Europe the increasing atmospheric CO_2 and higher temperatures are expected to increase forest growth and wood production, at least in the short-medium term (Lindner *et al.*, 2010). On the other hand, in Southern and eastern Europe, increasing drought and disturbance risks will cause adverse effects and productivity is expected to decline (Hlásny *et al.*, 2011; Keenan *et al.*, 2011; Lavalle *et al.*, 2009; Lindner *et al.*, 2010; Silva *et al.*, 2012; Sirotenko and Abashina, 2008). By 2100, climate change is expected to reduce the economic value of European forest land depending on interest rate and climate scenario, which equates to potential damages of several hundred billion Euros (Hanewinkel *et al.*, 2013).

In Southern Europe, fire frequency and wildfire extent significantly increased after the 1970s compared with previous decades (Pausas and Fernández-Muñoz, 2012) due to fuel accumulation (Koutsias *et al.*, 2012), climate change (Lavalle *et al.*, 2009) and extreme weather events (Camia and Amatulli, 2009; Carvalho *et al.*, 2011; Hoinka *et al.*, 2009; Koutsias *et al.*, 2012; Salis *et al.*, 2013) especially in the Mediterranean basin (Marques *et al.*, 2011; Pausas and Fernández-Muñoz, 2012)(Fernandes *et al.*, 2010; Koutsias *et al.*, 2012). The most severe events in France, Greece, Italy, Portugal, Spain, and Turkey in 2010 were associated with strong winds during a hot dry period (EEA, 2010c). However, for the Mediterranean region as a whole, the total burned area has decreased since 1985 and the number of wildfires has decreased from 2000 to 2009, with large inter-annual variability (Marques *et al.*, 2011; San-Miguel-Ayanz *et al.*, 2012; Turco *et al.*, 2013). Megafires, triggered by extreme climate events, had caused record maxima of burnt areas in some Mediterranean countries during last decades (San-Miguel-Ayanz *et al.*, 2013).

Future wildfire risk is projected to increase in Southern Europe (Carvalho *et al.*, 2011; Dury *et al.*, 2011; Lindner *et al.*, 2010; Vilén and Fernandes, 2011), with an increase in the occurrence of high fire danger days (Arca *et al.*, 2012; Lung *et al.*, 2012) and in fire season length (Pellizzaro *et al.*, 2010). The annual burned area is projected to increase by a factor of 3 to 5 in Southern Europe compared to the present under the A2 scenario by 2100 (Dury *et al.*, 2011). In Northern Europe, fires are projected to become less frequent due to increased humidity (Rosan and Hammarlund, 2007). Overall, the projected increase in wildfires is likely to lead to a significant increase in greenhouse gas emissions due to biomass burning (Chiriacò *et al.*, 2013; Pausas *et al.*, 2008; Vilén and Fernandes, 2011), even if often difficult to quantify (Chiriacò *et al.*, 2013).

[INSERT FIGURE 23-5 HERE
Figure 23-5: Changes in forest fire risk in Europe for two time periods: baseline (left) and 2041–2070 (right), based on high-resolution regional climate models and the SRES A1B emission scenario. Source: Lung et al., 2013.]

Wind storm damage to forests in Europe has recently increased (Usbeck *et al.*, 2010). Boreal forests will become more vulnerable to autumn/early spring storm damage due to expected decrease in period of frozen soil (Gardiner *et al.*, 2010). Increased storm losses by 8-19% under A1B and B2 scenarios respectively is projected in Western

Germany for 2060-2100 compared to 1960-2000, with the highest impacts in the mountainous regions (Klaus *et al.*, 2011; Pinto *et al.*, 2010).

An increase in the incidence of diseases has been observed in many European forests (FAO, 2008b; Marcais and Desprez-Loustau, 2007). In Continental Europe, some species of fungi benefit from milder winters and others spread during drought periods from south to north (Drenkhan *et al.*, 2006; Hanso and Drenkhan, 2007). Projected increased late summer warming events will favour diffusion of bark beetle in Scandinavia, in lowland parts of central Europe and Austria (Jönsson *et al.*, 2011; Jönsson *et al.*, 2009)(Seidl *et al.*, 2009).

Possible response approaches to the impacts of climate change on forestry include short-term and long-term strategies that focus on enhancing ecosystem resistance and resilience and responding to potential limits to carbon accumulation (Millar *et al.*, 2007; Nabuurs *et al.*, 2013). Fragmented small-scale forest ownership can constrain adaptive capacity (Lindner *et al.*, 2010). Landscape planning and fuel load management may reduce the risk of wildfires but may be constrained by the higher flammability due to warmer and drier conditions (Moreira *et al.*, 2011). Strategies to reduce forest mortality include preference of species better adapted to relatively warm environmental conditions (Resco *et al.*, 2007). The selection of tolerant or resistant families and clones may also reduce the risk of damage by pests and diseases in pure stands (Jactel *et al.*, 2009).

23.4.5. Bioenergy Production

The potential distribution of temperate oilseeds (e.g. oilseed rape, sunflower), starch crops (e.g. potatoes), cereals (e.g. barley) and solid biofuel crops (e.g. sorghum, Miscanthus) is projected to increase in Northern Europe by the 2080s, due to increasing temperatures, and to decrease in Southern Europe due to increased drought frequency) (Tuck *et al.*, 2006). Mediterranean oil and solid biofuel crops, currently restricted to Southern Europe, are likely to extend further north (Tuck *et al.*, 2006). The physiological responses of bioenergy crops, in particular C3 Salicaceae trees, to rising atmospheric CO_2 concentration may increase drought tolerance due to improved plant water use, consequently yields in temperate environments may remain high in future climate scenarios (Oliver *et al.*, 2009).

A future increase in the northward extension of the area for short rotation coppice (SRC) cultivation leading to greenhouse gas neutral is expected (Liberloo *et al.*, 2010). However, the northward expansion of SRC would erode the European terrestrial carbon sink due to intensive management and high turnover of SRC compared to conventional forest where usually harvesting is less than annual growth (Liberloo *et al.*, 2010).

23.4.6. Fisheries and Aquaculture

In AR4, Easterling *et al*. (2007) reported that the recruitment and production of marine fisheries in the North Atlantic are *likely* to increase. In European seas, warming causes a displacement to the north and/or in depth of fish populations (Daufresne *et al.*, 2009) (AR5 WG2 Chapter 6, 23.6.4) which has a direct impact on fisheries (Cheung *et al.*, 2010; Cheung *et al.*, 2013; Tasker, 2008). For instance, in British waters, the lesser sandeel (*Ammodytes marinus*), which is a key link in the food web, shows declining recruitments since 2002 and is projected to further decline in the future with a warming climate (Heath *et al.*, 2012). In the Baltic Sea, although some new species would be expected to immigrate because of an expected increase in sea temperature, only a few of these species would be able to successfully colonize the Baltic because of its low salinity (Mackenzie *et al.*, 2007). In response to climate change and intensive fishing, widespread reductions in fish body size (Daufresne *et al.*, 2009) and in the mean size of zooplankton (Beaugrand and Reid, 2012) have been observed over time and these trends further affect the sustainability of fisheries (Pitois and Fox, 2006)(Beaugrand and Kirby, 2010) [see also Chapter 6]. Aquaculture can be affected as the areal extent of some habitats that are suitable for aquaculture can be reduced by sea-level rise. Observed higher water temperatures have adversely affected both wild and farmed freshwater salmon production in the southern part of the distribution areas (Jonsson and Jonsson, 2009). In addition, ocean acidification may disrupt the early developmental stages of shellfish (Callaway *et al.*, 2012).

Numerous studies confirm the amplification through fishing of the effects of climate change on population dynamics and consequently on fisheries (Planque *et al.*, 2010). The decline of the North Sea cod during the 1980-2000 period results from the combined effects of overfishing and of an ecosystem regime shift due to climate change (Beaugrand and Kirby, 2010). Over the next decade, this stock was not restored from its previous collapse (Mieszkowska *et al.*, 2009)(ICES, 2010). In North Sea and Celtic Seas, the steep decline in boreal species (Henderson, 2007) was compensated for by the arrival of southern (Lusitanian) species (Engelhard *et al.*, 2011; Lenoir *et al.*, 2011; ter Hofstede *et al.*, 2010).

Climate change may reinforce parasitic diseases and impose severe risks for aquatic animal health [See Chapter 6]. As water temperatures increase, a number of endemic diseases of both wild and farmed salmonid populations are *likely* to become more prevalent and threats associated with exotic pathogens may rise (Marcos-Lopez *et al.*, 2010). In Iberian Atlantic, the permitted harvesting period for the mussel aquaculture industry was reduced because of harmful algal blooms resulting from changes in phytoplankton communities linked to a weakening of the Iberian upwelling (Perez *et al.*, 2010). With freshwater systems, summer heat waves boost the development of harmful cyanobacterial blooms (Johnk *et al.*, 2008). For oysters in France, toxic algae may be linked to both climate warming and direct anthropogenic stressors (Buestel *et al.*, 2009).

Fishery management thresholds will have to be reassessed as the ecological basis on which existing thresholds have been established changes, and new thresholds will have to be developed for immigrant species (Mackenzie *et al.*, 2007)(Beaugrand and Reid, 2012). These changes may lead to loss of productivity, but also the opening of new fishing opportunities, depending on the interactions between climate impacts, fishing grounds and fleet types. They will also affect fishing regulations, the price of fish products and operating costs, which in turn will affect the economic performance of the fleets (Cheung *et al.*, 2012). Climate change impacts on fisheries profits range from negative for sardine fishery in the Iberian Atlantic fishing grounds (Perez *et al.*, 2010)(Garza-Gil *et al.*, 2010), to non-significant for the Bay of Biscay (Le Floc'h *et al.*, 2008) and positive on the Portuguese coast, since most of the immigrant fish species are marketable (Vinagre *et al.*, 2011). Human social fishing systems dealing with high variability upwelling systems with rapidly reproducing fish species may have greater capacities to adjust to the additional stress of climate change than human social fishing systems focused on longer-lived and generally less variable species (Perry *et al.*, 2011; Perry *et al.*, 2010). Climate change adaptation is being considered for integration in European maritime and fisheries operational programs (European Commission, 2013).

_____ START BOX 23-1 HERE _____

Box 23-1. Assessment of Climate Change Impacts on Ecosystem Services by Sub-Region

Ecosystems provide a number of vital provisioning, regulating and cultural services for people and society that flow from the stock of natural capital (Stoate *et al.*, 2009)(Harrison *et al.*, 2010). Provisioning services such as food from agro-ecosystems or timber from forests derive from intensively managed ecosystems; regulating services underpin the functioning of the climate and hydrological systems; and, cultural services such as tourism, recreation and aesthetic value are vital for societal well-being (see section 23.5.4). The table summarises the potential impacts of climate change on ecosystem services in Europe by sub-region based on an assessment of the published literature (2004-2013). The direction of change (increasing, decreasing or neutral) is provided, as well as the number of studies/papers on which the assessment was based (in brackets). Empty cells indicate the absence of appropriate literature. Unless otherwise stated, impacts assume no adaptation and are assessed for the mid-century (2050s). A decrease in natural hazard regulation (e.g. for wildfires) implies an increased risk of the hazard occurring. Biodiversity is included here as a service (for completeness), although it is debated whether biodiversity should be considered as a service or as part of the natural capital from which services flow. What is agreed, however, is that biodiversity losses within an ecosystem will have deleterious effects on service provision (Mouillot *et al.*, 2013).

The provision of ecosystem services in Southern Europe is projected to decline across all service categories in response to climate change [*high confidence*]. Other European sub-regions are projected to have both losses and gains in the provision of ecosystem services [*high confidence*]. The Northern sub-region will have increases in provisioning services arising from climate change [*high confidence*]. Except for the Southern sub-region, the effects of climate change on regulating services are balanced with respect to gains and losses [*high confidence*]. There are fewer studies for cultural services, although these indicate a balance in service provision for the Alpine and Atlantic regions, with decreases in service provision for the Continental, Northern and Southern sub-regions [*low confidence*].

[INSERT BOX 23-1 TABLE HERE]

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23.5. Implications of Climate Change for Health and Social Welfare

23.5.1. Human Population Health

Climate change is likely to have a range of health effects in Europe. Further studies since AR4 have confirmed the effects of heat on mortality and morbidity in European populations and particularly in older people and those with chronic disease (Corobov *et al.*, 2012; Corobov *et al.*, 2013; Kovats and Hajat, 2008; Åström *et al.*, 2011). With respect to sub-regional vulnerability, populations in southern Europe appear to be most sensitive to hot weather (Baccini *et al.*, 2011; D'Ippoliti *et al.*, 2010; Michelozzi *et al.*, 2009; Michelozzi *et al.*, 2009), and also will experience the highest heat exposures (Figure 23-2). However, populations in Continental (Hertel *et al.*, 2009) and Northern Europe (Rocklöv and Forsberg, 2010)(Armstrong *et al.*, 2011)(Varakina *et al.*, 2011) are also vulnerable to heat wave events. Adaptation measures to reduce heat health effects include heat wave plans (Bittner *et al.*, 2013) which have been shown to reduce heat-related mortality in Italy (Schifano *et al.*, 2012), but evidence of effectiveness is still very limited (Hajat *et al.*, 2010; Lowe *et al.*, 2011). There is little information about how future changes in housing and infrastructure (23.3.2) would reduce the regional or local future burden of heat-related mortality or morbidity. Climate change is likely to increase future heat-related mortality (Baccini *et al.*, 2011; Ballester *et al.*, 2011; Huang *et al.*, 2011) and morbidity (Åström *et al.*, 2013), although most published risk assessments do not include consideration of adaptation (Huang *et al.*, 2011). For most countries in Europe, the current burden of cold-related mortality (Analitis *et al.*, 2008) is greater than the burden of heat mortality. Climate change is likely to reduce future cold-related mortality (Ballester *et al.*, 2011; HPA, 2012)(AR5 WG2 11.4.1).

Mortality and morbidity associated with flooding is becoming better understood although the surveillance of health effects of disasters remains inadequate (WHO, 2013). Additional flood mortality due to sea level rise has been estimated in the Netherlands (Maaskant *et al.*, 2009); and in the UK for river flooding (Hames and Vardoulakis, 2012) but estimates of future mortality due to flooding are highly uncertain. There remains limited evidence regarding the long term mental health impacts of flood events (Paranjothy *et al.*, 2011; WHO, 2013).

Evidence about future risks from climate change with respect to infectious diseases is still limited (Randolph and Rogers, 2010; Semenza and Menne, 2009; Semenza *et al.*, 2012). There have been developments in mapping the current and potential future distribution of important disease vector species in Europe. The Asian tiger mosquito *Aedes albopictus* (a vector of dengue and Chikungunya (Queyriaux *et al.*, 2008) is currently present in Southern Europe (ECDC, 2009) and may extend eastward and northward under climate change (Caminade *et al.*, 2012; Fisher *et al.*, 2011; Roiz *et al.*, 2011). The risk of introduction of dengue remains very low because it would depend upon the introduction and expansion of the *Ae. Aegypti* together with the absence of effective vector control measures (ECDC, 2012).

Climate change is unlikely to affect the distribution of visceral and cutaneous leishmaniasis (currently present in the Mediterranean region) in the near term (Ready, 2010). However, in the long term (15-20 years), there is potential for climate change to facilitate the expansion of either vectors or current parasites northwards (Ready, 2010). The risk of introduction of exotic Leishmania species was considered very low due to the low competence of current vectors (Fischer *et al.*, 2010a). The effect of climate change on the risk of imported or locally-transmitted (autochthonous) malaria in Europe has been assessed in Spain (Sainz-Elipe *et al.*, 2010), France (Linard *et al.*, 2009) and the UK (Lindsay *et al.*, 2010). Disease re-emergence would depend upon many factors including: the introduction of a large population of infectious people or mosquitoes, high levels of people-vector contact, resulting from significant changes in land use, as well as climate change (see chapter 11).

Since AR4, there is more evidence on implications of climate change on food safety at all stages from production to consumption (FAO, 2008a; Jacxsens *et al.*, 2010; Popov Janevska *et al.*, 2010). The sensitive of salmonellosis to temperature has declined in recent years (Lake *et al.*, 2009) and the overall incidence of salmonellosis is declining in most European countries (Semenza *et al.*, 2012). Climate change may also have affects on food consumption patterns. Weather affects pre and post harvest mycotoxin production but the implications of climate change are unclear. Cold regions may become liable to temperate-zone problems concerning contamination ochratoxin *A*, *patulin* and *Fusarium* toxins (Paterson and Lima, 2010). A control of the environment of storage facilities may avoid post-harvest problems but at additional cost (Paterson and Lima, 2010).

Other potential consequences concern marine biotoxins in seafood following production of phycotoxins by harmful algal blooms and the presence of pathogenic bacteria in foods following more frequent extreme weather conditions (Miraglia *et al.*, 2009). There is little evidence that climate change will affect human exposures to contaminants in the soil or water (e.g. persistent organic pollutants). Risk modelling is often developed for single exposure agents (e.g. a pesticide) with known routes of exposure. These are difficult to scale up to the population level. The multiple mechanisms by climate may affect transmission or contamination routes also makes this very complex (Boxall *et al.*, 2009).

Adaptation in the health sector has so far been largely limited to the development of heat health warning systems, but many research gaps regarding effective adaptation options (HPA, 2012). A survey of national infectious disease experts in Europe identified several institutional changes that needed to be addressed to improve future responses to climate change risks: ongoing surveillance programs, collaboration with veterinary sector and management of animal disease outbreaks, national monitoring and control of climate-sensitive infectious diseases, health services during an infectious disease outbreak and diagnostic support during an epidemic (Semenza *et al.*, 2012).

23.5.2. Critical Infrastructure

Critical national infrastructure is defined as the assets (physical or electronic) that are vital to the continued delivery and integrity of the essential services upon which a country relies, the loss or compromise of which would lead to severe economic or social consequences or to loss of life. Extreme weather events, such as floods, heat waves and wild fires are known to damage critical infrastructure. The UK floods in 2007 led to significant damage to power and water utilities, and to communications and transport infrastructure (Chatterton *et al.*, 2010) (Table 23-1). Forest fires can affect transport infrastructure, as well as the destruction of buildings. Major storms in Sweden and Finland have led to loss of trees, with damage to the power distribution network, leading to electricity blackouts lasting weeks, as well as the paralysis of services such as rail transport and other public services that depend on grid electricity.

Health system infrastructure (hospitals, clinics) is vulnerable to extreme events, particularly flooding (Radovic *et al.*, 2012). The heat waves of 2003 and 2006 had adverse effects on patients and staff in hospitals from overheating of buildings. Evidence from France and Italy indicate that death rates in in-patients increased significantly during heat wave events (Ferron *et al.*, 2006; Stafoggia *et al.*, 2008). Further, higher temperatures have had serious implications for the delivery of healthcare, as well drug storage and transport (Carmichael *et al.*, 2013).

23.5.3. Social Impacts

There is little evidence regarding the implications of climate change for employment and/or livelihoods in Europe. However, the evidence so far (as reviewed in this chapter) indicates that there are likely to be changes to some industries (e.g. tourism, agriculture) that may lead to changes in employment opportunities by region and by sector.

Current damages from weather-related disasters (floods and storms) are significant (23.3.1). Disasters have long lasting effects of the affected populations (Schnitzler *et al.*, 2007). Households are often displaced while their homes are repaired (Whittle *et al.*, 2010). Little research has been carried out on the impact of extreme weather events such as heat waves and flooding on temporary or permanent displacement in Europe. Coastal erosion associated with sea level rise, storm surges and coastal flooding will require coastal retreat in some of Europe's low lying areas (Philippart *et al.*, 2011). Managed retreat is also an adaptation option in some coastal areas. Concerns have been raised about equality of access to adaptation within coastal populations at risk from climate change. For example, a study in the UK found that vulnerability to climate change in coastal communities is likely to be increased by social deprivation (Zsamboky *et al.*, 2011).

In the European region, the indigenous populations are present in Arctic regions are considered vulnerable to climate change impacts on livelihoods and food sources (Arctic Climate Impact Assessment, 2005) [12.3.4, 28.2.4]. Research has focussed on indigenous knowledge, impacts on traditional food sources and community responses/adaptation (Mustonen and Mustonen, 2011a; Mustonen and Mustonen, 2011b). However, these communities are also experiencing rapid social, economic and other non-climate-related environmental changes (such as oil and gas exploration) [see 28.2.4]. There is evidence the climate change has altered the seasonal behaviour of pastoralist populations, such as the Nenets reindeer herders in northern Russia (Amstislavski *et al.*, 2013). However, socio-economic factors may be more important than climate change for the future sustainability of Reindeer husbandry (Rees *et al.*, 2008) [28.2.3.5].

23.5.4. Cultural Heritage and Landscapes

Climate change will affect culturally-valued buildings (Storm *et al.*, 2008) through extreme events and chronic damage to materials (Brimblecombe *et al.*, 2006; Brimblecombe and Grossi, 2010; Brimblecombe, 2010a; Brimblecombe, 2010b; Grossi *et al.*, 2011)(Sabbioni *et al.*, 2012). Cultural heritage is a non-renewable resource and impacts from environmental changes are assessed over long timescales (Brimblecombe and Grossi, 2008)(Bonazza *et al.*, 2009a; Bonazza *et al.*, 2009b; Brimblecombe and Grossi, 2009; Brimblecombe and Grossi, 2010; Grossi *et al.*, 2008). Climate change may also affect indoor environments where cultural heritage is preserved (Lankester and Brimblecombe, 2010) as well as visitor behaviour at heritage sites (Grossi *et al.*, 2010). There is also evidence to suggest that climate change and sea level rise will affect maritime heritage in the form of shipwrecks and other submerged archaeology (Björdal, 2012).

Surface recession on marble and compact limestone will be affected by climate change (Bonazza *et al.*, 2009a). Marble monuments in Southern Europe will continue to experience high levels of thermal stress (Bonazza *et al.*, 2009b) but warming is likely to reduce frost damage across Europe, except in Northern and Alpine Europe and permafrost areas (Iceland) (Grossi *et al.*, 2007; Sabbioni *et al.*, 2008). Damage to porous materials due to salt crystallisation may increase all over Europe (Benavente *et al.*, 2008; Grossi *et al.*, 2011). In Northern and Eastern Europe, wood structures will need additional protection against rainwater and high winds (Sabbioni *et al.*, 2012). AR4 concluded that current flood defences would not protect Venice from climate change. Venice now has a flood forecasting system, and is introducing the MOSE system of flood barriers (Keskitalo, 2010). Recent evidence suggests, however, that climate change may lead to a decrease in the frequency of extreme storm surges in this area (Troccoli *et al.*, 2012a).

Europe has many unique rural landscapes, which reflect the cultural heritage that has evolved from centuries of human intervention, e.g. the cork oak based Montado in Portugal, the Garrigue of southern France, Alpine meadows, grouse moors in the UK, machair in Scotland, peatlands in Ireland, the polders of Belgium and the Netherlands and vineyards. Many, if not all, of these cultural landscapes are sensitive to climate change and even small changes in the climate could have significant impacts (Gifford *et al.*, 2011). Alpine meadows, for example, are culturally important within Europe, but although there is analysis of the economics (tourism, farming) and functionality (water run-off, flooding and carbon sequestration) of these landscapes there is very little understanding of how climate change will affect the cultural aspects on which local communities depend. Because of their societal value, cultural landscapes are often protected and managed through rural development and environmental policies. The peat-rich uplands of northern Europe, for example, have begun to consider landscape management as a means of adapting to the effects of climate change (e.g. the moors for the future partnership in the Peak District National Park, UK). For a discussion of the cultural implications of climate change for vineyards see Box 23-2.

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Box 23-2. Implications of Climate Change for European Wine and Vineyards

Wine production in Europe accounts for more than 60% of the global total (Goode, 2012) and makes an important contribution to cultural identity. Apart from impacts on grapevine yield, higher temperatures are also expected to affect wine quality in some regions and grape varieties by changing the ratio between sugar and acids (Bock *et al.*, 2011)(Santos *et al.*, 2011)(Duchêne *et al.*, 2010). In western and central Europe, projected future changes could benefit wine quality, but might also demarcate new potential areas for viticulture (Malheiro *et al.*, 2010). Adaptation measures are already occurring in some vineyards (e.g. vine management, technological measures, production control and to a smaller extent relocation) (Battaglini *et al.*, 2009; Duarte Alonso and O'Neill, 2011; Holland and Smit, 2010; Malheiro *et al.*, 2010; Moriondo *et al.*, 2011; Santos *et al.*, 2011).Vineyards may be displaced geographically beyond their traditional boundaries ('terroir' linked to soil, climate and traditions) (Metzger and Rounsevell, 2011), and in principle, wine producers could adapt to this problem by growing grape varieties that are more suited to warmer climates. Such technical solutions, however, do not account for the unique characteristics of wine production cultures and consumer perceptions of wine quality that strongly affect the prices paid for the best wines (Metzger and Rounsevell, 2011)(White *et al.*, 2009). It would become very difficult, for example, to produce fine wines from the cool-climate Pinot Noir grape within its traditional 'terroir' of Burgundy under many future climate scenarios, but consumers may not be willing to pay current day prices for red wines produced from other grape varieties (Metzger and Rounsevell, 2011). An additional barrier to adaptation is that wine is usually produced within rigid, regionally-specific, regulatory frameworks that often prescribe, amongst other things, what grapes can be grown where, e.g., the French AOC or the Italian DOC and DOCG designations. Suggestions have been made to replace these rigid concepts of regional identity with a geographically flexible 'terroir' that ties a historical or constructed sense of culture to the wine maker and not to the region (White *et al.*, 2009).

_____ END BOX 23-2 HERE _____

23.6. Implications of Climate Change for the Protection of Environmental Quality and Biological Conservation

Terrestrial and freshwater ecosystems provide a number of vital services for people and society, such as biodiversity, food, fibre, water resources, carbon sequestration and recreation (Box 23-1).

23.6.1. Air Quality

Climate change will have complex and local effects on pollution chemistry, transport, emissions and deposition. Outdoor air pollutants have adverse effects on human health, biodiversity, crop yields and cultural heritage. The main outcomes of concern are both the average (background) levels and peak events for tropospheric ozone, particulates, sulphur oxides (SO_x) and nitrogen oxides (NO_x). Future pollutant concentrations in Europe have been assessed using atmospheric chemistry models, principally for ozone (Forkel and Knoche, 2006; Forkel and Knoche, 2007). Reviews have concluded that GCM/CTM studies find that climate change per se (assuming no change in future emissions or other factors) is likely to increase summer tropospheric ozone levels (range 1–10 ppb) by 2050s in polluted areas (that is, where concentrations of precursor nitrogen oxides are higher) (AQEG, 2007; Jacob and Winner, 2009)[see also 21.4.1.3.2.]. The effect of future climate change alone on future concentrations of particulates, nitrogen oxides and volatile organic compounds is much more uncertain. Higher temperatures also affect natural emissions volatile organic compounds (VOCs) which are ozone precursors (Hartikainen *et al.*, 2012). One study has projected an increase in fire-related air pollution (O3 and PM10) in Southern Europe (Carvalho *et al.*, 2011).

Overall, the model studies are inconsistent regarding future projections of background level and exceedences. Recent evidence has shown adverse impacts on agriculture from even low concentrations of ozone, however, there is more consistent evidence now regarding the threshold for health (mortality) impacts of ozone. Therefore, it is unclear whether increases in background levels below health-related thresholds would be associated with an increased burden of ill health.

Some studies have attributed an observed increase in European ozone levels to observed warming (Meleux *et al.*, 2007), which appears to be driven by the increase in extreme heat events in 2003, 2006 and 2010 (Solberg *et al.*, 2008). Peak ozone events were observed during the major heat waves in Europe in multiple countries. Wildfire events have had an impact on local and regional on air quality (Hodzic *et al.*, 2007; Liu *et al.*, 2009; Miranda *et al.*, 2009) which have implications for human health (Analitis *et al.*, 2012) (Table 23-1).

23.6.2. Soil Quality and Land Degradation

The current cost of soil erosion, organic matter decline, salinisation, landslides and contamination is estimated to be EUR 38 billion annually for the EU (JRC-EEA, 2010), in the form of damage to infrastructures, treatment of water contaminated through the soil, disposal of sediments, depreciation of land and costs related to the ecosystem functions of soil (JRC-EEA, 2010). Projections show significant reductions in summer soil moisture in the Mediterranean region, and increases in the north-eastern part of Europe (Calanca *et al.*, 2006). Climate change impacts on erosion shows diverging evidence under the A2 scenario. In Tuscany, even with a decline in precipitation volume until 2070, in some month higher erosion rates would occur due to higher rainfall erosivity (Marker *et al.*, 2008). For two Danish river catchments, assuming a steady-state land use, suspended sediment transport would increase by 17-27% by 2071-2100 (Thodsen *et al.*, 2008; Thodsen, 2007). In Upper-Austria, with the regional climate model HadRM3H, a small reduction in average soil losses is projected for croplands in all tillage systems, however with high uncertainty (Scholz *et al.*, 2008). In Northern Ireland, erosion decreases are generally projected with downscaled GCMs for a case study hillslope (Mullan *et al.*, 2012).

Adaptive land-use management can reduce the impact of climate change through soil conservation methods like zero tillage and conversion of arable to grasslands (Klik and Eitzinger, 2010). In central Europe, compared to conventional tillage, conservation tillage systems reduced modelled soil erosion rates under future climate scenarios by between 49 and 87% (Scholz *et al.*, 2008). Preserving upland vegetation reduced both erosion and loss of soil carbon and favoured the delivery of a high quality water resource (House *et al.*, 2011); (McHugh, 2007). Maintaining soil water retention capacity, e.g. through adaptation measures (Post *et al.*, 2008), contributes to reduce risks of flooding as soil organic matter absorbs up to twenty times its weight in water.

23.6.3. Water Quality

Climate change may affect water quality in several ways, with implications for food production and forestry (23.4.3), ecosystem functioning (Box 23-1), human and animal health, and compliance with environmental quality standards, including those of the Water Framework Directive. Shallower waters will witness a more rapid temperature increase than deeper waters, since heat is absorbed mainly in the upper water layers and turbulent mixing is truncated by shallow depth. In parallel, a decrease in saturating oxygen concentrations occurs. Since AR4, there is further evidence of adverse effects caused by extreme weather events: reductions in dissolved oxygen, algal blooms (Mooij *et al.*, 2007; Ulén and Weyhenmeyer, 2007) during hot weather, and contamination of surface and coastal waters with sewage and/or chemicals (pesticides) after rainfall (Boxall *et al.*, 2009). A reduction in rainfall may lead to low flows which increase concentrations of biological and chemical contaminants. Reduced drainage can also enhance sedimentation in drainage systems and hence enhance particle-bound phosphorous retention and reduce phosphorous load to downstream higher order streams (Hellmann and Vermaat, 2012).

Variability in changes in rainfall and run-off, as well as water temperature increases, will lead to differences in water quality impacts by sub-region. Climate change is projected to increase nutrient loadings: in Northern Europe this is caused by increased surface runoff; in Southern Europe this is caused by increased evapotranspiration and increased concentrations due to reduced volumes of receiving lakes (Jeppesen *et al.*, 2011). Local studies generally confirm this pattern: increased nutrient loads are foreseen in Danish watersheds (Andersen *et al.*, 2006), France (Delpla *et al.*, 2011) and the UK (Howden *et al.*, 2010; Macleod *et al.*, 2012; Whitehead *et al.*, 2009); AR5 WG2 Chapter

4.3.2.5). In larger rivers, such as the Meuse, increased summer temperature and drought can lead to more favourable conditions for algal blooms and reduced dilution capacity of effluent from industry and sewage works (van Vliet and Zwolsman, 2008).

23.6.4. Terrestrial and Freshwater Ecosystems

Current and future climate changes including CO_2 increase are determining negative effects of habitat loss on species density and diversity (Mantyka-pringle *et al.*, 2012)(Rickebusch *et al.*, 2008). Projected habitat loss is greater for species at higher elevations (Engler *et al.*, 2011)(Castellari, 2009; Dullinger *et al.*, 2012) and suitable habitats for Europe's breeding birds are projected to shift nearly 550 km northeast by the end of the century (Huntley *et al.*, 2007). Aquatic habitats and habitat connectivity in river networks may become increasingly fragmented (Blaustein *et al.*, 2010; Della Bella *et al.*, 2008; Elzinga *et al.*, 2007; Gómez-Rodríguez *et al.*, 2010; Hartel *et al.*, 2011; Morán-López *et al.*, 2012)(Harrison *et al.*, 2008)(Clark *et al.*, 2010a)(Clark *et al.*, 2010; Fronzek *et al.*, 2006; Fronzek *et al.*, 2010; Fronzek *et al.*, 2011; Gallego-Sala *et al.*, 2010). Despite some local successes and increasing responses, the rate of biodiversity loss does not appear to be slowing (Butchart *et al.*, 2010). The effectiveness of Natura 2000 areas to respond to climate change has been questioned (Araújo *et al.*, 2011). However, when considering connectivity related to the spatial properties of the network, the Natura 2000 network appears rather robust (Mazaris *et al.*, 2013). Several studies now highlight the importance of taking into account climate change projections in the selection of conservation areas (Araújo *et al.*, 2011; Ellwanger *et al.*, 2011; Filz *et al.*, 2013; Virkkala *et al.*, 2013).

Observed changes in plant communities in European mountainous regions show a shift of species ranges to higher altitudes resulting in species richness increase in boreal-temperate mountain regions and decrease in Mediterranean mountain regions (Pauli *et al.*, 2012)(Gottfried *et al.*, 2012). In Southern Europe, a great reduction in phylogenetic diversity of plant, bird and mammal assemblages will occur, and gains are expected in regions of high latitude or altitude for 2020, 2050 and 2080. However, losses will not be offset by gains and a trend towards homogenization across the continent will be observed (Thuiller *et al.*, 2011)(Alkemade *et al.*, 2011). Large range contractions due to climate change are projected for several populations of *Pinus cembra* and *Pinus Sylvestris* (Casalegno et al.,2010)(Giuggiola *et al.*, 2010) while for the dominant Mediterranean tree species, Holm oak, a substantial range expansion is projected under A1B emissions scenario (Cheaib *et al.*, 2012). The human impacts on distribution of tree species landscape may make them more vulnerable to climate change (del Barrio *et al.*, 2006; Hemery *et al.*, 2010).

Observed climate changes are altering breeding seasons, timing of spring migration, breeding habitats, latitudinal distribution and migratory behaviour of birds (Feehan *et al.*, 2009) (Jonzén *et al.*, 2006; Rubolini *et al.*, 2007a; Rubolini *et al.*, 2007b)(Lemoine *et al.*, 2007a; Lemoine *et al.*, 2007b). A northward shift in bird community composition has been observed (Devictor *et al.*, 2008). Common species of European birds with the lowest thermal maxima have showed the sharpest declines between 1980 and 2005 (Jiguet *et al.*, 2010).

Projections for 120 native terrestrial non-volant European mammals suggest that 5-9% are at risk of extinction, assuming no migration, during the 21st century due to climate change, while 70-78% may be severely threatened under A1 and B2 climatic scenarios (Levinsky *et al.*, 2007). Those populations not showing a phenological response to climate change may decline (Moller *et al.*, 2008), such as amphibian and reptile species (Araújo *et al.*, 2006), or experience ecological mismatches (Saino *et al.*, 2011). Climate change can affect trophic interactions, as co-occurring species may not react in a similar manner. Novel emergent ecosystems composed of new species assemblages arising from differential rates of range shifts of species can occur (Keith *et al.*, 2009; Montoya and Raffaelli, 2010; Schweiger *et al.*, 2012).

Since invasive alien species rarely change their original climatic niches (Petitpierre *et al.*, 2012), climate change can exacerbate the threat posed by invasive species to biodiversity in Europe (West *et al.*, 2012) amplifying the effects of introduction of the exotic material such as alien bioenergy crops (EEA, 2012), pest and diseases (Aragòn and Lobo, 2012), tropical planktonic species (Cellamare *et al.*, 2010) and tropical vascular plants (Skeffington and Hall, 2011; Taylor *et al.*, 2012).

23.6.5. Coastal and Marine Ecosystems

Climate change will affect Europe's coastal and marine ecosystems by altering the biodiversity, functional dynamics and ecosystem services of coastal wetlands, dunes, inter-tidal and subtidal habitats, offshore shelves, seamounts and currents (Halpern *et al.*, 2008) through changes in eutrophication, invasive species, species range shifts, changes in fish stocks and habitat loss (Doney *et al.*, 2011)(EEA, 2010d). The relative magnitude of these changes will vary temporally and spatially, requiring a range of adaptation strategies that target different policy measures, audiences and instruments (Philippart *et al.*, 2011)(Airoldi and Bec, 2007).

Europe's northern seas are experiencing greater increases in sea surface temperatures (SSTs) than the southern seas, with the Baltic, North and Black seas warming at 2-4 times the mean global rate (Philippart *et al.*, 2011)(Belkin, 2009). In the Baltic, decreased sea ice will expose coastal areas to more storms, changing the coastal geomorphology (BACC, 2008)(HELCOM, 2007). Warming SSTs will influence biodiversity and drive changes in depth and latitudinal range for intertidal and sub-tidal marine communities, particularly in the North and Celtic seas (Hawkins *et al.*, 2011)(Sorte *et al.*, 2010)(Wethey *et al.*, 2011).

Warming is affecting food chains and changing phenological rates (Durant *et al.*, 2007). For example, changes in the timing and location of phytoplankton and zooplankton are affecting North Sea cod larvae (Beaugrand *et al.*, 2010)(Beaugrand and Kirby, 2010). Temperature changes have affected the distribution of fisheries in all seas over the past 30 years (Beaugrand and Kirby, 2010)(Hermant *et al.*, 2010). Warmer waters also increase the rate of the establishment and spread of invasive species, further altering trophic dynamics and the productivity of coastal marine ecosystems (Molnar *et al.*, 2008)(Rahel and Olden, 2008). Changes in the semi-enclosed seas could be indicative of future conditions in other coastal-marine ecosystems (Lejeusne *et al.*, 2009). In the Mediterranean, invasive species have arrived in recent years at the rate of one introduction every 4 to 5 weeks (Streftaris *et al.*, 2005). While in this case the distribution of endemic species remained stable, most non-native species have spread northward by an average of 300 km since the 1980s, resulting in an area of spatial overlap with invasive species replacing natives by nearly 25% in 20 years.

Dune systems will be lost in some places due to coastal erosion from combined storm surge and sea level rise, requiring restoration (Day *et al.*, 2008)(Ciscar *et al.*, 2011)(Magnan *et al.*, 2009). In the North Sea, the Iberian coast, and Bay of Biscay, a combination of coastal erosion, infrastructure development and sea defences may lead to narrower coastal zones ("coastal squeeze") (EEA, 2010d)(Jackson and McIlvenny, 2011)(OSPAR, 2010).

23.7. Cross-Sectoral Adaptation Decision-making and Risk Management

Studies on impacts and adaptation in Europe generally consider single sectors or outcomes, as described in the previous sections of this chapter. For adaptation decision-making, more comprehensive approaches are required. Considerable progress has been made to advance planning and development of adaptation measures, including the economic analyses (Section 23.7.6) (see Box 23-3), and the developed of climate services (Medri *et al.*, 2012; WMO, 2011). At the international level, the European Union has started adaptation planning, through information sharing (Climate-ADAPT platform) and legislation (EC, 2013a). National and local governments are also beginning to monitor progress on adaptation, including the development of a range of indicators (UK-ASC, 2011).

_____ START BOX 23-3 HERE _____

Box 23-3. National and Local Adaptation Strategies

The increasing number of national (EEA, 2013) and local (Heidrich *et al.*, 2013) adaptation strategies in Europe has led to research on their evaluation and implementation (Biesbroek *et al.*, 2010b). Many adaptation strategies were found to be agendas for further research, awareness raising and/or coordination and communication for implementation (e.g. (Dumollard and Leseur, 2011; Pfenniger *et al.*, 2010). Actual implementation often was limited to disaster risk reduction, environmental protection, spatial planning (23.7.4), and coastal zone and water resources management. The implementation of planned adaptation at the national level was attributed to political will and good financial and information capacity (Westerhoff *et al.*, 2011). Analysis of seven national adaptation strategies (Denmark, Finland, France, Germany, Netherlands, Spain, UK) found that that while there is a high political commitment to adaptation planning and implementation, evaluation of the strategies and actual implementation is yet to be defined (Biesbroek *et al.*, 2010a; Swart *et al.*, 2009b; Westerhoff *et al.*, 2011). One of the earliest national adaptation strategies (Finland) has been evaluated, in order to compare identified adaptation measures with those launched in different sectors. It has found that while good progress has been made on research and identification of options, few measures have been implemented except in the water resources sector (Ministry of Agriculture and Forestry, 2009).

At the local government level, adaptation plans are being developed in several cities (EEA, 2013), including London (GLA, 2010), Madrid, Manchester, Copenhagen, Helsinki, and Rotterdam. Adaptation in general is a low priority for many European cities, and many plans do not have adaptation priority as the main focus (Carter, 2011). Many studies are covering sectors sensitive to climate variability, as well as sectors that are currently under pressure from socioeconomic development. A recent assessment found a lack of cross-sector impact and adaptation linkages as an important weakness in the city plans (Hunt and Watkiss, 2011). Flexibility in adaptation decision making needs to be maintained (Hallegatte *et al.*, 2008)(Biesbroek *et al.*, 2010b).

_____ END BOX 23-3 HERE _____

23.7.1. Coastal Zone Management

Coastal zone management and coastal protection plans that integrate adaptation concerns are now being implemented. Underlying scientific studies increasingly assess effectiveness and costs of specific options (Hilpert *et al.*, 2007)(Kabat *et al.*, 2009)(Dawson *et al.*, 2011) (23.7.6). Early response measures are needed for floods and coastal erosion, to ensure that climate change considerations are incorporated into marine strategies, with mechanisms for regular updating (OSPAR, 2010; UNEP, 2010).

In the Dutch plan for flood protection (Delta Committee, 2008), adaptation to increasing river runoff and sea level rise plays a prominent role. It also includes synergies with nature conservation and fresh water storage (Kabat *et al.*, 2009), and links to urban renovation (cost estimates are included in Section 23.7.6). While that plan mostly relies on large scale measures, new approaches such as small-scale containment of flood risks through compartmentalisation are also studied (Klijn *et al.*, 2009). The UK government has developed extensive adaptation plans (TE2100) to adjust and improve flood defences for the protection of London from future storm surges and flooding (Environmental Agency, 2009). An elaborate analysis has provided insight in the pathways for different adaptation options and decision-pointss that will depend on the eventual sea-level rise.

23.7.2. Integrated Water Resource Management

Water resources management in Europe has experienced a general shift from “hard” to “soft” measures that allow more flexible responses to environmental change (Pahl-Wostl, 2007). Integrated water resource management explicitly includes the consideration of environmental and social impacts (Wiering and Arts, 2006). Climate change has been incorporated into water resources planning in England and Wales (Arnell, 2011)(Charlton and Arnell, 2011)(Wade *et al.*, 2013) and in the Netherlands (de Graaff *et al.*, 2009). The robustness of adaptation strategies for water management in Europe has been tested in England (Dessai and Hulme, 2007) and Denmark (Haasnoot *et al.*, 2012; Refsgaard *et al.*, 2013). Other studies have emphasised the search for robust pathways, for instance in the Netherlands (Haasnoot *et al.*, 2012; Kwadijk *et al.*, 2010). Public participation has also increased in decision making, e.g. river basin management planning (Huntjens *et al.*, 2010), flood defence plans (e.g. TE2100), and drought contingency plans (Iglesias *et al.*, 2007). Guidance has been developed on the inclusion of adaptation in water management (UNECE, 2009) and river basin management plans (EC, 2009b). Adaptation in the water sector could also be achieved through the EU Water Framework and Flood Directives (Quevauviller, 2011), but a study of decision makers, including local basin managers, identified several important barriers to this (Brouwer *et al.*, 2013). Water allocation between upstream and downstream countries is challenging in regions exposed to prolonged droughts such as the Euphrates-Tigris river basin, where Turkey plans to more than double water abstraction by 2023(EEA, 2010a).

23.7.3. Disaster Risk Reduction and Risk Management

A series of approaches to disaster risk management are employed in Europe, in response to national and European policy developments to assess and reduce natural hazard risks. New developments since the AR4 include assessment and protection efforts in accordance with the EU Floods Directive (European Parliament and Council, 2007), the mapping of flood risks, improve civil protection response and early warning systems (Ciavola *et al.*, 2011). Most national policies address hazard assessment and do not include analyses of possible impacts (de Moel *et al.*, 2009). The effectiveness has been assessed of flood protection (Bouwer *et al.*, 2010) and also non-structural or household level measures to reduce losses from river flooding (Botzen *et al.*, 2010a)(Dawson *et al.*, 2011). Some studies show that current plans may be insufficient to cope with increasing risks from climate change, as shown for instance for the Rhine river basin (Te Linde *et al.*, 2010a; Te Linde *et al.*, 2010b).

Other options that are being explored are the reduction of consequences, response measures, and increasing social capital (Kuhlicke *et al.*, 2011), as well as options for insuring and transferring losses (Section 23.3.7). The Netherlands carried out a large-scale analysis and simulation exercise to study the possible emergency and evacuation response for a worst-case flood event (ten Brinke *et al.*, 2010). Increasing attention is also being paid in Europe to non-government actions that can reduce possible impacts from extreme events. Terpstra and Gutteling (2008) found through a survey that individual citizens are willing to assume some responsibility for managing flood risk, and they are willing to contribute to preparations in order to reduce impacts. Survey evidence is available for Germany and the Netherlands that, under certain conditions, individuals can be encouraged to adopt loss prevention measures (Thieken *et al.*, 2006)(Botzen *et al.*, 2009). Small businesses can reduce risks when informed about possibilities immediately after an event (Wedawatta and Ingirige, 2012).

23.7.4. Land Use Planning

Spatial planning policies can build resilience to the impacts of climate change (Bulkeley, 2010). However, the integration of adaptation into spatial planning is often limited to a general level of policy formulation that can sometimes lack concrete instruments and measures for implementation in practice (Mickwitz *et al.*, 2009)(Swart *et al.*, 2009a). There is evidence to suggest the widespread failure of planning policy to account for future climate change (Branquart *et al.*, 2008). Furthermore, a lack of institutional frameworks to support adaptation is, potentially, a major barrier to the governance of adaptation through spatial planning (ESPACE, 2007)[chapter 16]. Climate change adaptation is often treated as a water management or flooding issue, which omits other important aspects of the contribution of land use planning to adaptation (Mickwitz *et al.*, 2009)(Wilson, 2006)(Van Nieuwaal *et al.*, 2009). For example, in the UK, houses were still being built in flood risk areas (2001-2011) due to competing needs to increase the housing stock (ARUP, 2011).

City governance is also dominated by the issues of climate mitigation and energy consumption rather than in adapting to climate change (Bulkeley, 2010; Heidrich *et al.*, 2013). Some cities, e.g. Rotterdam, have started to create climate adaptation plans and this process tends to be driven by the strong political leadership of mayors (Sanchez-Rodriguez, 2009). The Helsinki Metropolitan Area's Climate Change Adaptation Strategy (HSY, 2010) is a regional approach focusing on the built environment in the cities of Helsinki, Espoo, Vantaa and Kauniainen, and their surroundings. It includes approaches for dealing with increasing heat waves, more droughts, milder winters, increasing (winter) precipitation, heavy rainfall events, river floods, storm surges, drainage water floods and sea level rise.

Green infrastructure provides both climate adaptation and mitigation benefits as well as offering a range of other benefits to urban areas, including health improvements, amenity value, inward investment, and the reduction of noise and outdoor air pollution. Green infrastructure is an attractive climate adaptation option since it also contributes to the sustainable development of urban areas (Gill *et al.*, 2007; James *et al.*, 2009). Urban green space and green roofs can moderate temperature and decrease surface rainwater run-off (Gill *et al.*, 2007). Despite the benefits however of urban green space, conflict can occur between the use of land for green space and building developments (Hamin and Gurran, 2009).

European policies for biodiversity (e.g. the European Biodiversity Strategy (EC, 2011)) look to spatial planning to help protect and safeguard internationally and nationally designated sites, networks and species, as well as locally valued sites in urban and non-urban areas, and to create new opportunities for biodiversity through the development process (Wilson, 2008). Conservation planning in response to climate change impacts on species aims to involve several strategies to better manage isolated habitats, increase colonisation capacity of new climate zones and optimise conservation networks to establish climate refugia (Vos *et al.*, 2008).

23.7.5. Rural Development

Rural development is one of the key policy areas for Europe, yet there is little or no discussion about the role of climate change in affecting future rural development. The EU White Paper on adapting to climate change (EC, 2009a) encourages Member States to embed climate change adaptation into the three strands of rural development aimed at improving competitiveness, the environment, and the quality of life in rural areas. It appears however that little progress has been made in achieving these objectives.

For example, the EUs Leader programme was designed to help rural actors improve the long-term potential of their local areas by encouraging the implementation of sustainable development strategies. Many Leader projects address climate change adaptation, but only as a secondary or in many cases a non-intentional by-product of the primary rural development goals. The World Bank’s community adaptation project has seen a preponderance of proposals from rural areas in Eastern Europe and Central Asia (Heltberg *et al.*, 2012) suggesting that adaptation based development needs in Eastern Europe are currently not being met by policy.

23.7.6. Economic Assessments of Adaptation

Compared to studies assessed in AR4 (AR4 WG2 Chapter 17.2.3), costs estimates for Europe are increasingly derived from bottom-up and sector-specific studies, aimed at costing response measures (Watkiss and Hunt, 2010), in addition to the economy-wide assessments (Aaheim *et al.*, 2012). The evidence base, however, is still fragmented and incomplete. The coverage of adaptation costs and benefit estimates is dominated by structural (physical) protection measures, where effectiveness and cost components can be more easily identified. For energy, agriculture, infrastructure there is medium coverage of cost and benefit categories. There is a lack of information regarding adaptation costs in the health and social care sector. Table 23-2 summarises some of the more comprehensive cost estimates for Europe for sectors at regional and national level. It is stressed that the costing studies use a range of methods and metrics and relate to different time periods and sectors, which renders robust comparison difficult. As an example, there are large differences between the cost estimates for coastal and river protection in the Netherlands and other parts of Europe (Table 23-2), this is due to the objectives for adaptation and the large differences in the level of acceptable risk. For example, Rojas *et al.* (2013) assess a 1 in 100 year level of protection for Europe, while the Netherlands has set standards up to 1 in 4,000 and 10,000 year level return periods. More detailed treatment of the economics of adaptation is provided in AR5 WG2 Chapter 17.

[INSERT TABLE 23-2 HERE
Table 23-2: Selected published cost estimates for planned adaptation in European countries.]

23.7.7. Barriers and Limits to Adaptation

The implementation of adaptation options presents a range of opportunities, constraints and limits. Constrains (barriers) to implementation are financial, technical and political (see discussion in AR5 WG2 16). Some impacts will be unavoidable due to limits (physical, technological, social, economic or political). Examples of limits in the European context are described by sector in Table 23-3. For example, the contraints on building or extending flood defences would include pressure for land, conservation needs, and amenity value of coastal areas (AR5 WG2 5.5.5).

Towards the end of the century, it is likely that adaptation limits are expected to be reached earlier under higher rates of warming. Opportunities and co-benefits of adaptation are also discussed in section 23.8 below.

[INSERT TABLE 23-3 HERE
Table 23-3: Limits to adaptation to climate change.]

23.8. Co-Benefits and Unintended Consequences of Adaptation and Mitigation

Scientific evidence for decision making is more useful if impacts are considered in the context of impacts on other sectors and in relation to adaptation, mitigation and other important policy goals. The benefits of adaptation and mitigation policies can be felt in the near term and in the local population, although benefits relating to greenhouse gas emissions reduction may not be apparent until the longer term. The benefits of adaptation measures are often assessed using conventional economic analyses, some of which include non-markets costs and benefits (externalities)(Watkiss and Hunt, 2010). This section will describe policies, strategies and measures where there is good evidence regarding mitigation/adaptation costs and benefits. Few studies have quantified directly the trade-offs/synergies for a given policy.

23.8.1. Production and Infrastructure

Mitigation policies (decarbonisation strategies) are likely to have important implications for dwellings across Europe. The unintended consequences of mitigation in the housing sector include: changes to household energy prices and adverse effects from decreased ventilation in dwellings (Mavrogianni *et al.*, 2012)(Davies and Oreszczyn, 2012)(Jenkins *et al.*, 2008; Jenkins, 2009). The location, type and dominant energy use of the building will determine its overall energy gain or loss to maintain comfort levels. Adaptation measures such as the use of cooling devices will probably increase a building's energy consumption if no other mitigation measures are applied. The potential for cooling dwellings without increased energy consumption, and with health benefits is large (Wilkinson *et al.*, 2009).

When looking at the broader context of urban infrastructures, despite existing efforts to include both adaptation, and mitigation into sustainable development strategies at city level (e.g. Hague, Rotterdam, Hamburg, Madrid, London, Manchester), priority on adaptation still remains low (Carter, 2011). There is potential to develop strategies that can address both mitigation and adaptation solutions, as well as have health and environmental benefits (Milner *et al.*, 2012). In energy supply, the adverse effect of climate change on water resources in some coastal regions in southern Europe may further enhance the development of desalination plants as an adaptation measure, possibly increasing energy consumption and thus greenhouse gases emissions. Coastal flood defence measures may alter vector habits and have implications for local vector-borne disease transmission (Medlock and Vaux, 2013).

In tourism, adaptation and mitigation may be antagonistic, as in the case of artificial snowmaking in European ski resorts which requires significant amounts of energy and water (OECD, 2007; Rixen *et al.*, 2011) and the case of desalination for potable water production which also requires energy. However, depending on the location and size of the resort, implications are expected to differ and thus need to be investigated on a case-by-case basis. A similar relationship between adaptation and mitigation may hold for tourist settlements in southern Europe, where expected temperature increases during the summer may require increased cooling in order to maintain tourist comfort and thus increase greenhouse gas emissions and operating costs. Furthermore, a change of tourist flows as a result of tourists adapting to climate change may affect transport emissions, while mitigation in transport could also lead to a change in transport prices and thus possibly affect tourist flows.

23.8.2. Agriculture, Forestry, and Bioenergy

Agriculture and forestry face two challenges under climate change, both to reduce emissions and to adapt to a changing and more variable climate (Smith and Olesen, 2010)(Lavalle *et al.*, 2009). The agriculture sector contributes to about 10% of the total anthropogenic greenhouse gas (GHG) emissions in the EU27 (EEA, 2010b). Estimates of European carbon dioxide, methane and nitrous oxide fluxes between 2000 and 2005 suggest that methane emissions from livestock and nitrous oxide emissions from agriculture are fully compensated for by the carbon dioxide sink provided by forests and by grassland soils (Schulze *et al.*, 2010). However, projections following a baseline scenario suggest a significant decline (-25 to -40%) of the forest carbon sink of the EU until 2030 compared to 2010. Using wood for bioenergy results initially in a carbon debt due to reduced storage in forests, which affects the net GHG balance depending on the energy type that is replaced and the time span considered (McKechnie et al., 2011). Including additional bioenergy targets of EU member states has an effect on the development of the European forest carbon sink (and on the carbon stock), which is not accounted for in the EU emission reduction target (Bottcher *et al.*, 2012).

In arable production systems, adapting to climate change by increasing the resilience of crop yields to heat and to rainfall variability would have positive impacts on mitigation by reducing soil erosion, as well as soil organic carbon and nitrogen losses. Improving soil water holding capacity through the addition of crop residues and manure to arable soils, or by adding diversity to the crop rotations, may contribute both to adaptation and to mitigation (Smith and Olesen, 2010). There are also synergies and trade-offs between mitigation and adaptation options for soil tillage, irrigation and livestock breeding (Smith and Olesen, 2010). Reduced tillage (and no-till) may contribute to both adaptation and mitigation as it tends to reduce soil erosion and run-off (Soane *et al.*, 2012) and fossil-fuel use (Khaledian *et al.*, 2010), while increasing in some situations soil organic carbon stock (Powlson *et al.*, 2011). However, increased N_2O emission may negate the mitigation effect of reduced tillage (Powlson *et al.*, 2011). Irrigation may enhance soil carbon sequestration in arable systems (Rosenzweig *et al.*, 2008)(Rosenzweig and Tubiello, 2007), but increased irrigation under climate change would increase energy use and may reduce water availability for hydro-power (reduced mitigation potential) (Wreford *et al.*, 2010). In intensive livestock systems, warmer conditions in the coming decades might trigger the implementation of enhanced cooling and ventilation in farm buildings (Rosenzweig and Tubiello, 2007), thereby increasing energy use and associated GHG emissions. In grass-based livestock systems, adaptation by adjusting the mean annual animal stocking density to the herbage growth potential (Graux *et al.*, 2012) is *likely* to create a positive feedback on GHG emissions per unit area (Soussana and Luscher, 2007; Soussana *et al.*, 2010).

Land management options may also create synergies and trade-offs between mitigation and adaptation. Careful adaptation of forestry and soil management practices will be required to preserve a continental ecosystem carbon sink in Europe (Schulze *et al.*, 2010) despite the vulnerability of this sink to climatic extremes (Ciais *et al.*, 2005) and first signs of carbon sink saturation in European forest biomass (Nabuurs *et al.*, 2013). In areas that are vulnerable to extreme events (e.g. fires, storms, droughts) or with high water demand, the development of bioenergy production from energy crops and from agricultural residues (De Wit *et al.*, 2011) (Fischer *et al.*, 2010b) could further increase demands on adaptation (Wreford *et al.*, 2010). Conversely, increased demands on mitigation could be induced by the potential expansion of agriculture at high latitudes which may release large amounts of carbon and nitrogen from organic soils (Rosenzweig and Tubiello, 2007).

23.8.3. Social and Health Impacts

Significant research has been undertaken since AR4 on the health co-benefits of mitigation policies (see WGIII chapters on Housing, Transport and Energy, and WGII chapter 11). Several assessment have quantified benefits in terms of lives saved by reducing particulate air pollution, and trying to coherent policy objectives for emissions reductions in local and global pollution. Policies that improve health from changes in transport and energy can be said to have a general benefit to population health and resilience (Haines *et al.*, 2009a; Haines *et al.*, 2009b).

Changes to housing and energy policies also have indirect implications for human health. Researches on the benefits of various housing options (including retrofitting) have been intensively addressed in the context of low energy, healthy and sustainable housing (see WGIII).

23.8.4. Environmental Quality and Biological Conservation

There are several conservation management approaches that can address both mitigation, adaptation and biodiversity objectives (Lal *et al.*, 2011). Some infrastructure adaptation strategies, such as desalinisation, sea defences and flood control infrastructure may have negative effects on both mitigation and biodiversity. However, approaches, such as forest conservation and urban green space (23.7.4) have multiple benefits and potentially significant effects. There has been relatively little research about the impacts of future land use demand for bioenergy production, food production and urbanisation on nature conservation.

Figure 23-6 (Paterson *et al.*, 2008) summarizes the evidence regarding mitigation and adaptation options on biodiversity assessed from the literature. The figure shows that the options that come closest to being win-win-win are green rooftops, urban tree planting, forest conservation and low-till cultivation. Other options with clear benefits are afforestation, forest pest control, increased farmland irrigation and species translocation.

[INSERT FIGURE 23-6 HERE
Figure 23-6: Adaptation and mitigation options and their effects on biodiversity. The horizontal axis ranges from positive effects on biodiversity (left-hand side) to negative effects (right-hand side). Each mitigation/adaptation option is located on the biodiversity effect axis (solid bars), including an estimate of the uncertainties associated with the assessment (error bars). The various options are given vertically with mitigation at the top and adaptation at the bottom. Options located toward the centre of the vertical axis have benefits for both mitigation and adaptation. Thus, options located at the centre left of the figure have benefits for mitigation, adaptation and biodiversity and hence are labelled as 'win-win-win'. Other combinations of benefits and dis-benefits are labelled accordingly, e.g. win-lose-win, lose-win-lose, etc. Based on Paterson et al., 2009.]

23.9. Synthesis of Key Findings

23.9.1. Key Vulnerabilities

Climate change will have adverse impacts in nearly all sectors and across all sub-regions. Table 23-4 describes the range of impacts projected in 2050 on infrastructure, settlements, environmental quality and the health and welfare of the European population. The projected impacts of climate change on ecosystem services (including food production) are described in Box 23-1. A key finding is that all sub-regions are vulnerable to some impacts from climate change but that these impacts differ significantly in type between the sub-regions. Impacts in neighbouring regions (inter-regional) may also redistribute economic activities across the European landscape. The sectors most likely to be affected by climate change, and therefore with implications for economic activity and population movement (changes in employment opportunities) include: tourism (23.3.6), agriculture (23.4.1), and forestry (23.4.4).

[INSERT TABLE 23-4 HERE
Table 23-4: Assessment of climate change impacts by sub-region by 2050, assuming a medium emissions scenario, and no planned adaptation. Impacts assume economic development, including land use change. Impacts are assessed for the whole sub-region, although differences in impact within sub-regions are estimated for some impacts.]

The majority of published assessments are based on climate projections in the range 1-4 degrees global mean temperature per century. Under these scenarios, regions in Europe may experience higher rates of warming (in the range 4-6 degrees per century), due to climate variability (Jacob et al. 2013). Limited evidence exists on the potential impacts in Europe under very high rates of warming (>4 degrees above pre-industrial levels) but these would lead to large increase in coastal flood risk as well as impacts on global cereal yields and other effects on the global economy (AR5 WG2 19.5.1).

Many key vulnerabilities are already well known since the AR4, but some new vulnerabilities are emerging based on the evidence reviewed in this report. The policy/governance context in Europe is extremely important in determining key vulnerabilities (either reducing or exacerbating vulnerability) since Europe is a highly regulated region. Further, vulnerability will be strongly affected by changes in the non-climate drivers of change (e.g. economic, social protection measures, governance, technological drivers).

Extreme events affect multiple sectors and have the potential to cause a systemic impacts from secondary effects (chapter 19). Past events indicate the vulnerability of transport, energy, agriculture, water resources and health systems. Resilience to very extreme events varies by sector, and by country (Ludwig *et al.*, 2011; Pitt, 2008; Ulbrich *et al.*, 2012). Extreme events (heat waves and droughts) have had significant impacts on populations as well impacts on multiple economic sectors (Table 23-1), and resilience to future heat waves has only been addressed within some sectors. However, there is surprisingly little evidence regarding the impacts of major extreme events (e.g. Russian heat wave of 2010) and on responses implemented post-event to increase resilience. Future vulnerability will also be strongly affected by cross-sectoral (indirect) interactions, e.g. flooding-ecosystems, agriculture-species, agriculture-cultural landscapes, and so on.

Climate change is likely to have significant impacts on future water availability, and the increased risks of water restrictions in Southern, Central and Atlantic sub-regions. Studies indicate a significant reduction in water availability from river abstraction and from groundwater resources, combined to increased demands from a range of sectors (irrigation, energy and industry, domestic use) and to reduced water drainage and run-off (as a result of increased evaporative demand) (Ludwig *et al.*, 2011).

Climate change will affect rural landscapes by modifying relative land values, and hence competition, between different land-uses (Smith *et al.*, 2010). This will occur directly, e.g. through changes in the productivity of crops and trees [23.4], and indirectly through climate change impacts on the global supply of land-based commodities and their movement through international trade [23.9.2].

Climate change will have a range of impacts in different European sub-regions. The adaptive capacity of populations is likely to vary significantly within Europe. Adaptive capacity indicators have been developed based on future changes in socio-economic indicators and projections (Lung *et al.*, 2012; Metzger *et al.*, 2008)(Acosta *et al.*, 2013). These studies concluded that the Nordic countries have higher adaptive capacity than most of the Southern European countries, with countries around the Mediterranean having a lower capacity than the countries around the Baltic Sea region. Some regions or areas are particularly vulnerable to climate change:

- Populations and infrastructure in coastal regions are likely to be adversely affected by sea level rise, particularly after mid-century [23.3.1, 23.5.3].
- Urban areas are also vulnerable due to high density of people and built infrastructure from weather extremes [23.3, 23.5.1].
- High mountains. Due to high impact of climate change on natural hazard, water and snow resources and lack of migration possibilities for plant species, mountain regions concentrate vulnerabilities in infrastructure for transport and energy sectors, as well as for tourism, agriculture and biodiversity
- Mediterranean region will suffer multiple stresses and systemic failures due to climate changes. Changes in species composition, increase of alien species, habitat losses and degradation both in land and sea together with agricultural and forests production losses due to increasing heat waves and droughts exacerbated also by the competition for water will increase the sub-region vulnerability (Ulbrich *et al.*, 2012).

The following risks have emerged from observations of climate sensitivity and observed adaptation:

- Arable crop yields. There is new evidence to suggest that crop yields and production may be more vulnerable as a result of increasing climate variability. This will limit the potential poleward expansion of agricultural production. Limits to genetic progress to adapt are increasingly reported.

- New evidence regarding implications during summer on inland waterways (decreased access) and long range ocean transport (increased access).
- Terrestrial and freshwater species are vulnerable from climate-change shifts in habitats. There is new evidence that species cannot populate new habitat due to habitat fragmentation (urbanization). Observed migration rates are less than that assumed in modelling studies. There are legal barriers to introducing new species (e.g. forest species in France). New evidence that phenological mismatch will cause additional adverse effects on some species.
- A positive (and emerging) effect that may reduce vulnerability is that many European governments (and individual cities) have become aware of the need to adapt to climate change and so are developing and/or implementing adaptation strategies and measures.

Additional risks have emerged from the assessed literature:

- Increased summer energy demand, especially in southern Europe, requires additional power generation capacity, which will be under-utilised during the rest of the year, entailing higher supply costs.
- Housing will be affected, with increased overheating under no adaptation and damage from subsidence and flooding. Passive cooling measures alone are unlikely to be sufficient to address adaptation in all regions and types of buildings. Retrofitting current housing stock will be expensive.
- An emerging concern is the vulnerability of cultural heritage, including monuments/buildings and cultural landscapes. Some cultural landscapes will disappear. Grape production is highly sensitive to climate, but production (of grape varieties) is strongly culturally-dependent and adaptation is potentially limited by the regulatory context.
- Good evidence that climate change will increase distribution and seasonal activity of pests and diseases. Limited evidence that such effects already occurring. Increased threats to plant and animal health. Public policies are in place to reduce pesticide use in agriculture use and antibiotics in livestock, and this will increase vulnerability to the impact of climate change on agriculture and livestock production.
- Lack of institutional frameworks is a major barrier to adaptation governance. In particularly, the systematic failure in land use planning policy to account for climate change.

[INSERT TABLE 23-5 HERE
Table 23-5: Key risks from climate change in Europe and the potential for reducing risk through mitigation and adaptation. Risk levels are presented in three timeframes: the present, near-term (2030-2040), and longer-term (2080-2100). For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions. Key risks were identified based on assessment of the literature and expert judgment.]

23.9.2. Climate Change Impacts Outside Europe and Inter-Regional Implications

With increasing globalization, the impacts of climate change outside the European region are likely to have implications for countries within the region. For example, the Mediterranean region (Southern Europe and non-European Mediterranean countries) has been considered high vulnerable to climate change (Navarra, 2013). Eastern European countries have, in general, lower adaptive capacity than Western or Northern European countries. The high volume of international travel increases Europe’s vulnerability to invasive species, including the vectors of human and animal infectious diseases. The transport of animals and animal products has facilitated the spread of animal diseases (Conraths and Mettenleiter, 2011). Important “exotic” vectors that have become established in Europe include the vector *Aedes albopictus* (Becker, 2009) (23.5.1).

Another inter-regional implication concerns the changes in the location of commercial fish stocks shared between countries. Such changes may render existing international agreements regarding the sharing of yield from these stocks obsolete giving rise to international disputes (Arnason, 2012). For instance, the North Sea mackerel stock has recently been extending westwards beyond the EU jurisdiction into the Exclusive Economic Zones of Iceland and the Faroe Islands, which unilaterally claimed quota for mackerel Territorial disagreements of this type could increase in the future with climate change.

Although several studies have proposed a role of climate change to increase migration pressures in low and middle income countries in the future, there is little robust information regarding the role of climate change, environmental resource depletion and weather disasters in future inter-continental population movements. The effect of climate change on external migration flows into Europe is highly uncertain (see chapter 12.4.1 for a more complete discussion). Modelling future migration patterns is complex and so far no robust approaches have been developed.

23.9.3. Effects of Observed Climate Change in Europe

Table 23-6 summarises the evidence with respect to key indicators in Europe for the detection of a trend and the attribution of that trend to observed changes in climate factors. The attribution of local warming to anthropogenic climate change is less certain (see Chapter 18 for a full discussion). Further and better quality evidence since 2007 supports the conclusion of AR4 (Europe chapter, Alcamo et al., 2007) that climate change is affecting land, freshwater and marine ecosystems in Europe. Observed warming has caused advancement in the life cycles of many animal groups, including frogs spawning, birds nesting and the arrival of migrant birds and butterflies (see WGII chapter 4 and review by (Feehan *et al.*, 2009). There is further evidence that observed climate change is already affecting agricultural, forest and fisheries productivity (see 23.4).

The frequency of river flood events, and annual flood and windstorm damages in Europe have increased over recent decades, but this increase is mainly due to increased exposure and the contribution of observed climate change is unclear (high confidence – based on robust evidence and high agreement)(SREX 4.5.3, (Barredo, 2010).

The observed increase in the frequency of hot days and hot nights (high confidence, WGI) is likely to have increased heat-related health effects in Europe (medium confidence), and well as a decrease in cold related health effects (medium confidence) (Christidis *et al.*, 2010). Multiple impacts on health, welfare and economic sectors were observed due to the major heat wave events of 2003 and 2010 in Europe (Table 23-5) (see Chapter 18 for discussion on attribution of events).

[INSERT TABLE 23-6 HERE
Table 23-6: Observed changes in key indicators in ecological and human systems attributable to climate factors.]

23.9.4. Key Knowledge Gaps and Research Needs

There is a clear mismatch between the volume of scientific work on climate change since the AR4 and the insights and understanding required for policy needs, as many categories of impacts are still understudied. Some specific research needs have been identified:

- Little information is available on integrated and cross-sectoral climate change impacts in Europe, as the impact studies typically describe a single sector [see sections 23.3 to 23.6]. This also includes a lack of information on cross-sector vulnerabilities, and the indirect effects of climate change impacts and adaptation responses. This is a major barrier in developing successful evidence-based adaptation strategies that are cost-effective.
- Climate change impact models are difficult to validate [sections 23.3 to 23.6]; proper testing of the characteristics of baseline impact estimates against baseline information and data would improve their reliability, or the development of alternative methods where baseline data are not available.
- There is little knowledge on the co-benefits and unintended consequences of adaptation options across a range of sectors [section 23.3 to 23.6].
- There is a need to better monitor and evaluate local and national adaptation and mitigation responses to climate change, in both public and private sectors [23.7; Box 23-3]. This includes policies and strategies– as well as the effectiveness of individual adaptation measures. Evaluation of adaptation strategies, over a range of time-scales, would better support decision-making. While some means for reporting of national

actions exist in Europe (e.g. EU Climate-ADAPT), there is no consistent method of monitoring or a mechanism for information exchange [23.7].
- There are now more economic methods and tools available for the costing and valuation of specific adaptation options, in particular for flood defences, water, energy, and agriculture sectors [23.7.6]. However, for other sectors, such as biodiversity, business and industry, and population health costs, cost estimates are still lacking or incomplete. The usefulness of this costing information in decision making need to be evaluated and research can be undertaken to make economic evaluation more relevant to decision making.
- The need for local climate information to inform decision making also needs to be evaluated.
- Further research is needed on the effects of climate change on critical infrastructure (including transport, and water and energy supplies, health services) [23.5.2].
- Further research is needed on the role of governance in adaptation (including local and national institutions) with respect to implementation of measures in the urban environment, including flood defences, over-heating, and urban planning.
- The impacts for Europe from high end scenarios of climate change (above 4°C global average warming, with higher temperature change in Europe) are yet unknown. This is because such scenarios have only recently become available, and related impact studies still need to be undertaken for Europe.
- More study of the implications of climate change for rural development would inform policy in this area [23.7.5]. There is also a lack of information on the resilience of cultural landscapes and communities, and how to manage adaptation, particularly in low technology (productively marginal) landscapes.
- More research is needed for the medium and long- term monitoring of forest responses and adaptation to climate change and on the predictive modelling of wildfire distribution to better address adaptation and planning policies. There is also a lack of information on the impact of climate changes and climate extremes on carbon sequestration potential of agricultural and forestry systems [23.4.4].
- More research on the impacts of climate change on transport, especially on the vulnerability of road and rail infrastructure, and on the contribution of climatic and non-climatic parameters in the vulnerability of air transport (e.g. changes in air traffic volumes, airport capacities, air traffic demand, weather at the airports of origin, intermediate and final destination) [23.3.3].
- Improved monitoring of droughts is needed to support the management of crop production [23.4]. Remote sensing could be complemented by field experiments that assess the combined effects of elevated CO_2 and extreme heat and drought on crops and pastures.
- Research is needed on the resilience of human populations to extreme events (factors which increase resilience), including responses to flood and heat wave risks. Inequalities – and how adaptation policies may increase or reduce social inequalities [23.5].
- Development of improved risk models for vector borne disease (human and animal diseases) in order to support health planning and surveillance [23.4.2, 23.5.1].

A major barrier to research is lack of access to data, which is variable across regions and countries (especially with respect to socio-economic data, climate data, forestry, and routine health data). There is a need for long term monitoring of environmental and social indicators and to ensure open access to data for long-term and sustainable research programmes. Cross-regional cooperation could also ensure compatibility and consistency of parameters across the European region.

Frequently Asked Questions

FAQ 23.1: Will I still be able to live on the coast in Europe? *[to remain at the end of the chapter]*
Coastal areas affected by storm surges will face increased risk both because of the increasing frequency and of storms and because of higher sea level. Most of this increase in risk will occur after the middle of this century. Models of the coast line suggest that populations in the north western region of Europe are most affected and many countries, including the Netherlands, Germany, France, Belgium, Denmark, Spain and Italy, will need to strengthen their coastal defences. Some countries have already raised their coastal defence standards. The combination of raised sea defences and coastal erosion may lead to narrower coastal zones in the North Sea, the Iberian coast, and Bay of Biscay. Adapting dwellings and commercial buildings to occasional flooding is another response to climate change.

But while adapting buildings in coastal communities and upgrading coastal defences can significantly reduce adverse impacts of sea level rise and storm surges, they cannot eliminate these risks, especially as sea levels will continue to rise over time. In some locations, 'managed retreat' is likely to become a necessary response.

FAQ 23.2: Will climate change introduce new infectious diseases into Europe?
[to remain at the end of the chapter]
Many factors play a role in the introduction of infectious diseases into new areas. Factors that determine whether a disease changes distribution include: importation from international travel of people, vectors or hosts (insects, agricultural products), changes in vector or host susceptibility, drug resistance, and environmental changes, such as land use change or climate change. One area of concern that has gained attention is the potential for climate change to facilitate the spread tropical diseases, such as malaria, into Europe. Malaria was once endemic in Europe. Even though its mosquito vectors are still present and international travel introduces fresh cases, malaria has not become established in Europe because infected people are quickly detected and treated. Maintaining good health surveillance and good health systems are therefore essential to prevent diseases from spreading. When an outbreak has occurred (i.e. the introduction of a new disease) determining the causes is often difficult. It is likely that a combination of factors will be important. A suitable climate is a necessary but not a sufficient factor for the introduction of new infectious diseases.

FAQ 23.3: Will Europe need to import more food because of climate change?
[to remain at the end of the chapter]
Europe is one of the world's largest and most productive suppliers of food, but also imports large amounts of some agricultural commodities. A reduction in crop yields, particularly wheat in southern Europe, is expected under future climate scenarios. A shift in cultivation areas of high value crops, such as grapes for wine, may also occur. Loss of food production may be compensated by increases in other European sub-regions. However, if the capacity of the European food production system to sustain climate shock events is exceeded, the region would require exceptional food importation.

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Table 23-1: Impacts of climate extremes in the last decade in Europe.

Year	**Region**	**Meteorological Characteristics**	**Production Systems and Physical Infrastructure, settlements**	**Agriculture, Fisheries, Forestry, Bioenergy**	**Health and Social Welfare**	**Environmental Quality and Biological Conservation**	**Mega-fire**
2003	Western and Central Europe	Hottest summer in at least 500 years (Luterbacher *et al.*, 2004)	Damage to road and rail transport systems. Reduced/ interrupted operation of nuclear power plants (mostly in France). High transport prices in Rhine due to low water levels.	Grain harvest losses of 20% (Ciais, et al. 2005)	35,000 deaths in August in Central and Western Europe, (Robine *et al.* 2008)	Decline in water quality (Daufresne et al. 2007). High outdoor pollution levels (EEA 2012)	Yes
2004/ 2005	Iberian Peninsula - Portugal	Hydrological drought	-	Grain harvest losses of 40% (EEA, 2010c)	-	-	
2007	Southern Europe	Hottest summer on record in Greece since 1891 (Founda & Giannakopoulos 2009)	1710 buildings burned down or rendered uninhabitable in Greece (JRC, 2008)	Approx. 575,500 hectares burnt area (JRC, 2008)	Significant mortality impact: 6 deaths in Portugal, 80 deaths in Greece.	Several protected conservation sites (Natura 2000) were destroyed (JRC, 2008)	Yes, - Greece
2007	England and Wales	May–July wettest since records began in 1766.	Estimated total losses £4 billion (£3 billion insured losses) (Chatterton et al. 2010). Failure of pumping station led to 20,000 people without water for 2 weeks	78 farms flooded. Impacts on agriculture £50 million (Chatterton et al. 2010)	13 deaths and 48,000 flooded homes (Pitt, 2008). Damage costs for health effects, incl. loss of access to education £ 287 million (Chatterton et al. 2010)		
2010	Western Russia	Hottest summer since 1500 (Barriopedro *et al.*, 2011)		Fire damage to forests (Shvidenko et al., 2011). Reduction in crop yields (Coumou and Rahmstorf, 2012)	Estimated 10,000 excess deaths due to heatwave in Moscow in July and August (Revich and Shaposhnikov, 2012)	High outdoor pollution levels in Moscow (Bondur, 2011, Revich and Shaposhnikov, 2012)	Yes
2011	France	Hottest and driest spring in France since 1880	Reduction in snow cover for skiing	8% decline in wheat yield (AGRESTE, 2011)			

* Extreme events derived from Coumou and Rahmstorf, 2012.

Table 23-2: Selected published cost estimates for planned adaptation in European countries.

Region	**Cost estimate**	**Time period**	**Sectors/Outcomes**	**Reference**
Europe	€2.6-3.5 billion/a	In 2100	Coastal adaptation costs	Hinkel et al. 2010
Europe	€1.7 billion/a €3.4 billion/a €7.9 billion/a	By 2020s By 2050s By 2080s	Protection from river flood risk for EU27	Rojas et al., in press
Netherlands	€1.2–1.6 billion/a €0.9–1.5 billion/a	up to 2050 2050–2100	Protection from coastal and river flooding	Delta Committee, 2008
Sweden	total of up to €10 billion	2010-2100	Multi sector	Swedish Commission on Climate and Vulnerability, 2007
Italy	€0.4-2 billion Up to € 44 billion	By 2080s	Coastal protection Hydrogeological protection	Bosello et al. 2012, Medri et al. 2013.
Greece	€0.4-3.3 billion	Up to 2100	Coastal protection	Bank of Greece, 2011
UK	€1.8 billion €2.2 billion €7-8 billion	Until 2035 2035-2050 At 2100	Maintain and improve Thames flood protection Renew and improve Thames flood protection New Thames barrier for London	EA, 2011

Table 23-3: Limits to adaptation to climate change.

Area/Location	**System**	**Adaptation measures**	**Limits to adaptation measure(s)**	**References**
Low altitude/ small-size ski resorts	Ski tourism	Artificial snowmaking	Climatic, technological and environmental constraints Economic viability Social acceptability of charging for previously free skiing. Social acceptability of alternatives for winter sport/leisure.	Landauer et al, 2012 ; Steiger, 2010; Steiger, 2011; Steiger and Mayer, 2008, Unbehaun et al., 2008
Thermal power plants/ cooling through river intake and discharge	Once-through cooling systems	Closed- circuit cooling	High investment cost for retrofitting existing plants	van Vliet et al., 2012, Koch and Vögele, 2009, Hoffman et al., 2013
Rivers used for freight transport	Inland transport	Reduced load factor of inland ships	Increased transport prices (Rhine and Moselle market)	Jonkeren, 2009, Jonkeren et al., 2007
		Use of smaller ships	Existing barges below optimal size (Rhine)	Demirel, 2011
Agriculture, Northern and Continental Europe.	Arable crops	Sowing date as agricultural adaptation	Other constraints (e.g. frost) limit farmer behaviour	Oort, 2012
Agriculture, Northern and Continental Europe.	Arable crops	Irrigation	Groundwater availability, competition with other users.	Olesen *et al.*, 2011
Agriculture, Viticulture	High value crops	Change distribution	Legislation on cultivar and geographical region	Box 23-1
Conservation Cultural landscapes	Alpine meadow/	Extend habitat	No technological adaptation option.	Engler *et al.*, 2011, Dullinger *et al.*, 2012
Conservation of species richness	Movement of species	Extend habitat	Landscape barriers and absence of climate projections in selection of conservation areas.	Butchart et al., 2010, Araújo *et al.*, 2011; Filz *et al.*, 2012; Virkkala *et al.*, 2013
Forests	Movement of species and productivity reduction	Introduce new species	Not socially acceptable, Legal barriers to non-native species	Giuggiola *et al.*, 2010; Hemery *et al.*, 2010; García-López J.M. and Alluéa, 2011, Casalegno *et al.*, 2007

Table 23-4: Assessment of climate change impacts by sub-region by 2050, assuming a medium emissions scenario, and no planned adaptation. Impacts assume economic development, including land use change. Impacts are assessed for the whole sub-region, although differences in impact within sub-regions are estimated for some impacts.

	Alpine	**Southern**	**Northern**	**Continental**	**Atlantic**	
Energy						
Wind energy production		[1]				23.3.4
Hydropower generation	[2]					23.3.4
Thermal power production						23.3.4, 8.2.3.2
Energy consumption (net annual change)						23.3.4, 23.8.1
Transport						
Road accidents [3]						23.3.3
Rail delays (weather-related)	?	?		?	[4]	23.3.3, 8.3.3.6
Load factor of inland ships	?	?	?			23.3.3
Transport time and cost in ocean routes	?	?			?	23.3.3, 18.3.3.3.5
Settlements						
River flood damages						23.3.1
Coastal flood damages	n/a					23.3.1
Tourism						
Length of ski season		?			?	23.3.6, 3.5.7
Human health						
Heat wave mortality and morbidity						23.5.1
Food safety						23.5.1

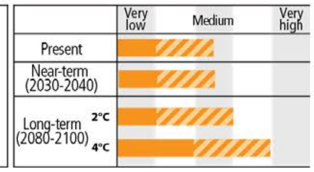
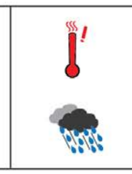
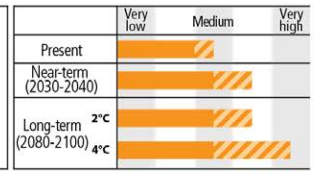
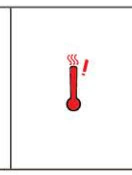
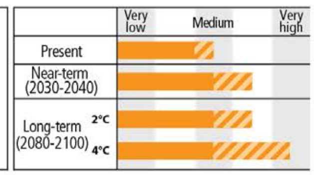
Social and cultural Impacts						
Social costs of floods	→	→	→	↗ (red) ↘ (green)	↗ (red) ↘ (green)	23.5.3
Damage on cultural buildings	↗ (red)	↗ (red) ↘ (green)	↗ (red)	↗ (red)	↗ (red)	23.5.4
Loss of cultural landscapes	↗ (red)	?	↗ (red)	↗ (red)	↗ (red)	23.5.4
Environmental quality						
Air quality (ozone background levels)	?	↗ (red) ↘ (green)	↗ (red) ↘ (green)	↗ (red) ↘ (green)	↗ (red) ↘ (green)	23.6.1
Air quality (particulates)	?	→	→	→	→	23.6.1
Water quality	→	↘ (red)	→	→	↘ (red)	23.6.3

Key:
Green means a "beneficial" change
Red means a "harmful" change
? means no relevant literature found

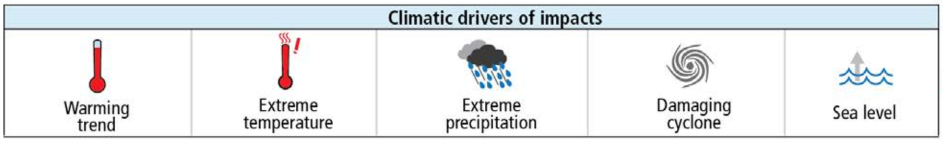
Confidence levels:
Risks were identified based on assessment of the literature and expert judgment.

Footnotes:
[1] Simulations have been performed, but mostly for the period after 2070.
[2] The increasing trend is for Norway.
[3] The decreasing trend refers mainly to the number of severe accidents.
[4] Impacts have been studied and quantified for UK only. The increasing trend stands for summer delays and the decreasing trend for winter delays.
[5] In both seasons, no significant impacts are expected by 2020, while more substantial changes are expected by 2080. For 2050 impacts are assumed to vary linearly (although this may not be the case).
[6] The constant trend stands for the Mediterranean, where some studies estimate no changes due to climate change at least until 2030 or even 2060.

Table 23-5: Key risks from climate change in Europe and the potential for reducing risk through mitigation and adaptation. Risk levels are presented in three timeframes: the present, near-term (2030-2040), and longer-term (2080-2100). For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions. Key risks were identified based on assessment of the literature and expert judgment.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe / Risk for current and high adaptation
Increased economic losses and people affected by flooding in river basins and coasts, driven by increasing urbanisation and by increasing sea-levels and increasing peak river discharges (*high confidence*)	Adaptation can prevent most of the projected damages (high confidence). The experience in hard flood protection technologies is significant. Main issues include the high costs for increasing flood protection demand for land in Europe, and environmental and landscape concerns.		23.2.3, 23.3.1, 23.7	
Increased water restrictions. Significant reduction in water availability from river abstraction and from groundwater resources, combined to increased demands from a range of sectors (irrigation, energy and industry, domestic use) and to reduced water drainage and run-off (as a result of increased evaporative demand) (*high confidence*)	Proven adaptation potential from changes in technologies and adoption of more water efficient technologies and of water saving strategies (irrigation, crop species, land cover, industries, domestic use). Further adaptation possible through solar desalinization (to limit fossil fuel demand).		23.4.3, 23.4.4, 23.7.2	
Increased economic losses and people affected by extreme heat events: impacts on health, welfare (overheating in buildings), labour productivity, crop production, reduced air quality (*medium confidence*)	Implementation of warning systems, adaptation of dwellings and work places, and transport and energy infratructure. Reductions in emissions to improve air quality. Improved wild fire management.		23.3.2, 23.3.4, 23.3.3, 23.5, 23.6.1, 23.6.3, 23.7.4	

Climatic drivers of impacts



Risk & potential for adaptation

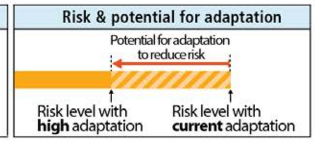


Table 23-6: Observed changes in key indicators in ecological and human systems attributable to climate factors.

Indicator	*Change in indicator*	*Confidence in detection*	*Confidence in attribution to change in climate factors [**]*	*Key references*	*Section*
Bio-Physical Systems					
Glacier retreat	Fast mass loss of 30 Swiss glaciers since the 1980s	High confidence	Medium confidence	Huss, 2010	18.3.1.3 WG1 10.5
Infrastructure					
Storm losses	Increase since 1970s	High confidence	No causal role for climate	Barredo, 2010	23.3.7
Hail losses	Increase in parts of Germany	Low confidence	Low confidence	Kunz *et al.*, 2009	23.3.7
Flood losses	Increasing general trend in economic losses in Europe since 1970s; none in some locations	Medium confidence	No causal role for climate	Barredo, 2009; Barredo et al., 2012	23.3.1
Agriculture, Fisheries, Forestry, and Bioenergy Production					
C3 crop yield	CO_2 induced positive contribution to yield since preindustrial for C3 crops	High confidence (high agreement, robust evidence)	High confidence (high agreement, robust evidence)	Amthor, 2001; Long *et al.*, 2006; McGrath and Lobell, 2011	7.2.1
Wheat yield	Stagnation of wheat yields in some countries in recent decades	High confidence	Medium confidence	Lobell *et al*. 2011 ; Brisson et al., 2010; Kristensen et al., 2011	23.4.1
Phenology –leaf greening	Earlier greening, Earlier leaf emergence and fruit set in temperate and boreal climate,	High confidence (high agreement, robust evidence)	High confidence (high agreement, robust evidence)	Menzel *et al.*, 2006	4.4.1.1
Phytoplankton productivity	Increased phytoplankton productivity in NE. Atlantic, decrease in warmer regions, due to warming trend and hydroclimatic variations	High confidence	Medium confidence	Beaugrand *et al.*, 2002; Edwards and Richardson, 2004	6.3.2
Ocean systems	Northward movement of species and increased species richness due to warming trend	High confidence	Medium confidence	Philippart *et al.* , 2011	6.3.2
Environmental quality and biodiversity					
Biodiversity	Increased number of colonization events by alien plant species in Europe	Medium confidence (high agreement, medium evidence)	Medium confidence	Walther *et al.*, 2009	4.2.4.6
Migratory birds	Decline over the period 1990-200 of species that did not advance their spring migration	Medium confidence (medium agreement, medium evidence)	Medium confidence	Moller *et al.*, 2008	4.4.1.1
Tree species	Upward shift in tree line in Europe	Medium evidence (medium agreement, high evidence)	Medium confidence	Gehrig-Fasel *et al.*, 2007, Lenoir *et al.*, 2008	18.3.2.1
Forest fires	Increase in burnt area	High confidence	High confidence (high agreement, robust evidence)	Camia and Amatulli 2009; Hoinka et al., 2009; Carvalho et al., 2010; Salis et al., in press; Pereira et al., 2005; Koutsias et al., 2012	23.4.4

NOTE: The studies included in this table are those with good evidence of a detection of a long term trend in the outcome of interested, and where there has been an assessment of the attribution of the trend to an observed change in climate factor. It is not possible to make an attribution to anthropogenic climate change at this scale – see chapter 18 for a more complete discussion.

BOX 23-1 TABLE

	Alpine	**Atlantic**	**Continental**	**Northern**	**Southern**
Provisioning services:					
Food production	No (1) ∨ (4)	∨ (1)	∨ (1)	∧ (1) ∨ (1)	∨ (1)
Livestock production	No (1) ∨ (1)				
Fibre production	∨ (1)				
Bioenergy production	∧ (1)			∧ (1)	∨ (1)
Fish production		No (1) ∨ (1)	∨ (1)	No (1) ∨ (1)	No (1) ∨ (2)
Timber production	∧ (5) No (2) ∨ (5)	∧ (2) No (3)	∧ (1) No (2) ∨ (1)	∧ (6) No (1)	V (2)
Non-wood forest products				∧ (1) No (1)	∨ (1)
Sum of effects on provisioning services	∧ (6) No (4) ∨ (11)	∧ (2) No (4) ∨ (2)	∧ (1) No (2) ∨ (3)	∧ (9) No (3) ∨ (2)	No (1) ∨ (7)
Regulating services:					
Climate regulation (carbon sequestration)					
- General/forests	∧ (4) No (1) ∨ (3)	∧ (4) No (1)	∧ (3) No (1)	∧ (4) No (1) ∨ (1)	∧ (3) ∨ (1)
- Wetland		No (1) ∨ (1)	∨ (1)	No (1) ∨ (1)	No (1) ∨ (1)
- Soil carbon stocks	No (1) ∨ (2)	No (1) ∨ (2)	No (1) ∨ (1)	∨ (3)	No (1) ∨ (1)
Pest control	∧ (1)		∧ (1)	∧ (1)	∨ (1)
Natural hazard regulation*					
- Forest fires / wildfires		∨ (1)	∨ (2)		∨ (1)
- Erosion, avalanche, landslide	∧ (2) ∨ (1)				
- Flooding	∨ (1)				
- Drought			∨ (1)		No (1) ∨ (1)
Water quality regulation		∨ (1)		∨ (1)	
Biodiversity	∧ (2) ∨ (4)	∧ (2) No (1) ∨ (4)	∧ (2) ∨ (4)	∧ (3) ∨ (2)	∧ (1) ∨ (8)
Sum of effects on regulating services	∧ (9) No (2) ∨ (11)	∧ (6) No (4) ∨ (9)	∧ (6) No (2) ∨ (9)	∧ (8) No (2) ∨ (8)	∧ (4) No (3) ∨ (14)
Cultural services:					
Recreation (fishing, nature enjoyment)		∨ (1)		∧ (1) ∨ (2)	∨ (1)
Tourism (skiing)	∨ (1)			∨ (1)	

	Alpine	**Atlantic**	**Continental**	**Northern**	**Southern**
Asthetic/heritage (landscape character, cultural landscapes)	∧ (1)	∨ (1)	No (1) ∨ (1)		∨ (1)
Sum of effects on cultural services	∧ (1) ∨ (1)	∧ (1) ∨ (1)	No (1) ∨ (1)	∧ (1) ∨ (3)	∨ (2)

Key:
∨ = decreasing impacts
∧ = increasing impacts
No = neutral effect
(1) = number in brackets refers to the number of studies supporting the change (increasing, decreasing, neutral) in ecosystem service.

Footnotes:
* A decline in ecosystem services implies an increased risk of the specified natural hazard
^ Entries for biodiversity are those that were found during the literature search for climate change impacts on ecosystem services. A wider discussion of the impacts of climate change on biodiversity can be found in Section 23.6 and AR5 4.3.4.

References:
Albertson *et al.*, 2010; Bastian, 2013; Bolte *et al.*, 2009; Briner *et al.*, 2012; Canu *et al.*, 2010; Civantos *et al.*, 2012; Clark *et al.*, 2010a; Forsius *et al.*, 2013; Fuhrer *et al.*, 2006; Garcia-Fayos and Bochet, 2009; Gret-Regamy *et al.*, 2008; Gret-Regamy *et al.*, 2013; Hemery, 2008; Johnson *et al.*, 2009; Koca *et al.*, 2006; Lindner *et al.*, 2010; Lorz *et al.*, 2010; Metzger *et al.*, 2008; Milad *et al.*, 2011; Okruszko *et al.*, 2011; Palahi *et al.*, 2008; Rusch, 2012; Schroter *et al.*, 2005; Seidl *et al.*, 2011; Seidl and Lexer, 2013; Wessel *et al.*, 2004.

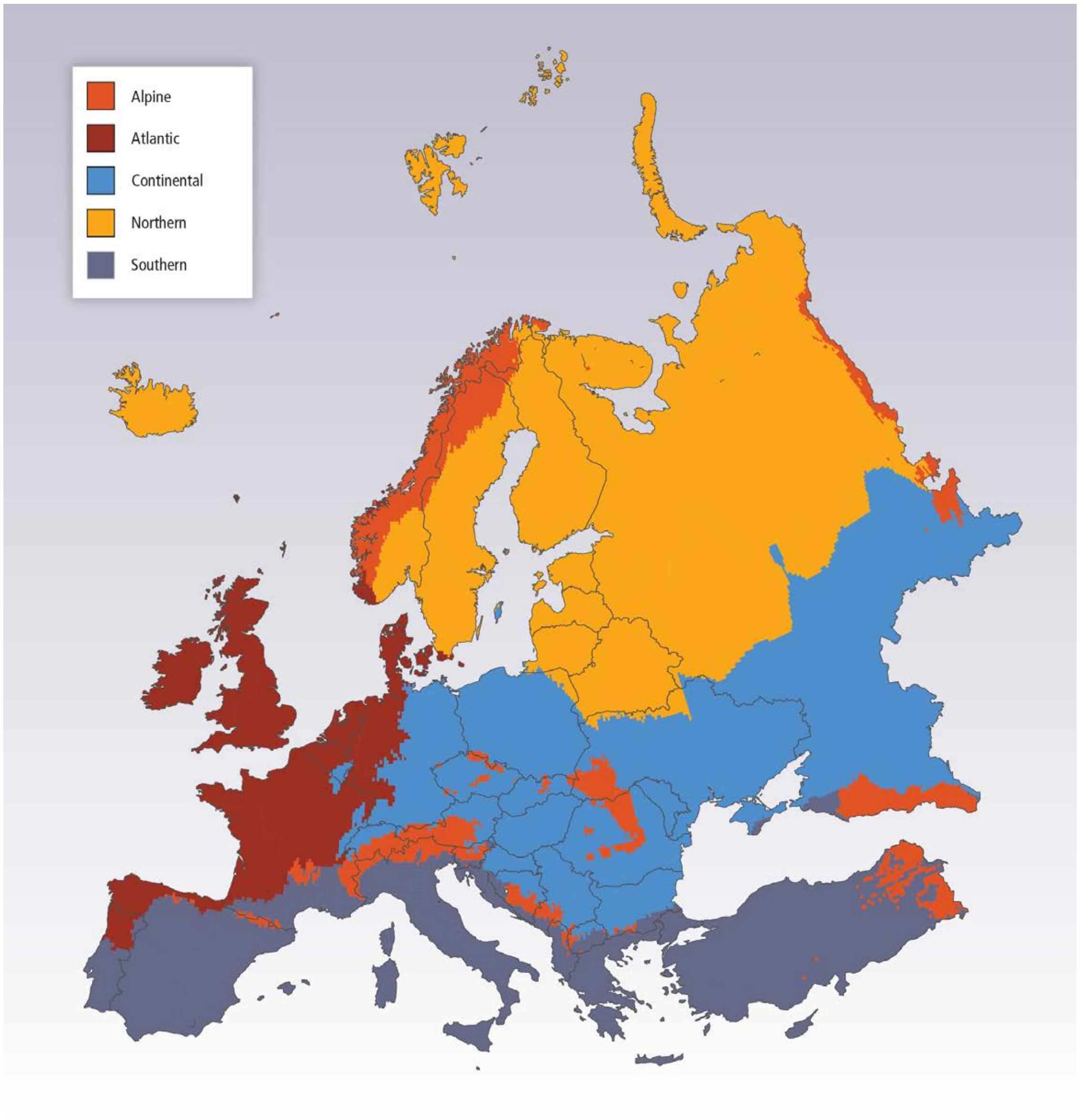


Figure 23-1: Sub-regional classification of the IPCC Europe region. Based on Metzger et al., 2005.

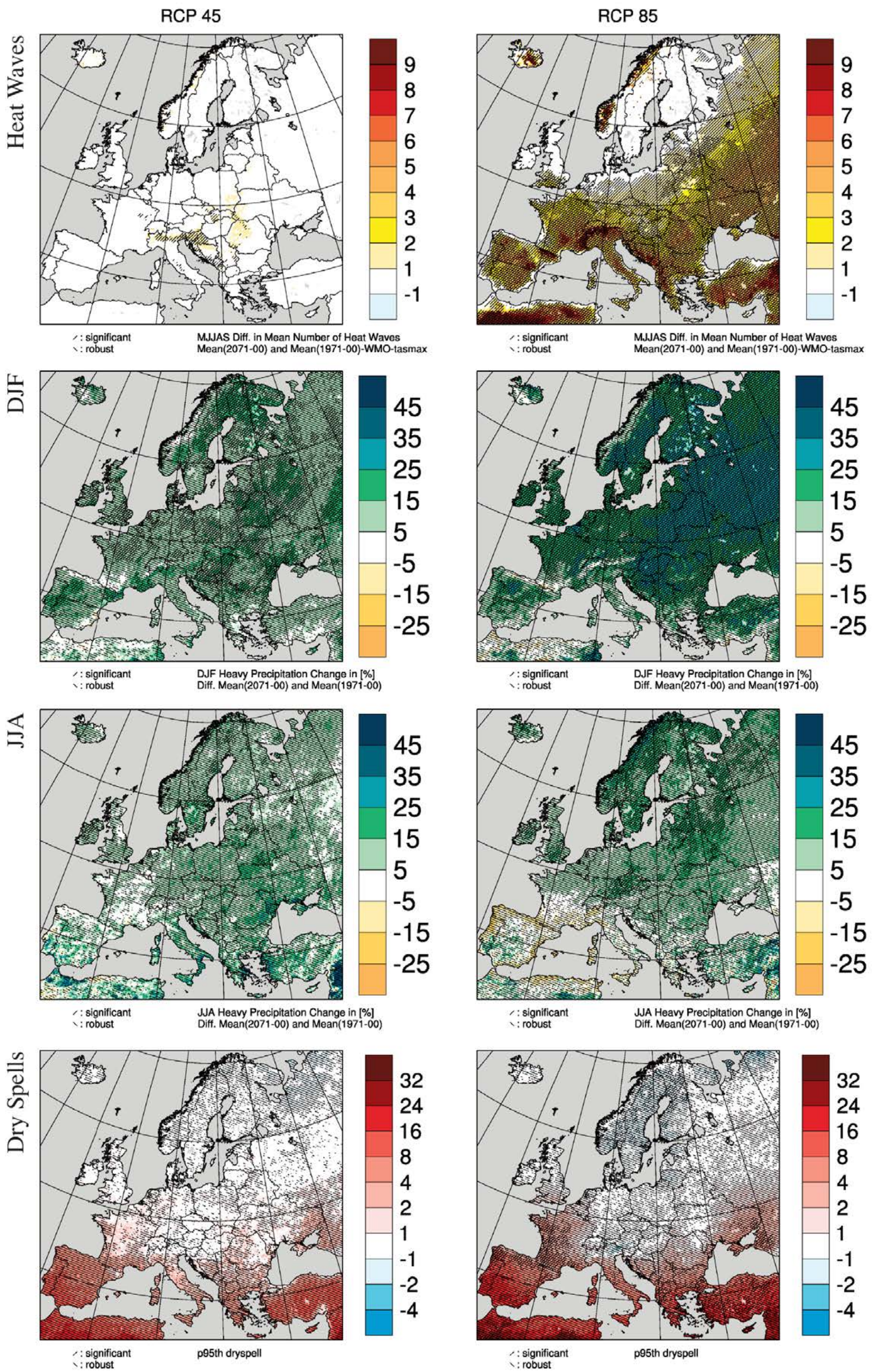

RCP 45
RCP 85
Heat Waves
DJF
JJA
Dry Spells
9
8
7
6
5
4
3
2
1
-1
⁄ : significant
∖ : robust
MJJAS Diff. in Mean Number of Heat Waves
Mean(2071-00) and Mean(1971-00)-WMO-tasmax
45
35
25
15
5
-5
-15
-25
DJF Heavy Precipitation Change in [%]
Diff. Mean(2071-00) and Mean(1971-00)
JJA Heavy Precipitation Change in [%]
Diff. Mean(2071-00) and Mean(1971-00)
32
24
16
8
4
2
1
-1
-2
-4
p95th dryspell

Figure 23-2: First row: Projected changes in the mean number of heat waves occurring in the months May to September for the period 2071-2100 compared to 1971-2000 (number per 30 years). Heat waves are defined as periods of more than 5 consecutive days with daily maximum temperature exceeding the mean maximum temperature of the May to September season of the control period (1971-2000) by at least 5°C. Second and third rows: Projected seasonal changes in heavy precipitation defined as the 95th percentile of daily precipitation (only days with precipitation > 1mm/day are considered) for the period 2071-2100 compared to 1971-2000 (in %) in the months December to January (DJF) and June to August (JJA). Fourth row: Projected changes in the 95th percentile of the length of dry spells for the period 2071-2100 compared to 1971-2000 (in days). Dry spells are defined as periods of at least 5 consecutive days with daily precipitation below 1mm. Hatched areas indicate regions with robust (at least 66% of models agree in the sign of change) and/or statistical significant change (significant on a 95% confidence level using Mann-Whitney-U test). For the eastern parts of Black Sea, Eastern Anatolia and Southeast Anatolia (Turkey), no regional climate model projections are available. Changes represent the mean over 8 (RCP4.5, left side) and 9 (RCP8.5, right side) regional model simulations compiled within the EURO-CORDEX initiative. Adapted from Jacob et al. (2013). **[Illustration to be redrawn to conform to IPCC publication specifications.]**

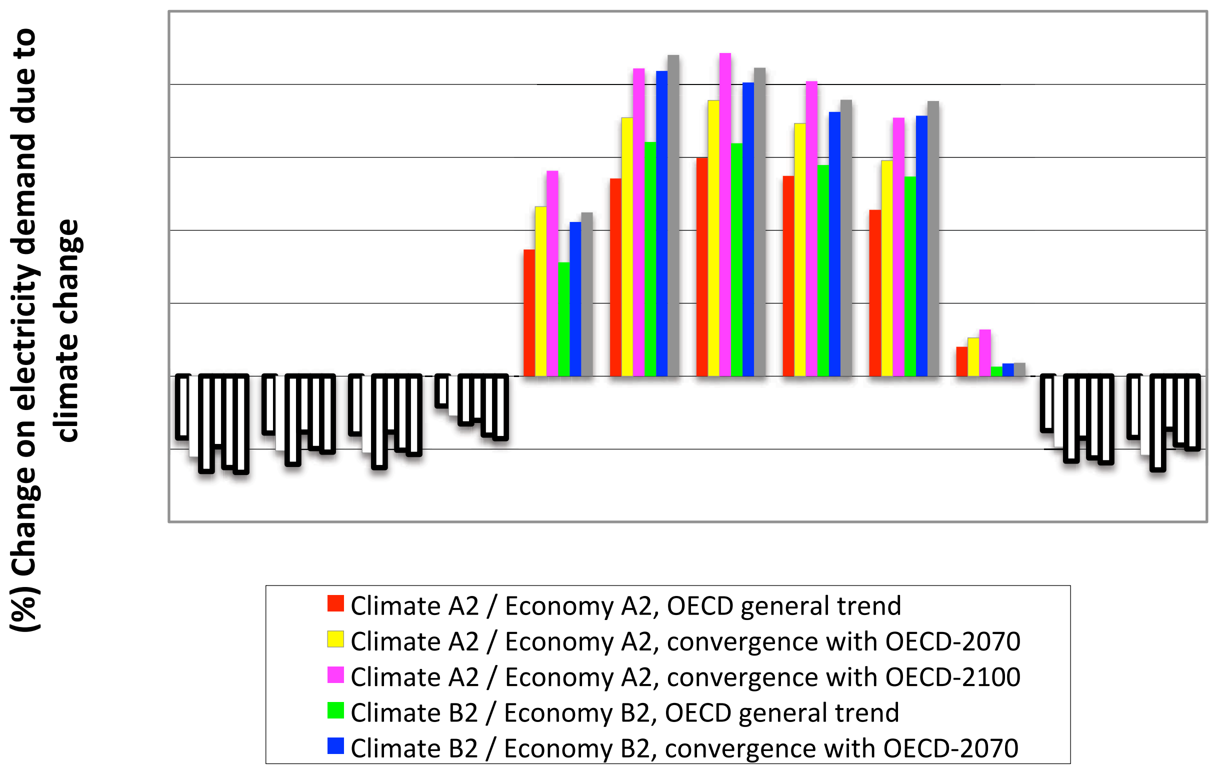


Figure 23-3: Percentage change in electricity demand in Greece attributable to climate change, under a range of climate scenarios and economic assumptions. Source: Mirasgedis et al., 2007.
[Illustration to be redrawn to conform to IPCC publication specifications.]

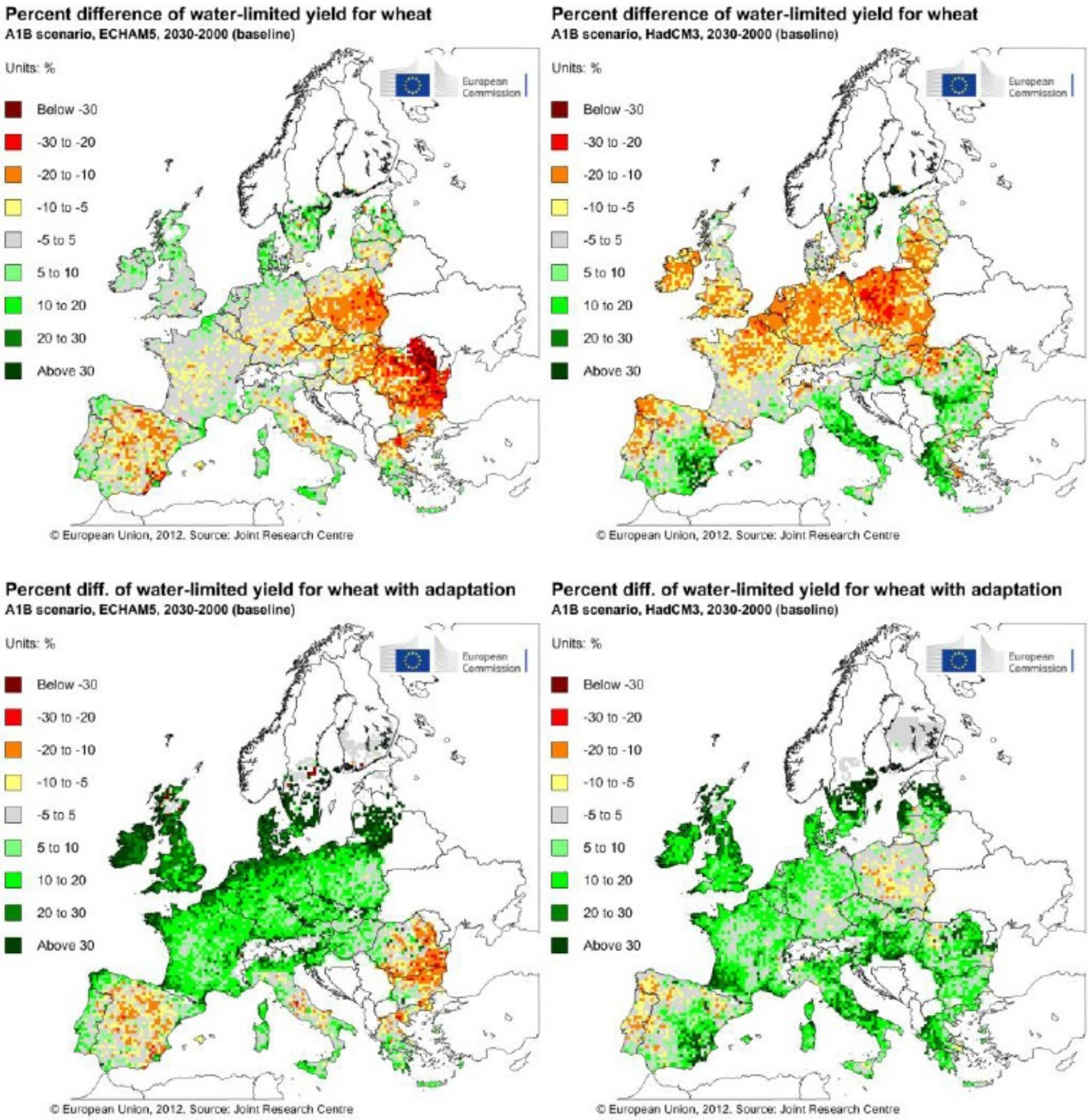


Figure 23-4: Percentage change in simulated water-limited yield for winter wheat in 2030 with respect to the 2000 baseline for the A1B scenario using ECHAM5 (left column) and HadCM3 (right) GCMs. Upper maps to do not take adaptation into account. Bottom maps include adaptation. Source: Donatelli et al., 2012.
[Illustration to be redrawn to conform to IPCC publication specifications.]

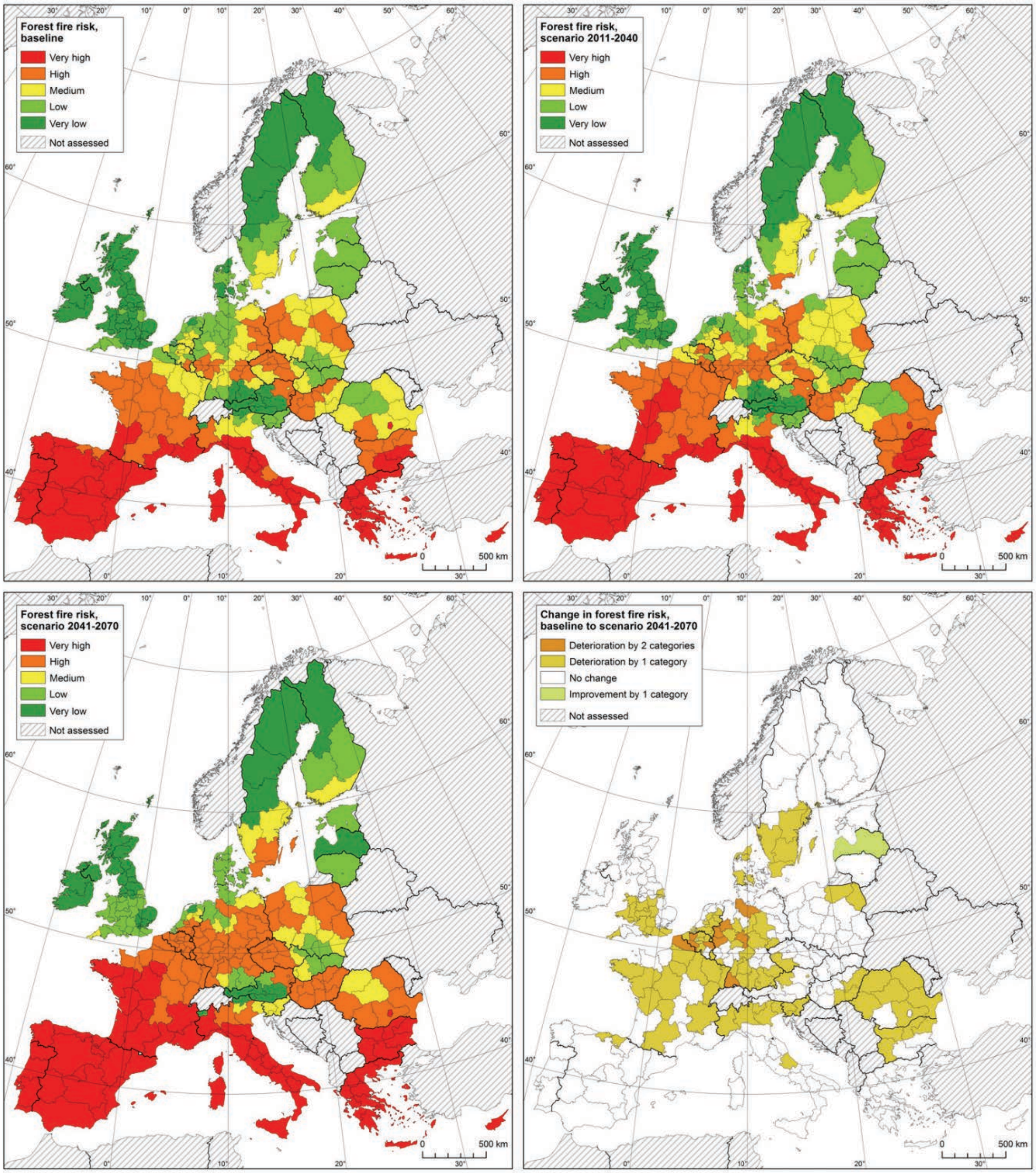


Figure 23-5: Changes in forest fire risk in Europe for two time periods: baseline (left) and 2041–2070 (right), based on high-resolution regional climate models and the SRES A1B emission scenario. Source: Lung et al., 2013.
[Illustration to be redrawn to conform to IPCC publication specifications.]

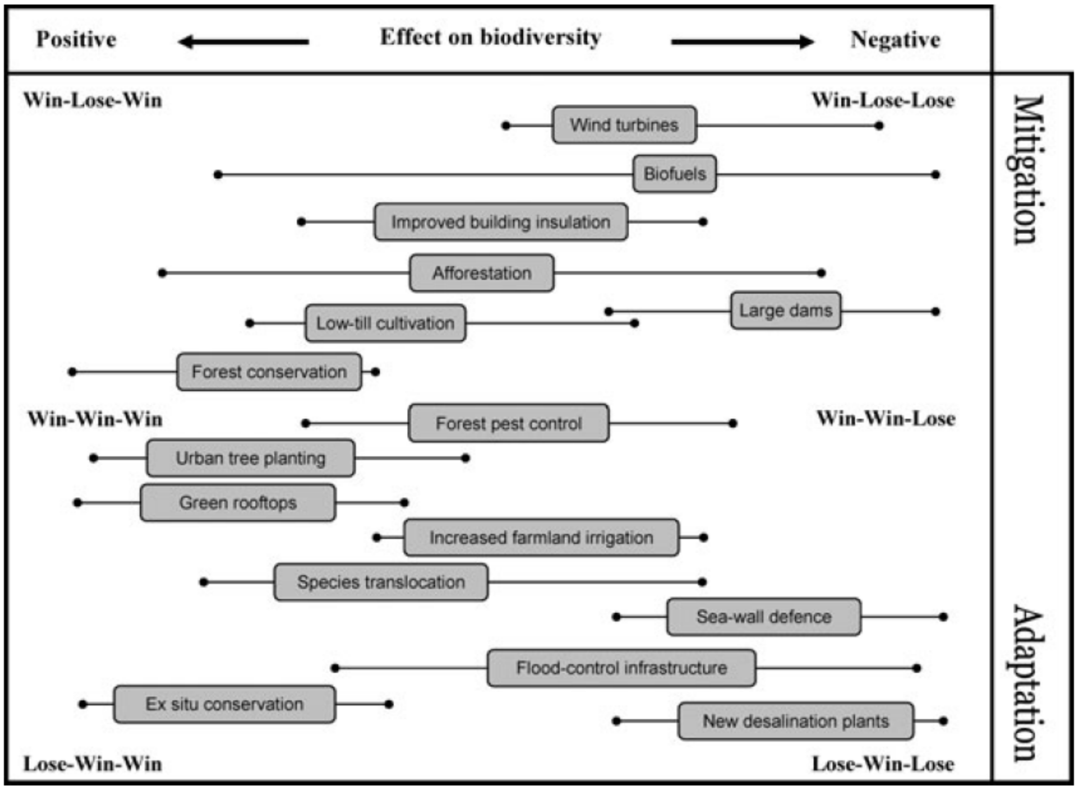


Figure 23-6: Adaptation and mitigation options and their effects on biodiversity. The horizontal axis ranges from positive effects on biodiversity (left-hand side) to negative effects (right-hand side). Each mitigation/adaptation option is located on the biodiversity effect axis (solid bars), including an estimate of the uncertainties associated with the assessment (error bars). The various options are given vertically with mitigation at the top and adaptation at the bottom. Options located toward the centre of the vertical axis have benefits for both mitigation and adaptation. Thus, options located at the centre left of the figure have benefits for mitigation, adaptation and biodiversity and hence are labelled as 'win-win-win'. Other combinations of benefits and dis-benefits are labelled accordingly, e.g. win-lose-win, lose-win-lose, etc. Based on Paterson et al., 2009.
[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 24. Asia

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Contents

Executive Summary

Warming trends and increasing temperature extremes have been observed across most of the Asian region over the past century (*high confidence*) [24.3]. Increasing numbers of warm days and decreasing numbers of cold days have been observed, with the warming trend continuing into the new millennium. Precipitation trends including extremes are characterized by strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia.

Water scarcity is expected to be a major challenge for most of the region due to increased water demand and lack of good management (*medium confidence*) [24.4.3]. Water resources are important in Asia because of the massive population and vary among regions and seasons. However, there is *low confidence* in future precipitation projections at a subregional scale and thus in future freshwater availability in most parts of Asia. Population growth and increasing demand arising from higher standards of living could worsen water security in many parts in Asia and affect many people in future. Integrated water management strategies could help adapt to climate change, including developing water saving technologies, increasing water productivity, and water reuse.

The impacts of climate change on food production and food security in Asia will vary by region with many regions to experience a decline in productivity (*medium confidence*) [24.4.4]. This is evident in the case of rice production. Most models, using a range of GCMs and SRES scenarios, show that higher temperatures will lead to lower rice yields as a result of shorter growing periods. There are a number of regions that are already near the heat stress limits for rice. However, CO_2 fertilization may at least in part offset yield losses in rice and other crops. In Central Asia, some areas could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters and slight increase in winter precipitation), while others could be losers (western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase water demand for irrigation, and exacerbate desertification). In the Indo-Gangetic Plains of South Asia there could be a decrease of about 50% in the most favorable and high yielding wheat area due to heat stress at 2x CO_2. Sea-level rise will inundate low lying areas and will especially affect rice growing regions. There are many potential adaptation strategies being practiced and being proposed but research studies on their effectiveness are still few.

Terrestrial systems in many parts of Asia have responded to recent climate change with shifts in the phenologies, growth rates, and the distributions of plant species, and permafrost degradation, and the projected changes in climate during the 21st Century will increase these impacts (*high confidence*) [24.4.2]. Boreal trees will *likely* invade treeless arctic vegetation, while evergreen conifers will *likely* invade deciduous larch forest. Large changes may also occur in arid and semiarid areas, but uncertainties in precipitation projections make these more difficult to predict. The rates of vegetation change in the more densely populated parts of Asia may be reduced by the impact of habitat fragmentation on seed dispersal, while the impacts of projected climate changes on the vegetation of the lowland tropics are currently poorly understood. Changes in animal distributions have also been projected, in response to both direct impacts of climate change and indirect impacts though changes in the availability of suitable habitats.

Coastal and marine systems in Asia are under increasing stress from both climatic and non-climatic drivers (*high confidence*) [24.4.3]. It is *likely* that mean sea-level rise will contribute to upward trends in extreme coastal high water levels [WG1 Section 3.7.6]. In the Asian Arctic, rising sea-levels are expected to interact with projected changes in permafrost and the length of the ice-free season to cause increased rates of coastal erosion (*high agreement, medium evidence*). Mangroves, salt marshes and seagrass beds may decline unless they can move inland, while coastal freshwater swamps and marshes will be vulnerable to saltwater intrusion with rising sea-levels**.** Widespread damage to coral reefs correlated with episodes of high sea-surface temperature has been reported in recent decades and there is *high confidence* that damage to reefs will increase during the 21^{st} century as a result of both warming and ocean acidification. Marine biodiversity is expected to increase at temperate latitudes as warm-water species expand their ranges northwards (*high confidence*), but may decrease in the tropics if thermal tolerance limits are exceeded (*medium confidence*).

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

Extreme climate events will have an increasing impact on human health, security, livelihoods, and poverty, with the type and magnitude of impact varying across Asia (*high confidence*) [24.4.6]. More frequent and intense heat-waves in Asia will increase mortality and morbidity in vulnerable groups. Increases in heavy rain and temperature will increase the risk of diarrheal diseases, dengue fever and malaria. Increases in floods and droughts will exacerbate rural poverty in parts of Asia due to negative impacts on the rice crop and resulting increases in food prices and the cost of living.

Studies of observed climate changes and their impacts are still inadequate for many areas, particularly in North, Central and West Asia (*high confidence*) [24.8]. Improved projections for precipitation, and thus water supply, are most urgently needed. Understanding of climate change impacts on ecosystems in Asia is currently limited by the incompleteness and inaccessibility of biodiversity information. Major research gaps in the tropics include the temperature dependence of carbon fixation by tropical trees and the thermal tolerances and acclimation capacities of both plants and animals. Interactions between climate change and the direct impacts of rising CO_2 on crops and natural ecosystems are also currently poorly understood. More research is needed on impacts, vulnerability and adaptation in urban settlements, especially cities with populations under 500,000. More generally, there is a need to develop low-cost adaptation measures appropriate to the least developed parts of the region.

24.1. Introduction

Asia is defined here as the land and territories of 51 countries/regions (see Figure 24-1). It can be broadly divided into six subregions based on geographical position and coastal peripheries. These are (in alphabetical order) Central Asia (5 countries), East Asia (7 countries/regions), North Asia (2 countries), South Asia (8 countries), Southeast Asia (12 countries) and West Asia (17 countries). The population of Asia was reported to be about 4,299 million in 2013, which is about 60% of the world population (UN, 2013). The population density was reportedly about 134 per square kilometer in 2012 (PRB, 2012). The highest life expectancy at birth is 84 (Japan) and the lowest is 50 (Afghanistan) (CIA, 2013). The GDP per capita ranged from US$620 (Afghanistan for 2011) to US$46,720 (Japan for 2012) (World Bank, 2013).

[INSERT FIGURE 24-1 HERE
Figure 24-1: The land and territories of 51 countries in Asia.
NOTE: Currently in production and will be brought to specification using the current UN-accepted maps.]

24.2. Major Conclusions from Previous Assessments

Major highlights from previous assessments for Asia include:

- Warming trends including higher extremes are strongest over the continental interiors of Asia, and warming in the period 1979 onwards was strongest over China in winter, and northern and eastern Asia in spring and autumn (see WGI AR4 Section 3.2.2.7 and SREX Section 3.3.1).
- From 1900 to 2005, precipitation increased significantly in northern and central Asia but declined in parts of southern Asia (see WGI AR4 SPM).
- Future climate change is *likely* to affect water resource scarcity with enhanced climate variability and more rapid melting of glaciers (see WGII AR4 Section 10.4.2)
- Increased risk of extinction for many plant and animal species in Asia is *likely* as a result of the synergistic effects of climate change and habitat fragmentation (see WGII AR4 Section 10.4.4).

- Projected sea-level rise is *very likely* to result in significant losses of coastal ecosystems (see WGII AR4 Sections 10.4.3.2, 10.6.1).
- There will be regional differences within Asia in the impacts of climate change on food production (see WGII AR4 Section 10.4.1.1).
- Due to projected sea-level rise, a million or so people along the coasts of South and Southeast Asia will *likely* be at risk from flooding (*high confidence*, see WGII AR4 Section 10.4.3.1).
- It is *likely* that climate change will impinge on sustainable development of most developing countries of Asia as it compounds the pressures on natural resources and the environment associated with rapid urbanisation, industrialisation and economic development (see WGII AR4 Section 10.7).
- Vulnerabilities of industry, infrastructure, settlements and society to climate change are generally greater in certain high-risk locations, particularly coastal and riverine areas (see WGII AR4 Section 7.3, 7.4, 7.5).

_____ START BOX 24-1 HERE _____

Box 24-1. What's New on Asia in AR5?

- Improved country coverage on observed and future impacts of climate change
- Increase in the number of studies reflecting advances in research tools (e.g. more use of remote sensing and modeling of impacts); with an evaluation of detection and attribution where feasible.
- More conclusions have confidence statements, while confidence levels have changed in both directions since AR4.
- Expanded coverage of issues: for example discussion of the Himalayas has been expanded to cover observed and projected impacts (see Box 3-2), including those on: tourism (see Section10.6.2); livelihood assets such as water and food (see Sections 9.3.3.1, 13.3.1.1, 18.5.3 and 19.6.3); poverty (see Section 13.3.2.3); culture (see Sections 12.3.2); flood risks (see Sections 18.3.1.1 and 24.2.1); health risks (see Section 24.4.6.2); and ecosystems (see Section 24.4.2.2).

_____ END BOX 24-1 HERE _____

24.3. Observed and Projected Climate Change

24.3.1. Observed Climate Change

Temperature. It is *very likely* that mean annual temperature has increased over the past century over most of the Asia region, but there are areas of the interior and at high latitudes where the monitoring coverage is insufficient for the assessment of trends (see WGI AR5 Chapter 2, Figure 24-2). New analyses continue to support the AR4 and SREX conclusions that it is *likely* that the numbers of cold days and nights have decreased and the numbers of warm days and nights have increased across most of Asia since about 1950, and heat wave frequency has increased since the middle of the 20th century in large parts of Asia (see WGI AR5 Section 2.6.1).

As a part of the polar amplification, large warming trends (>2°C per 50 years) in the second half of the 20th century were observed in the northern Asian sector (see WGI AR5 Section 14.8.8). Over the period 1901-2009, the warming trend was particularly strong in the cold season between November and March, with an increase of 2.4°C in the mid-latitude semi-arid area of Asia (see WGI AR5 Section 14.8.8). Increasing annual mean temperature trends at the country scale in East and South Asia have been observed during the 20th century (Table 24-SM-1). In West Asia, upward temperature trends are notable and robust in recent decades (see WGI AR5 Section 14.8.10). Across Southeast Asia, temperature has been increasing at a rate of 0.14°C to 0.20°C per decade since the 1960s, coupled with a rising number of hot days and warm nights, and a decline in cooler weather (see WGI AR5 Section 14.8.12).

Precipitation and Monsoons. Most areas of the Asian region lack sufficient observational records to draw conclusions about trends in annual precipitation over the past century (see WGI AR5 Chapter 2, Figure 24-2, Table 24-SM-2). Precipitation trends, including extremes, are characterized by strong variability, with both increasing and decreasing trends observed in different parts and seasons of Asia (see WGI AR5 Chapter 14 and Table 24-SM-2). In northern Asia, the observations indicate some increasing trends of heavy precipitation events, but in central Asia, no spatially coherent trends were found (see WGI AR5 Section 14.8.8). Both the East Asian summer and winter monsoon circulations have experienced an interdecadal scale weakening after the 1970s, due to natural variability of the coupled climate system, leading to enhanced mean and extreme precipitation along the Yangtze River valley (30°N), but deficient mean precipitation in North China in summer (see WGI AR5 Section 14.8.9). A weakening of the East Asian summer monsoon since the 1920s was also found in sea level pressure gradients (*low confidence*, see WGI AR5 Section 2.7.4). In West Asia, a weak but non-significant downward trend in mean precipitation was observed in recent decades, although with an increase in intense weather events (see WGI AR5 Section 14.8.10). In South Asia, seasonal mean rainfall shows interdecadal variability, noticeably a declining trend with more frequent deficit monsoons under regional inhomogeneities (see WGI AR5 Section 14.8.11). Over India, the increase in the number of monsoon break days and the decline in the number of monsoon depressions are consistent with the overall decrease in seasonal mean rainfall (see WGI AR5 Section 14.8.11). But an increase in extreme rainfall events occurred at the expense of weaker rainfall events over the central Indian region and in many other areas (see WGI AR5 Section 14.2.2.1). In South Asia, the frequency of heavy precipitation events is increasing, while light rain events are decreasing (see WGI AR5 Section 14.8.11). In Southeast Asia, annual total wet-day rainfall has increased by 22 mm per decade, while rainfall from extreme rain days has increased by 10 mm per decade, but climate variability and trends differ vastly across the region and between seasons (see WGI AR5 Section 14.4.12, 14.8.12). In Southeast Asia, between 1955 and 2005 the ratio of rainfall in the wet to the dry seasons increased. While an increasing frequency of extreme events has been reported in the northern parts of Southeast Asia, decreasing trends in such events are reported in Myanmar (see WGI AR5 Section 14.4.12). In Peninsular Malaya during the southwest monsoon season, total rainfall and the frequency of wet days decreased, but rainfall intensity increased in much of the region. On the other hand, during the northeast monsoon, total rainfall, the frequency of extreme rainfall events, and rainfall intensity all increased over the peninsula (see WGI AR5 Section 14.4.12).

Tropical and Extratropical Cyclones. Significant trends in tropical cyclones making landfall are not found on shorter timescales. Time series of cyclone indices show weak upward trends in the western North Pacific since the late 1970s, but interpretation of longer-term trends is constrained by data quality concerns (see WGI AR5 Section 2.6.3). A decrease in extratropical cyclone activity and intensity over the last 50 years has been reported for northern Eurasia (60°N-40°N), including lower latitudes in East Asia (see WGI AR5 Section 2.6.4).

Surface Wind Speeds. Over land in China, including the Tibetan region, a weakening of the seasonal and annual mean winds, as well as the maximums, is reported from around the 1960s or 1970s to the early 2000s (*low confidence,* see WGI AR5 Section 2.7.2).

Oceans. A warming maximum is observed at 25°N-65°N with signals extending to 700 m depth and is consistent with poleward displacement of the mean temperature field (see WGI AR5 Section 3.2.2). The pH measurements between 1983 and 2008 in the western North Pacific showed a -0.0018 ± 0.0002 yr^{-1} decline in winter and -0.0013 ± 0.0005 yr^{-1} decline in summer (see WGI AR5 Section 3.8.2). Over the period 1993-2010, large rates of sea-level rise in the western tropical Pacific were reported, corresponding to an increase in the strength of the trade winds in the central and eastern tropical Pacific (see WGI AR5 Section 13.6.1). Spatial variation in trends in Asian regional sea level may also be specific to a particular sea or ocean basin. For example, a rise of 5.4 ± 0.3 mm yr^{-1} in the Sea of Japan from 1993 to 2001 is nearly two times the GMSL trend, with more than 80% of this rise being thermosteric, and regional changes of sea level in the Indian Ocean that have emerged since the 1960s are driven by changing surface winds associated with a combined enhancement of Hadley and Walker cells (see WGI AR5 Section 13.6.1).

24.3.2. Projected Climate Change

The AR4 assessed that warming is *very likely* in the 21st century (Christensen *et al.*, 2007), and that assessment still holds for all land areas of Asia in the mid- and late-21^{st}-century, based on the CMIP5 simulations under all four RCP scenarios (Figures 24-2, 24-SM-1, and Table 24-SM-3). Ensemble-mean changes in mean annual temperature exceed 2˚C above the late-20^{th}-century baseline over most land areas in the mid-21^{st}-century under RCP8.5, and range from greater than 3˚C over South and Southeast Asia to greater than 6˚C over high latitudes in the late-21^{st}-

century. The ensemble-mean changes are less than 2˚C above the late-20th-century baseline in both the mid- and late-21st-century under RCP2.6, with the exception of changes between 2˚C and 3˚C over the highest latitudes.

Projections of future annual precipitation change are qualitatively similar to those assessed in the AR4 (Christensen *et al.*, 2007) (Figure 24-2). Precipitation increases are *very likely* at higher latitudes by the mid-21st-century under the RCP8.5 scenario, and over eastern and southern areas by the late-21st-century. Under the RCP2.6 scenario, increases are *likely* at high latitudes by the mid-21st century, while it is *likely* that changes at low latitudes will not substantially exceed natural variability.

[INSERT FIGURE 24-2 HERE
Figure 24-2: Observed and projected changes in annual average temperature and precipitation in Asia.]

Tropical and Extra-Tropical Cyclones. The future influence of climate change on tropical cyclones is *likely* to vary by region, but there is *low confidence* in region-specific projections of frequency and intensity. However, better process understanding and model agreement in specific regions indicate that precipitation will likely be more extreme near the centers of tropical cyclones making landfall in West, East, South and Southeast Asia (see WGI AR5 Sections 14.6, 14.8.9, 14.8.10, 14.8.11, 14.8.12). There is *medium confidence* that a projected poleward shift in the North Pacific storm track of extratropical cyclones is *more likely than not*. There is *low confidence* in the magnitude of regional storm track changes and the impact of such changes on regional surface climate (see WGI AR5 Section 14.6)

Monsoons. Future increases in precipitation extremes related to the monsoon are *very likely* in East, South and Southeast Asia (see WGI AR5 Sections 14.2.1, 14.8.9, 14.8.11, 14.8.12). More than 85% of CMIP5 models show an increase in mean precipitation in the East Asian summer monsoons, while more than 95% of models project an increase in heavy precipitation events (see WGI AR5 Section 14.2.2 and Figure 14.4). All models and all scenarios project an increase in both the mean and extreme precipitation in the Indian summer monsoon (see WGI AR5 Section 14.2.2 and SAS in Figure 14.4). In these two regions, the interannual standard deviation of seasonal mean precipitation also increases (see WGI AR5 Section 14.2.2).

Oceans. The ocean in subtropical and tropical regions will warm in all RCP scenarios and will show the strongest warming signal at the surface (see WGI AR5 Section 12.4.7 and Figure 12.12). Negligible change or a decrease in mean significant wave heights are projected for the trade and monsoon wind regions of the Indian Ocean (see WGI AR5 Section 13.7.3).

24.4. Observed and Projected Impacts, Vulnerabilities, and Adaptation

The key observed and projected climate change impacts in Asia are summarized based on subsections 24.4.1 to 24.4.6 (Tables 24-1, 24-SM-4 and 24-SM-5).

[INSERT TABLE 24-1 HERE
Table 24-1: Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Asia.]

24.4.1 Freshwater Resources

24.4.1.1. Sub-Regional Diversity

Freshwater resources are very important in Asia because of the massive population and heavy economic dependence on agriculture, but water availability is highly uneven and requires assessment on the subregional scale because of Asia’s huge range of climates (Pfister *et al.*, 2009). Adequate water supply is one of the major challenges in many regions (Vörösmarty *et al.*, 2010), particularly Central Asia. Growing demand for water is driven by soaring populations, increasing per-capita domestic use, due to urbanization and thriving economic growth, and increasing use of irrigation.

24.4.1.2. Observed Impacts

The impact of changes in climate, particularly precipitation, on water resources varies cross Asia (Table 24-SM-4). There is *medium confidence* that water scarcity in northern China has been exacerbated by decreasing precipitation, doubling population, and expanding water withdrawal from 1951 to 2000 (Xu *et al.*, 2010). There is no evidence that suggests significant changes of groundwater in the Kherlen River Basin in Mongolia over the past half century (Brutsaert and Sugita, 2008). Apart from water availability, there is *medium confidence* that climate change also leads to degradation of water quality in most regions of Asia (Delpla *et al.*, 2009; Park *et al.*, 2010), although this is also heavily influenced by human activities (Winkel *et al.*, 2011).

Glaciers are important stores of water and any changes have the potential to influence downstream water supply in the long term (see Section 24.9.2). Glacier mass loss shows a heterogeneous pattern across Asia (Gardner *et al.*, 2013). Glaciers in the polar section of the Ural Mountains, in the Kodar Mountains of Southeast Siberia, in the Suntar Khayata and Chersky Ranges of Northeast Siberia, in Georgia and Azerbaijan on the southern flank of the Greater Caucasus Range, on the Tibetan Plateau (see Box 3-1) and the surrounding areas, and on Puncak Jaya, Papua, Indonesia lost 9-80% of their total area in different periods within the 1895-2010 time interval (Ananicheva *et al.*, 2005; Ananicheva *et al.*, 2006; Anisimov *et al.*, 2008; Prentice and Glidden, 2010; Allison, 2011; Shahgedanova *et al.*, 2012; Yao *et al.*, 2012a; Stokes *et al.*, 2013) due to increased temperature (Casassa *et al.*, 2009; Shrestha and Aryal, 2011). Changes in the Kamchatka glaciers are driven by both warming and volcanic activity, with the area of some glaciers decreasing, while others increased because they are covered by ash and clinker (Anisimov *et al.*, 2008).

24.4.1.3. Projected Impacts

Projected impacts of climate change on future water availability in Asia differ substantially among river basins and seasons (A1B scenario with 5 GCMs: Immerzeel *et al.*, 2010; A1B with MRI-AGCMS: Nakaegawa *et al.*, 2013) . There is *high confidence* that water demand in most Asian countries is increasing because of increases in population, irrigated agriculture (Lal, 2011) and industry.

Tropical Asia. Future projections (A1B with MRI-AGCMs) suggest a decrease in river runoff in January in the Chao Phraya River basin in Thailand (Champathong *et al.*, 2013). In a study of the Mahanadi River Basin in India, a water availability projection (A2, CGCM2) indicated increasing possibility of floods in September but increasing water scarcity in April (Asokan and Dutta, 2008). In the Ganges, an increase in river runoff could offset the large increases in water demand due to population growth in a +4ºC world (ensemble GCMs), due to a projected large increase in average rainfall, although high uncertainties remains at the seasonal scale (Fung *et al.*, 2011).

Northern and Temperate Asia. Projections (A2 and B2 with the GLASS model) suggest an increase in average water availability in Russia in the 2070s (Alcamo *et al.*, 2007). In China, a projection (downscaling HadAM3H A2 and B2 scenarios with the PRECIS regional model) suggests that there will be insufficient water for agriculture in the 2020s and 2040s due to the increases in water demand for non-agricultural uses, although precipitation may increase in some areas (Xiong *et al.*, 2010). In the late 21st century (MRI-AGCM, A1B), river discharge in northern Japan is projected to increase in February but decrease in May, due to increased winter precipitation and decreased spring snowmelt (Sato *et al.*, 2013).

Central and West Asia. Given the already very high level of water stress in many parts of Central Asia, projected temperature increases and precipitation decreases (SRES scenarios from IPCC AR4 23 models) in the western part of Kazakhstan, Uzbekistan, and Turkmenistan could exacerbate the problems of water shortage and distribution (Lioubimtseva and Henebry, 2009). Considering the dependence of Uzbekistan's economy on its irrigated agriculture, which consumes more than 90% of the available water resources of the Amu Darya basin, climate change impacts on river flows would also strongly affect the economy (Schlüter *et al.*, 2010).

24.4.1.4. Vulnerabilities to Key Drivers

It is suggested that freshwater resource will be influenced by changes in rainfall variability, snowmelt or glacier retreat in the river catchment (Im *et al.*, 2010; Ma *et al.*, 2010; Sato *et al.*, 2012; Yamanaka *et al.*, 2012; Nakaegawa *et al.*, 2013), and evapotranspiration, which are associated with climate change (Jian *et al.*, 2009). Mismanagement of water resources has increased tension due to water scarcity in arid areas (Biswas and Seetharam, 2008; Lioubimtseva and Henebry, 2009; Siegfried *et al.*, 2010; Aarnoudse *et al.*, 2012). Unsustainable consumption of groundwater for irrigation and other uses is considered to be the main cause of groundwater depletion in the Indian states of Rajasthan, Punjab and Haryana (Rodell *et al.*, 2009).

24.4.1.5. Adaptation Options

Adaptation of freshwater resources to climate change can be identified as developing adaptive/integrated water resource management (Sadoff and Muller, 2009; Schlüter *et al.*, 2010) of the trade-offs balancing water availability against increasing demand, in order to cope with uncertainty and change (Molle and Hoanh, 2009). Examples of the options include: developing water saving technologies in irrigation (Ngoundo *et al.*, 2007); water infrastructure development in the Ganges river basin (Bharati *et al.*, 2011); increasing water productivity in the Indus and Ganges river basins (Cai *et al.*, 2010), Taiwan, China and the Philippines (Barker and Levine, 2012), and Uzbekistan (Tischbein *et al.*, 2011); changing cropping systems and patterns in West Asia (Thomas, 2008); and water re-use in China (Yi *et al.*, 2011). During the second half of the 20th century, Asia built many reservoirs and almost tripled its surface water withdrawals for irrigation. Reservoirs partly mitigate seasonal differences and increase water availability for irrigation (Biemans *et al.*, 2011). Water management in river basins would benefit from integrated coordination among countries (Kranz *et al.*, 2010). For example, water management in the Syr Darya river basin relates to Kyrgyzstan, Tajikistan, Uzbekistan, Turkmenistan, and Kazakhstan (Siegfried *et al.*, 2010), while the Indus and Ganges-Brahmaputra-Meghna river basins concern Bangladesh, India, Nepal and Pakistan (Uprety and Salman, 2011).

24.4.2. Terrestrial and Inland Water Systems

24.4.2.1. Sub-Regional Diversity

Boreal forests and grasslands dominate in North Asia, deserts and semi-deserts in Central and West Asia, and alpine ecosystems on the Tibetan Plateau. Human-dominated landscapes predominate in the other subregions, but the major natural ecosystems are temperate deciduous and subtropical evergreen forests in East Asia, with boreal forest in the northeast and grasslands and deserts in the west, while Southeast Asia was largely covered in tropical forests. South Asia also has tropical forests, with semi-desert in the northwest and alpine ecosystems in the north. Asia includes several of the world’s largest river systems, as well as the world’s deepest freshwater lake, Lake Baikal, the semi-saline Caspian Sea, and the saline Aral Sea.

24.4.2.2. Observed Impacts

Biological changes consistent with climate trends have been reported in the north and at high altitudes, where rising temperatures have relaxed constraints on plant growth and the distributions of organisms. Few changes have been reported from tropical lowlands and none linked to climate change with *high confidence*, although data is insufficient to distinguish lack of observations from lack of impacts. Impacts on inland water systems have been difficult to disentangle from natural variability and other human impacts (Bates *et al.*, 2008; Vörösmarty *et al.*, 2010; Zheng, 2011; see Section 4.3.3.3). For example, the shrinking of the Aral Sea over the last 50 years has resulted largely from excessive water extraction from rivers, but was probably exacerbated by decreasing precipitation and increasing temperature (Lioubimtseva and Henebry, 2009; Kostianoy and Kosarev, 2010).

Phenology and Growth Rates. In humid temperate East Asia, plant observations and satellite measurements of ‘greenness’ (Normalized Difference Vegetation Index, NDVI; see 4.3.2.2) show a trend to earlier leafing in spring since the 1980s, averaging 2 days a decade, although details vary between sites, species and periods (Table 24-SM-6) (detected with *high confidence* and attributed to warming with *medium confidence*.). Earlier spring flowering and delayed autumn senescence have also been recorded (Table 24-SM-6). Trends in semi-arid temperate regions were heterogeneous in space and time (Liu *et al*., 2013a; Yu *et al*., 2013a, 2013b). Earlier greening has been reported from boreal forests (Delbart *et al*., 2008) and from the Hindu-Kush-Himalayan region (Panday and Ghimire, 2012; Shrestha *et al*., 2012), but with spatial and temporal heterogeneity. Patterns were also heterogeneous in Central Asia (Kariyeva *et al*., 2012). On the Tibetan Plateau, spring growth advanced until the mid-1990s, but the trend subsequently differs between areas and NDVI datasets (Yu *et al*., 2010; Yu *et al*., 2012; Dong *et al*., 2013; Jin *et al*., 2013; Shen *et al*., 2013; Yu *et al*., 2013a; Zhang *et al*., 2013a; Zhang *et al*., 2013b).

Satellite NDVI for Asia for 1988-2010 shows a general greening trend (i.e. increasing NDVI, a rough proxy for increasing plant growth), except where water is limiting (Dorigo *et al*., 2012). Changes at high latitudes (>60^{o}N) show considerable spatial and temporal variability, despite a consistent warming trend, reflecting water availability and non-climatic factors (Bi *et al*., 2013; Jeong *et al*., 2013). Arctic tundra generally showed increased greening since 1982, while boreal forests were variable (Goetz *et al*., 2011; de Jong *et al*., 2012; Epstein *et al*., 2012; Xu *et al*., 2013). An overall greening trend for 2000-2011 north of the boreal forest correlated with increasing summer warmth and ice retreat (Dutrieux *et al*., 2012). In China, trends have varied in space and time, reflecting positive impacts of warming and negative impacts of increasing drought stress (Peng *et al*., 2011; Sun *et al*., 2012; Xu *et al*., 2012). The steppe region of northern Kazakhstan showed an overall browning (decreasing NDVI) trend for 1982-2008, linked to declining precipitation (de Jong *et al*., 2012). In Central Asia, where NDVI is most sensitive to precipitation (Gessner *et al*., 2013), there was a heterogeneous pattern for 1982-2009, with an initial greening trend stalled or reversed in some areas (Mohammat *et al*., 2013).

Tree-ring data for 800-1989 for temperate East Asia suggests recent summer temperatures have exceeded those during past warm periods of similar length, although this difference was not statistically significant (Cook *et al*., 2012). Where temperature limits tree growth, growth rates have increased with warming in recent decades (Duan *et al*., 2010; Sano *et al*., 2010; Shishov and Vaganov, 2010; Borgaonkar *et al*., 2011; Xu *et al*., 2011; Li *et al*., 2012; Chen *et al*., 2012a, 2012b, 2012c, 2012d; Chen *et al*., 2013), while where drought limits growth, there have been increases (Li *et al*., 2006; Davi *et al*., 2009; Shao *et al*., 2010; Yang *et al*., 2010) or decreases (Li *et al*., 2007; Davi *et al* , 2009; Dulamsuren *et al*., 2010a, 2011; Kang *et al*., 2012; Wu *et al*., 2012; Kharuk *et al*., 2013; Liu *et al*., 2013b) reflecting decreasing or increasing water stress (*high confidence* in detection, *medium confidence* in attribution to climate change). In boreal forest, trends varied between species and locations, despite consistent warming (Lloyd and Bunn, 2007; Goetz *et al*., 2011).

Distributions of Species and Biomes. Changes in species distributions consistent with a response to warming have been widely reported: upwards in elevation (Soja *et al*., 2007; Bickford *et al*., 2010; Kharuk *et al*., 2010a, 2010b, 2010e; Moiseev *et al*., 2010; Chen *et al*., 2011; Jump *et al*., 2012; Telwala *et al*., 2013; Grigor’ev *et al*., 2013) or polewards (Tougou *et al*., 2009; Ogawa-Onishi and Berry, 2013) (*high confidence* in detection, *medium confidence* in attribution to climate change). Changes in the distributions of major vegetation types (biomes) have been reported from the north and high altitudes, where trees are invading treeless vegetation, and forest understories are being invaded from adjacent biomes (Soja *et al*., 2007; Kharuk *et al*., 2006; Bai *et al*., 2011; Singh *et al*., 2012; Wang and Liu, 2012; Ogawa-Onishi and Berry, 2013). In central Siberia, dark needle conifers (DNC) and birch have invaded larch-dominated forest over the last three decades (Kharuk *et al*., 2010c, d; Osawa *et al*., 2010; Lloyd *et al*., 2011). Meanwhile, warming has driven larch stand crown closure and larch invasion into tundra at a rate of 3–10 m/year in the northern forest-tundra ecotone (Kharuk *et al*., 2006). Shrub expansion in arctic tundra has also been observed (Blok *et al*., 2011; Myers-Smith *et al*., 2011; see 28.2.3.1.). Soil moisture and light are the main factors governing the forest-steppe ecotone (Soja *et al*., 2007; Zeng *et al*., 2008; Eichler *et al*., 2011; Kukavskaya *et al*., 2013) and Mongolian taiga forests have responded heterogeneously to recent climate changes, but declines in larch growth and regeneration are more widespread than increases (Dulamsuren *et al*., 2010a, 2010b).

Permafrost. Permafrost degradation, including reduced area and increased active layer thickness, has been reported from parts of Siberia, Central Asia, and the Tibetan Plateau (Romanovsky *et al.*, 2010; Wu and Zhang, 2010; Zhao *et al.*, 2010; Yang *et al.*, 2013) (*high confidence*). Most permafrost observatories in Asian Russia show substantial warming of permafrost during the last 20-30 years (Romanovsky *et al.*, 2008, 2010). Permafrost formed during the Little Ice Age is thawing at many locations and Late Holocene permafrost has begun to thaw at some undisturbed locations in northwest Siberia. Permafrost thawing is most noticeable within the discontinuous permafrost zone, while continuous permafrost is starting to thaw in a few places, so the boundary between continuous and discontinuous permafrost is moving northwards (Romanovsky *et al.*, 2008, 2010). Thawing permafrost may lead to increasing emissions of greenhouse gases from decomposition of accumulated organic matter (see Section 4.3.3.4 and 19.6.3.5). In Mongolia, mean annual permafrost temperature at 10-15 m depth increased over the past 10-40 years in the Hovsgol, Hangai and Hentei Mountain regions. Permafrost warming during the past 15–20 years was greater than during the previous 15-20 years (Sharkhuu *et al.*, 2008; Zhao *et al.*, 2010). In the Kazakh part of the Tien Shan Mountains, permafrost temperature and active layer thickness have increased since the early 1970s. Significant permafrost warming also occurred in the eastern Tien Shan Mountains, in the headwaters of the Urumqi River (Marchenko *et al.*, 2007; Zhao *et al.*, 2010). Monitoring across the Qinghai-Tibet Plateau over recent decades has also revealed permafrost degradation caused by warming and other impacts. Areas of permafrost are shrinking, the active layer depth is increasing, the lower altitudinal limit is rising, and the seasonal frost depth is thinning (Li *et al.*, 2008; Wu and Zhang, 2010; Zhao *et al.*, 2010). In the alpine headwater regions of the Yangtze and Yellow Rivers, rising temperatures and permafrost degradation have resulted in lower lake levels, drying swamps and shrinking grasslands (Cheng and Wu, 2007; Wang *et al.*, 2011).

24.4.2.3. Projected Impacts

Phenology and Growth Rates. Trends towards an earlier spring greening and longer growing season are expected to continue in humid temperate and boreal forest areas, although photoperiod or chilling requirements may reduce responses to warming in some species (Ge *et al.*, 2013; Hadano *et al.*, 2013; Richardson *et al.*, 2013). Changes in precipitation will be important for semi-arid and arid ecosystems, as may the direct impacts of atmospheric CO_2 concentrations, making responses harder to predict (Liancourt *et al.*, 2012; Poulter *et al.*, 2013). The ‘general flowering’ at multi-year intervals in lowland rainforests in Southeast Asia is triggered by irregular droughts (Sakai *et al.*, 2006), so changes in drought frequency or intensity could have large impacts.

Distributions of Species and Biomes. Climate change is expected to modify the vegetation distribution across the region (Tao and Zhang, 2010; Wang, 2013), but responses will be slowed by limitations on seed dispersal, competition from established plants, rates of soil development, and habitat fragmentation (Corlett and Westcott, 2013) (*high confidence*). Rising CO_2 concentrations are expected to favor increased woody vegetation in semi-arid areas (Higgins and Scheiter, 2012; Donohue *et al.*, 2013; Poulter *et al.*, 2013; Wang, 2013) (*medium confidence*). In North Asia, rising temperatures are expected to lead to large changes in the distribution of potential natural ecosystems (Ni, 2011; Tchebakova *et al.*, 2011; Insarov *et al.*, 2012; Pearson *et al.*, 2013) (*high confidence*). It is *likely* that the boreal forest will expand northward and eastward, and that tundra will decrease, although differences in models, time periods, and other assumptions have resulted in widely varying projections for the magnitude of this change (Woodward and Lomas, 2004; Kaplan and New, 2006; Lucht *et al.*, 2006; Golubyatnikov and Denisenko, 2007; Sitch *et al.*, 2008; Korzukhin and Tcelniker, 2010; Tchebakova *et al.*, 2010, 2011; Pearson *et al.*, 2013). Boreal forest expansion and the continued invasion of the existing larch-dominated forest by dark-needle conifers could lead to larch reaching the Arctic shore, while the traditional area of larch dominance turns into mixed forest (Kharuk *et al.*, 2006; Kharuk *et al.*, 2010c). Both the replacement of summer-green larch with evergreen conifers and expansion of trees and shrubs into tundra decrease albedo, causing regional warming and potentially accelerating vegetation change (Kharuk *et al.*, 2006; McGuire *et al.*, 2007; Kharuk *et al.*, 2010d; Pearson *et al.*, 2013). The future direction and rate of change of steppe vegetation are unclear because of uncertain precipitation trends (Golubyatnikov and Denisenko, 2007; Tchebakova *et al.*, 2010). The role of CO_2-fertilization is also potentially important here (Poulter *et al.*, 2013; see WG1 AR5 Box 6.3).

In East Asia, subtropical evergreen forests are projected to expand north into the deciduous forest and tropical forests to expand along China's southern coast (Choi *et al.*, 2011; Wang, 2013), but vegetation change may lag climate change by decades or centuries (Corlett and Westcott, 2013). On the Tibetan Plateau, projections suggest that alpine vegetation will be largely replaced by forest and shrubland, with tundra and steppe retreating to the north (Liang *et al.*, 2012; Wang, 2013). Impacts in Central and West Asia will depend on changes in precipitation. In India, a dynamic vegetation model (A2 and B2 scenarios) projected changes in more than a third of the forest area by 2100, mostly from deciduous to evergreen forest in response to increasing rainfall, although fragmentation and other human pressures are expected to slow these changes (Chaturvedi *et al.*, 2011). By 2100, large areas of tropical and subtropical lowland Asia are projected to experience combinations of temperature and rainfall outside the current global range, under a variety of model projections and emission scenarios (Williams *et al.*, 2007; Beaumont *et al.*, 2010; García-López and Allué, 2013), but the potential impacts of these novel conditions on biodiversity are largely unknown (Corlett, 2011).

In Southeast Asia, projected climate (A2 and B1 scenarios) and vegetation changes are expected to produce widespread declines in bat species richness, northward range shifts for many species, and large reductions in the distributions of most species (Hughes *et al.*, 2012). Projections for various bird species in Asia under a range of scenarios also suggest major impacts on distributions (Menon *et al.*, 2009; Li *et al.*, 2010; Ko *et al.*, 2012). Projections for butterflies in Thailand (A2 and B2 scenarios) suggest that species richness within protected areas will decline c. 30% by 2070-2099 (Klorvuttimontara *et al.*, 2011). Projections for dominant bamboos in the Qinling Mountains (A2 and B2 scenarios) suggest substantial range reductions by 2100, with potentially adverse consequences for the giant pandas which eat them (Tuanmu *et al.*, 2012). Projections for snow leopard habitat in the Himalayas (B1, A1B and A2 scenarios) suggest contraction by up to 30% as forests replace open habitats (Forrest *et al.*, 2012).

Permafrost. In the Northern Hemisphere, a 20-90% decrease in permafrost area and a 50-300 cm increase in active layer thickness driven by surface warming is projected for 2100 by different models and scenarios (Schaefer *et al.*, 2011). It is *likely* that permafrost degradation in North Asia will spread from the southern and low-altitude margins, advancing northwards and upwards, but rates of change vary greatly between model projections (Cheng and Wu, 2007; Riseborough *et al.*, 2008; Romanovsky *et al.*, 2008; Anisimov, 2009; Eliseev *et al.*, 2009; Nadyozhina *et al.*, 2010; Schaefer *et al.*, 2011; Wei *et al.*, 2011). Substantial retreat is also expected on the Qinghai-Tibet Plateau (Cheng and Wu, 2007). Near-surface permafrost is expected to remain only in Central and Eastern Siberia and parts of the QTP in the late 21st century.

Inland Waters. Climate change impacts on inland waters will interact with dam construction, pollution, and land-use changes (Vörösmarty *et al.*, 2010) (see also 24.9.1 and Section 3.3.2). Increases in water temperature will impact species and temperature-dependent processes (Hamilton, 2010; Dudgeon, 2011; Dudgeon, 2012). Coldwater fish will be threatened as rising water temperatures make much of their current habitat unsuitable (Yu *et al.*, 2013c). Climate change is also expected to change flow regimes in running waters and consequently impact habitats and species that are sensitive to droughts and floods (see Box CC-RF). Habitats that depend on seasonal inundation, including floodplain grasslands and freshwater swamp forests, will be particularly vulnerable (Maxwell, 2009; Bezuijen, 2011; Arias *et al.*, 2012). Reduced dry season flows are expected to combine with sea-level rise to increase saltwater intrusion in deltas (Hamilton, 2010; Dudgeon, 2012), although non-climatic impacts will continue to dominate in most estuaries (Syvitski *et al.*, 2009). For most Asian lakes, it is difficult to disentangle the impacts of water pollution, hydro-engineering, and climate change (Battarbee *et al.*, 2012).

24.4.2.4. Vulnerabilities to Key Drivers

Permafrost melting in response to warming is expected to impact ecosystems across large areas (Cheng and Wu, 2007; Tchebakova *et al.*, 2011) (*high confidence*). The biodiversity of isolated mountains may also be particularly vulnerable to warming, because many species already have small geographical ranges that will shrink further (La Sorte and Jetz, 2010; Liu *et al.*, 2010; Chou *et al.*, 2011; Noroozi *et al.*, 2011; Peh *et al.*, 2011; Jump *et al.*, 2012; Tanaka *et al.*, 2012a; Davydov *et al.*, 2013). Many freshwater habitats are similarly isolated and their restricted-range species may be equally vulnerable (Dudgeon, 2012). In flatter topography, higher velocities of climate change (the speeds that species need to move to maintain constant climate conditions) increase the vulnerabilities of species that are unable to keep pace, as a result of limited dispersal ability, habitat fragmentation, or other non-climatic constraints (Corlett and Westcott, 2013). In the tropics, temperature extremes above the present range are a potential threat to organisms and ecosystems (Corlett, 2011; Jevanandam *et al.*, 2013; Mumby *et al.*, 2013). For much of interior Asia, increases in drought stress, as a result of declining rainfall and/or rising temperatures, are the key concern. Because aridity is projected to increase in the northern Mongolian forest belt during the 21st century (Sato *et al.*, 2007), larch cover will *likely* be reduced (Dulamsuren *et al.*, 2010a). In the boreal forest region, a longer, warmer growing season will increase vulnerability to fires, although other human influences may overshadow climate impacts in accessible areas (Flannigan *et al.*, 2009; Liu *et al.*, 2012; Li *et al.*, 2013; see Section 4.3.3.1.1). If droughts intensify in lowland Southeast Asia, the synergies between warmth, drought, logging, fragmentation and fire (Daniau *et al.*, 2012), and tree mortality (Kumagai and Porporato, 2012; Tan *et al.*, 2013), possibly acerbated by feedbacks between deforestation, smoke aerosols and reduced rainfall (Aragão, 2012; Tosca *et al.*, 2012), could greatly increase the vulnerability of fragmented forest landscapes (*high confidence*).

24.4.2.5. Adaptation Options

Suggested strategies for maximizing the adaptive capacity of ecosystems include reducing non-climate impacts, maximizing landscape connectivity, and protecting 'refugia' where climate change is expected to be less than the regional mean (Hannah, 2010; Game *et al.*, 2011; Klorvuttimontara *et al.*, 2011; Murthy *et al.*, 2011; Ren *et al.*, 2011; Shoo *et al.*, 2011; Mandych *et al.*, 2012). Additional options for inland waters include operating dams to maintain environmental flows for biodiversity, protecting catchments, and preserving river floodplains (Vörösmarty *et al.*, 2010). Habitat restoration may facilitate species movements across climatic gradients (Klorvuttimontara *et al.*, 2011; Hughes *et al.*, 2012) and long-distance seed dispersal agents may need protection (McConkey *et al.*, 2012). Assisted migration of genotypes and species is possible where movements are constrained by poor dispersal, but risks and benefits need to be considered carefully (Liu *et al.*, 2010; Olden *et al.*, 2010; Tchebakova *et al.*, 2011; Dudgeon, 2012; Ishizuka and Goto, 2012; Corlett and Westcott, 2013). *Ex situ* conservation can provide back-up for populations and species most at risk from climate change (Chen *et al.*, 2009).

24.4.3. Coastal Systems and Low-Lying Areas

24.4.3.1. Sub-Regional Diversity

Asia's coastline includes the global range of shore types. Tropical and subtropical coasts support 45% of the world's mangrove forest (Giri *et al.*, 2011) and low-lying areas in equatorial Southeast Asia support most of the world's peat swamp forests, as well as other forested swamp types. Intertidal salt marshes are widespread along temperate and arctic coasts, while a variety of non-forested wetlands occur inland. Asia supports 40% of the world's coral reef area, mostly in Southeast Asia, with the world's most diverse reef communities in the 'coral triangle' (Spalding *et al.*, 2001; Burke *et al.*, 2011). Seagrass beds are widespread and support most of the world's seagrass species (Green and Short, 2003). Six of the seven species of sea turtle are found in the region and five nest on Asian beaches (Spotila, 2004). Kelp forests and other seaweed beds are important on temperate coasts (Bolton, 2010; Nagai *et al.*, 2011). Arctic sea-ice supports a specialized community of mammals and other organisms (see Sections 28.2.3.3. and 28.2.3.4.).

24.4.3.2. Observed Impacts

Most of Asia's non-Arctic coastal ecosystems are under such severe pressure from non-climate impacts that climate impacts are hard to detect (see Section 5.4.2). Most large deltas in Asia are sinking (as a result of groundwater withdrawal, floodplain engineering, and trapping of sediments by dams) much faster than global sea-level is rising (Syvitski *et al.*, 2009). Widespread impacts can be attributed to climate change only for coral reefs, where the temporal and spatial patterns of bleaching correlate with higher than normal sea surface temperatures (see Section 5.4.2.4 and CC-CR) (*very high confidence*). Increased water temperatures may also explain declines in large seaweed beds in temperate Japan (Nagai *et al.*, 2011; see Section 5.4.2.3). Warming coastal waters have also been implicated in the northwards expansion of tropical and subtropical macroalgae and toxic phytoplankton (Nagai *et al.*, 2011), fish (Tian *et al.*, 2012), and tropical corals, including key reef-forming species (Yamano *et al.*, 2011), over recent decades. The decline of large temperate seaweeds and expansion of tropical species in southwest Japan has been linked to rising sea surface temperatures (Tanaka *et al.*, 2012b), and these changes have impacted fish communities (Terazono *et al.*, 2012).

In Arctic Asia, changes in permafrost and the effects of sea-level rise and sea-ice retreat on storm-wave energy have increased erosion (Are *et al.*, 2008; Razumov, 2010; Handmer *et al.*, 2012). Average erosion rates range from 0.27 m/year (Chukchi Sea) to 0.87 m/year (East Siberian Sea), with a number of segments in the Laptev and East Siberian Sea experiencing rates greater than 3 m/year (Lantuit *et al.*, 2012).

24.4.3.3. Projected Impacts

Marine biodiversity at temperate latitudes is expected to increase as temperature constraints on warm-water taxa are relaxed (see Section 6.4.1.1) (*high confidence*), but biodiversity in tropical regions may fall if, as evidence suggests, tropical species are already near their thermal maxima (Cheung *et al.*, 2009, 2010; Nguyen *et al*., 2011) (*medium confidence*). Individual fish species are projected to shift their ranges northwards in response to rising sea surface temperatures (Tseng *et al.*, 2011; Okunishi *et al.*, 2012; Tian *et al.*, 2012). The combined effects of changes in distribution, abundance and physiology may reduce the body size of marine fishes, particularly in the tropics and intermediate latitudes (Cheung *et al.*, 2013).

Continuation of current trends in sea-surface temperatures and ocean acidification would result in large declines in coral-dominated reefs by mid-century (Hoegh-Guldberg, 2011; Burke *et al.*, 2011; see Section 5.4.2.4 and Box CC-CR) (*high confidence*). Warming would permit the expansion of coral habitats to the north but acidification is expected to limit this (Yara *et al.*, 2012). Acidification is also expected to have negative impacts on other calcified marine organisms (algae, molluscs, larval echinoderms), while impacts on non-calcified species are unclear (Branch *et al.*, 2013; Kroeker *et al.*, 2013; See CC-OA). On rocky shores, warming and acidification are expected to lead to range shifts and changes in biodiversity (see Section 5.4.2.2).

Future rates of sea-level rise are expected to exceed those of recent decades (see WGI AR5 Section 13.5.1), increasing coastal flooding, erosion, and saltwater intrusion into surface and groundwaters. In the absence of other impacts, coral reefs may grow fast enough to keep up with rising sea-levels (Brown *et al.*, 2011; Villanoy *et al.*, 2012; see Section 5.4.2.4), but beaches may erode and mangroves, salt marshes, and seagrass beds will decline, unless they receive sufficient fresh sediment to keep pace or they can move inland (Gilman *et al.*, 2008; Bezuijen, 2011; Kintisch, 2013; see Section 5.3.2.3). Loucks *et al.* (2010) predict a 96% decline in tiger habitat in Bangladesh's Sunderbans mangroves with a 28 cm sea-level rise if sedimentation does not increase surface elevations. Rising winter temperatures are expected to result in poleward expansion of mangrove ecosystems (see Section 5.4.2.3). Coastal freshwater wetlands may be vulnerable to saltwater intrusion with rising sea-levels, but in most river deltas local subsidence for non-climatic reasons will be more important (Syvitski *et al.*, 2009).
Current trends in cyclone frequency and intensity are unclear (see 24.3.2 and Box CC-TC), but a combination of cyclone intensification and sea-level rise could increase coastal flooding (Knutson *et al.*, 2010) and losses of coral reefs and mangrove forests would exacerbate wave damage (Gedan *et al.*, 2011; Villanoy *et al.*, 2012).

In the Asian Arctic, rates of coastal erosion are expected to increase as a result of interactions between rising sea-levels and changes in permafrost and the length of the ice-free season (Pavlidis *et al.*, 2007; Lantuit *et al.*, 2012) (*high agreement, medium evidence*). The largest changes are expected for coasts composed of loose permafrost rocks and therefore subject to intensive thermal abrasion. If sea-level rises by 0.5 m over this century, modeling studies predict that the rate of recession will increase 1.5-2.6-fold for the coasts of the Laptev Sea, East Siberian Sea, and West Yamal in the Kara Sea, compared to the rate observed in the first years of the 21st century.

24.4.3.4. Vulnerabilities to Key Drivers

Offshore marine systems are most vulnerable to rising water temperatures and ocean acidification, particularly for calcifying organisms such as corals. Sea-level rise will be the key issue for many coastal areas, particularly if combined with changes in cyclone frequency or intensity, or in Arctic Asia, with a lengthening open-water season. The expected continuing decline in the extent of sea-ice in the arctic may threaten the survival of some ice-associated organisms (see Section 28.2.2.1), with expanded human activities in previously inaccessible areas an additional concern (Post *et al.*, 2013).

24.4.3.5. Adaptation Options

The connectivity of marine habitats and dispersal abilities of marine organisms increase the capacity for autonomous (spontaneous) adaptation in coastal systems (Cheung *et al.*, 2009). Creating marine protected areas where sea surface temperatures are projected to change least may increase their future resilience (Levy and Ban, 2013). For coral reefs, potential indicators of future resilience include later projected onset of annual bleaching conditions (van Hooidonk *et al.*, 2013), past temperature variability, the abundance of heat-tolerant coral species, coral recruitment rates, connectivity, and macroalgae abundance (McClanahan *et al.*, 2012). Similar strategies may help identify reefs that are more resilient to acidification (McLeod *et al.*, 2013). Hard coastal defenses, such as sea walls, protect settlements at the cost of preventing adjustments by mangroves, salt marshes and seagrass beds to rising sea-levels. Landward buffer zones that provide an opportunity for future inland migration could mitigate this problem (Tobey *et al.*, 2010). More generally, maintaining or restoring natural shorelines where possible is expected to provide coastal protection and other benefits (Tobey *et al.*, 2010; Crooks *et al.*, 2011). Projected increases in the navigability of the Arctic Ocean because of declining sea-ice suggest the need for a revision of environmental regulations in order to minimize the risk of marine pollution (Smith and Stephenson, 2013).

24.4.4. Food Production Systems and Food Security

It is projected that climate change will affect food security by the middle of the 21st century, with the largest numbers of food-insecure people located in South Asia (see Chapter 7).

24.4.4.1. Sub-Regional Diversity

AR4 Section 10.4.1.1 pointed out that there will be regional differences within Asia in the impacts of climate change on food production. Research since then has validated this divergence and new data are available especially for West and Central Asia (Tables 24-SM-4 and 24-SM-5). In AR4 Section 10.4.1, climate change was projected to lead mainly to reductions in crop yield. New research shows there will also be gains for specific regions and crops in given areas. Thus, the current assessment encompasses an enormous variability, depending on the regions and the crops grown.

24.4.4.2. Observed Impacts

There are very limited data globally for observed impacts of climate change on food production systems (see Chapter 7) and this is true also for Asia. In Jordan, it was reported that the total production and average yield for wheat and barley were lowest in 1999 for the period 1996-2006 (Al-Bakri *et al.*, 2010), which could be explained by the low rainfall during that year, which was 30% of the average (*high confidence* in detection, *low confidence* in attribution). In China, rice yield responses to recent climate change at experimental stations were assessed for the period 1981–2005 (Zhang *et al.*, 2010). In some places, yields were positively correlated with temperature when they were also positively related with solar radiation. However, in other places, lower yield with higher temperature was accompanied by a positive correlation between yield and rainfall (*high confidence* in detection, *high confidence* in attribution). In Japan, where mean air temperature rose by about 1ºC over the 20th century, effects of recent warming include phenological changes in many crops, increases in fruit coloring disorders and incidences of chalky rice kernels, reductions in yields of wheat, barley, vegetables, flowers, milk and eggs, and alterations in the type of disease and pest (*high confidence* in detection, *high confidence* in attribution) (Sugiura *et al.*, 2012).

24.4.4.3. Projected Impacts

Production. AR4 Section 10.4.1.1 mainly dealt with cereal crops (rice, wheat corn). Since then, impacts of climate change have been modeled for additional cereal crops and subregions. It is *very likely* that climate change effects on crop production in Asia will be variable, negative for specific regions and crops in given areas and positive for other regions and crops (*high agreement, medium evidence*). It is also *likely* that an elevated CO_2 concentration in the atmosphere will be beneficial to most crops (*high agreement, medium evidence*).

In semi-arid and arid regions of Western Asia, rainfed agriculture is sensitive to climate change both positively and negatively (Ratnakumar *et al.*, 2011). In the mountainous Swat and Chitral districts of Pakistan (average altitudes 960 and 1500 m above sea level, respectively), there were mixed results as well (Hussain and Mudasser, 2007). Projected temperature increases of 1.5 and 3°C would lead to wheat yield declines (by 7% and 24% respectively) in Swat district but to increases (by 14% and 23%) in Chitral district. In India, climate change impacts on sorghum were analyzed using the InfoCrop-SORGHUM simulation model (Srivastava *et al.*, 2010). A changing climate was projected to reduce monsoon sorghum grain yield by 2-14% by 2020, with worsening yields by 2050 and 2080. In the Indo-Gangetic Plains, a large reduction in wheat yields is projected (see below), unless appropriate cultivars and crop management practices are adopted (Ortiz *et al.*, 2008). A systematic review and meta-analysis of data in 52 original publications projected mean changes in yield by the 2050s across South Asia of 16% for maize and 11% for sorghum (Knox *et al.*, 2012). No mean change in yield was projected for rice.

In China, modeling studies of the impacts of climate change on crop productivity have had mixed results. Rice is the most important staple food in Asia. Studies show that climate change will alter productivity in China but not always negatively. For example, an ensemble-based probabilistic projection shows rice yield in southeastern China would change on average by 7.5% to 17.5% (–10.4% to 3.0%), 0.0% to 25.0% (–26.7% to 2.1%), and –10.0% to 25.0% (–39.2% to –6.4%) during the 2020s, 2050s, and 2080s, respectively, in response to climate change, with (without) consideration of CO_2 fertilization effects, using all 10 combinations of two emission scenarios (A1FI and B1) and five GCMs (HadCM3, PCM, CGCM2, CSIRO2, and ECHAM4) relative to 1961–1990 levels (Tao and Zhang, 2013a). With rising temperatures, the process of rice development accelerates and reduces the duration for growth. Wassmann *et al.* (2009a, 2009b) concluded that, in terms of risks of increasing heat stress, there are parts of Asia where current temperatures are already approaching critical levels during the susceptible stages of the rice plant. These include: Pakistan/North India (October), South India (April, August), East India/Bangladesh (March-June), Myanmar/Thailand/Laos/Cambodia (March-June), Vietnam (April/August), Philippines (April/June), Indonesia (August) and China (July/August).

There have also been simulation studies for other crops in China. In the Huang-Huai-Hai Plain, China's most productive wheat growing region, modeling indicated that winter wheat yields would increase on average by 0.2 Mg ha^{-1} in 2015-2045 and by 0.8 Mg ha^{-1} in 2070-2099, due to warmer nighttime temperatures and higher precipitation, under A2 and B2 scenarios using the HadCM3 model (Thomson *et al.*, 2006). In the North China Plain, an ensemble-based probabilistic projection projected that maize yield will change by -9.7 to -9.1%, -19.0 to -15.7%, and -25.5% to -24.7%, during 2020s, 2050s, and 2080s as a percentage of 1961–1990 yields (Tao *et al.*, 2009). In contrast, winter wheat yields could increase with high probability in future due to climate change (Tao and Zhang, 2013b).

It should be noted that crop physiology simulation models such as those discussed above may overstate the impact of CO_2 fertilization. Free atmosphere carbon exchange (FACE) experiments show that measurable CO_2 fertilization effects are typically less than modeled results (see Section 7.3). Extreme weather events are also expected to negatively affect agricultural crop production (IPCC, 2012). For example, extreme temperatures could lower yields of rice (Mohammed and Tarpley, 2009; Tian *et al.*, 2010). With higher precipitation, flooding could also lead to lower crop production (see SREX Chapter 4).

Farming Systems and Crop Areas. Since the release of the AR4 (see WGII AR4 Section 10.4.1.2), more information is available on the impacts of climate change on farming systems and cropping areas in more countries in Asia and especially in Central Asia. Recent studies validate the *likely* northward shifts of crop production with current croplands under threat from the impacts of climate change (*medium agreement, medium evidence*). Cooler regions are *likely* to benefit as warmer temperatures increase arable areas (*high agreement, medium evidence*).

Central Asia is expected to become warmer in the coming decades and increasingly arid, especially in the western parts of Turkmenistan, Uzbekistan, and Kazakhstan (Lioubimtseva and Henebry, 2009). Some parts of the region could be winners (cereal production in northern and eastern Kazakhstan could benefit from the longer growing season, warmer winters and a slight increase in winter precipitation), while others could be losers (particularly western Turkmenistan and Uzbekistan, where frequent droughts could negatively affect cotton production, increase already extremely high water demands for irrigation, and exacerbate the already existing water crisis and human-induced desertification). In India, the Indo-Gangetic Plains are under threat of a significant reduction in wheat yields (Ortiz *et al.*, 2008). This area produces 90 million tons of wheat grain annually (about 14-15% of global wheat production). Climate projections based on a doubling of CO_2 using a CCM3 model downscaled to a 30 arc-second resolution as part of the WorldClim data set showed that there will be a 51% decrease in the most favorable and high yielding area due to heat stress. About 200 million people (using the current population) in this area whose food intake relies on crop harvests would experience adverse impacts.

Rice growing areas are also expected to shift with climate change throughout Asia. In Japan, increasing irrigation water temperature (1.6–2.0°C) could lead to a northward shift of the isochrones of safe transplanting dates for rice seedlings (Ohta and Kimura, 2007). As a result, rice cultivation period will be prolonged by approximately 25–30 days. This will allow greater flexibility in the cropping season than at present, resulting in a reduction in the frequency of cool-summer damage in the northern districts. Sea-level rise threatens coastal and deltaic rice production areas in Asia, such as those in Bangladesh and the Mekong River Delta (Wassmann *et al.*, 2009b). For example, about 7% of Vietnam’s agriculture land may be submerged due to sea-level rise (Dasgupta *et al.*, 2009). In Myanmar, salt water intrusion due to sea-level rise could also decrease rice yield (Wassmann *et al.*, 2009b).

Fisheries and Aquaculture. Asia dominates both capture fisheries and aquaculture (FAO, 2010). More than half of the global marine fish catch in 2008 was in the West Pacific and Indian Ocean, and the lower Mekong River basin supports the largest freshwater capture fishery in the world (Dudgeon, 2011). Fish production is also a vital component of regional livelihoods, with 85.5% of the world’s fishers (28 m) and fish farmers (10 m) in Asia in 2008. Many more people fish part-time. Fish catches in the Asian Arctic are relatively small, but important for local cultures and regional food security (Zeller *et al.*, 2011).

Inland fisheries will continue to be vulnerable to a wide range of on-going threats, including overfishing, habitat loss, water abstraction, drainage of wetlands, pollution, and dam construction, making the impacts of climate change hard to detect (see also 24.9.1). Most concerns have centered on rising water temperatures and the potential impacts of climate change on flow regimes, which in turn are expected to affect the reproduction of many fish species (Allison *et al.*, 2009; Barange and Perry, 2009; Bezuijen, 2011; Dudgeon, 2011; see also Section 24.4.2.3). Sea-level rise is expected to impact both capture fisheries and aquaculture production in river deltas (De Silva and Soto, 2009). For marine capture fisheries, Cheung *et al.* (2009, 2010) used a dynamic bioclimate envelope model to project the distributions of 1066 species of exploited marine fish and invertebrates for 2005-2055, based on the SRES A1B scenario and a stable-2000 $C0_2$ scenario. This analysis suggests that climate change may lead to a massive redistribution of fisheries catch potential, with large increases in high-latitude regions, including Asian Russia, and large declines in the tropics, particularly Indonesia. Other studies have made generally similar predictions, with climate change impacts on marine productivity expected to be large and negative in the tropics, in part because of the vulnerability of coral reefs to both warming and ocean acidification (see also Section 24.4.3.3), and large and positive in arctic and subarctic regions, because of sea-ice retreat and poleward species shifts (Sumaila *et al.*, 2011; Blanchard *et al.*, 2012; Doney *et al.*, 2012) (*high confidence*). Predictions of a reduction in the average maximum body weight of marine fishes by 14-24% by 2050 under a high-emission scenario are an additional threat to fisheries (Cheung *et al.*, 2013).

Future Food Supply and Demand. AR4 Section 10.4.1.4 was largely based on global models that included Asia. There are now a few quantitative studies in Asia and its individual countries. In general, these show that the risk of hunger, food insecurity and loss of livelihood due to climate change will *likely* increase in some regions (*medium agreement, low evidence*).

Rice is a key staple crop in Asia and 90% or more of the world's rice production is from Asia. An Asia-wide study revealed that climate change scenarios (using 18 GCMs for A1B, 14 GCMs for A2, and 17 GCMs for B1) would reduce rice yield over a large portion of the continent (Masutomi *et al.*, 2009). The most vulnerable regions were western Japan, eastern China, the southern part of the Indochina peninsula, and the northern part of South Asia. In Russia, climate change may also lead to "food production shortfall", which was defined as an event in which the annual potential (i.e. climate-related) production of the most important crops in an administrative region in a specific year falls below 50% of its climate-normal (1961–1990) average (Alcamo *et al.*, 2007). The study shows that the frequency of shortfalls in five or more of the main crop growing regions in the same year is around 2 years/decade under normal climate but could climb to 5–6 years/decade in the 2070s, depending on the scenario and climate model (using the GLASS and WaterGAP-2 models and ECHAM and HadCM3 under the A2 and B2 scenarios). The increasing shortfalls were attributed to severe droughts. The study estimated that the number of people living in regions that may experience one or more shortfalls each decade may grow to 82–139 million in the 2070s. Increasing frequency of extreme climate events will pose an increasing threat to the security of Russia's food system.

In contrast, climate change may provide a windfall for wheat farmers in parts of Pakistan. Warming temperatures would make it possible to grow at least two crops (wheat and maize) a year in mountainous areas (Hussain and Mudasser, 2007). In the northern mountainous areas, wheat yield was projected to increase by 50% under SRES A2 and by 40% under the B2 scenario, whereas in the sub-mountainous, semi-arid and arid areas, it is likely to decrease, by the 2080s (Iqbal *et al.*, 2009).

24.4.4.4. Vulnerabilities to Key Drivers

Food production and food security are most vulnerable to rising air temperatures (Wassmann *et al.*, 2009a, 2009b). Warmer temperatures could depress yields of major crops such as rice. However, warmer temperatures could also make some areas more favorable for food production (Lioubimtseva and Henebry, 2009). Increasing CO_2 concentration in the atmosphere could lead to higher crop yields (Tao and Zhang, 2013a). Sea-level rise will be a key issue for many coastal areas as rich agricultural lands may be submerged and taken out of production (Wassmann *et al.*, 2009b).

24.4.4.5. Adaptation Options

Since AR4, there have been additional studies of recommended and potential adaptation strategies and practices in Asia (Table 24-SM-7) and there is new information for West and Central Asia. There are also many more crop-specific and country-specific adaptation options available. Farmers have been adapting to climate risks for generations. Indigenous and local adaptation strategies have been documented for Southeast Asia (Peras *et al.*, 2008; Lasco *et al.*, 2010; Lasco *et al.*, 2011) and could be used as a basis for future climate change adaptation. Crop breeding for high temperature condition is a promising option for climate change adaptation in Asia. For example, in the North China Plain simulation studies show that using high-temperature sensitive varieties, maize yield in the 2050s could increase on average by 1.0–6.0%, 9.9–15.2%, and 4.1–5.6%, by adopting adaptation options of early planting, fixing variety growing duration, and late planting, respectively (Tao and Zhang, 2010). In contrast, no adaptation will result in yield declines of 13.2–19.1%.

24.4.5. Human Settlements, Industry, and Infrastructure

24.4.5.1. Sub-Regional Diversity

Around one in every five urban dwellers in Asia lives in large urban agglomerations and almost 50% of these live in small cities (UN, 2012). North and Central Asia are the most urbanized areas, with over 63% of the population living in urban areas, with the exception of Kyrgyzstan and Tajikistan (UN-Habitat, 2010; UN ESCAP, 2011). South and Southwest Asia are the least urbanized subregions, with only a third of their populations living in urban areas. However, these regions have the highest urban population growth rates within Asia at an average of 2.4% per year during 2005-2010 (UN ESCAP, 2011). By the middle of this century, Asia's urban population will increase by 1.4 billion and will account for over 50% of the global population (UN, 2012).

24.4.5.2. Observed Impacts

Asia experienced the highest number of weather- and climate-related disasters in the world during the period 2000-2008 and suffered huge economic losses, accounting for the second highest proportion (27.5%) of the total global economic loss (IPCC, 2012). Flood mortality risk is heavily concentrated in Asia. Severe floods in Mumbai in 2005 have been attributed to both climatic factors and non-climatic factors. Strengthened capacities to address the mortality risk associated with major weather-related hazards, such as floods, have resulted in a downward trend in mortality risk relative to population size, as in East Asia, where it is now a third of its 1980 level (UNISDR, 2011).

24.4.5.3. Projected Impacts

A large proportion of Asia's population lives in low elevation coastal zones that are particularly at risk from climate change hazards, including sea-level rise, storm surges and typhoons (see Sections 5.3.2.1 and 8.2.2.5, Box CC-TC). Depending on the region, half to two-thirds of Asia's cities with 1 million or more inhabitants are exposed to one or multiple hazards, with floods and cyclones the most important (UN, 2012).

Floodplains and Coastal Areas. Three of the world's five most populated cities (Tokyo, Delhi and Shanghai) are located in areas with high risk of floods (UN, 2012). Flood risk and associated human and material losses are heavily concentrated in India, Bangladesh, and China. At the same time, the East Asia region in particular is experiencing increasing water shortages, negatively affecting its socioeconomic, agricultural, and environmental conditions, which is attributed to lack of rains and high evapotranspiration, as well as over-exploitation of water resources (IPCC, 2012). Large parts of South, East and Southeast Asia are exposed to a high degree of cumulative climate-related risk (UN-Habitat, 2011). Asia has more than 90% of the global population exposed to tropical cyclones (IPCC, 2012); see Box CC-TC). Damage due to storm surge is sensitive to change in the magnitude of tropical cyclones. By the 2070s, the top Asian cities in terms of population exposure (including all environmental and socioeconomic factors) to coastal flooding are expected to be Kolkata, Mumbai, Dhaka, Guangzhou, Ho Chi Minh City, Shanghai, Bangkok, Rangoon, and Hai Phòng (Hanson *et al.*, 2011). The top Asian cities in terms of assets exposed are expected to be Guangdong, Kolkata, Shanghai, Mumbai, Tianjin, Tokyo, Hong Kong, and Bangkok. Asia includes 15 of the global top 20 cities for projected population exposure and 13 of the top 20 for asset exposure.

Other Issues in Human Settlements. Asia has a large – and rapidly expanding – proportion of the global urban exposure and vulnerability related to climate change hazards (see SREX Section 4.4.3). In line with the rapid urban growth and sprawl in many parts of Asia, the periurban interface between urban and rural areas deserves particular attention when considering climate change vulnerability (see also Section 18.4.1). Garschagen *et al.* (2011) find, for example, that periurban agriculturalists in the Vietnamese Mekong Delta are facing a multiple burden since they are often exposed to overlapping risks resulting from (a) socio-economic transformations, such as land title insecurity and price pressures; (b) local biophysical degradation, as periurban areas serve as sinks for urban wastes; and (c) climate change impacts, as they do not benefit from the inner-urban disaster risk management measures.

Nevertheless, the periurban interface is still underemphasized in studies on impacts, vulnerability and adaptation in Asia.

Groundwater sources, which are affordable means of high-quality water supply in cities of developing countries, are threatened due to over-withdrawals. Aquifer levels have fallen by 20-50 m in cities such as Bangkok, Manila and Tianjin and between 10-20 m in many other cities (UNESCO, 2012). The drop in groundwater levels often results in land subsidence, which can enhance hazard exposure due to coastal inundation and sea-level rise, especially in settlements near the coast, and deterioration of groundwater quality. Cities susceptible to human-induced subsidence (mainly, developing country cities in deltaic regions with rapidly growing populations) could see significant increases in exposure (Nicholls *et al.*, 2008). Settlements on unstable slopes or landslide-prone areas face increased prospects of rainfall-induced landslides (IPCC, 2012).

Industry and Infrastructure. The impacts of climate change on industry include both direct impacts on industrial production and indirect impacts on industrial enterprises due to the implementation of mitigation activities (Li, 2008). The impact of climate change on infrastructure deterioration cannot be ignored, but can be addressed by changes to design procedures, including increases in cover thickness, improved quality of concrete, and coatings and barriers (Stewart *et al.*, 2012). Climate change and extreme events may have a greater impact on large and medium-sized construction projects (Kim *et al.*, 2007).

Estimates suggest that by upgrading the drainage system in Mumbai, losses associated with a 1-in-100 year flood event today could be reduced by as much as 70%, and through extending insurance to 100% penetration, the indirect effects of flooding could be almost halved, speeding recovery significantly (Ranger *et al.*, 2011). On the east coast of India, clusters of districts with poor infrastructure and demographic development are also the regions of maximum vulnerability. Hence, extreme events are expected to be more catastrophic in nature for the people living in these districts. Moreover, the lower the district is in terms of the infrastructure index and its growth, the more vulnerable it is to the potential damage from extreme events and hence people living in these regions are prone to be highly vulnerable (Patnaik and Narayanan, 2009). In 2008, the embankments on the Kosi River (a tributary of the Ganges) failed, displacing over sixty thousand people in Nepal and three and a half million in India. Transport and power systems were disrupted across large areas. However, the embankment failure was not caused by an extreme event but represented a failure of interlinked physical and institutional infrastructure systems in an area characterized by complex social, political, and environmental relationships (Moench, 2010).

24.4.5.4. Vulnerabilities to Key Drivers

Disruption of basic services such as water supply, sanitation, energy provision, and transportation systems have implications for local economies and “strip populations of their assets and livelihoods”, in some cases leading to mass migration (UN-Habitat, 2010). Such impacts are not expected to be evenly spread among regions and cities, across sectors of the economy, or among socioeconomic groups. They tend to reinforce existing inequalities and disrupt the social fabric of cities and exacerbate poverty.

24.4.5.5. Adaptation Options

An ADB and UN report estimates that “about two-thirds of the $8 trillion needed for infrastructure investment in Asia and the Pacific between 2010 and 2020 will be in the form of new infrastructure, which creates tremendous opportunities to design, finance and manage more sustainable infrastructure” (ADB *et al.*, 2012).) Adaptation measures that offer a ‘no regrets’ solution are proposed for developing countries, “where basic urban infrastructure is often absent (e.g. appropriate drainage infrastructure), leaving room for actions that both increase immediate well-being and reduce vulnerability to future climate change” (Hallegatte and Corfee-Morlot, 2011). The role of urban planning and urban planners in adaptation to climate change impacts has been emphasized (Fuchs *et al.*, 2011; IPCC, 2012; Tyler and Moench, 2012). The focus on solely adapting through physical infrastructure in urban areas requires complementary adapting planning, management, governance and institutional arrangements to be able to deal with the uncertainty and the unprecedented challenges implied by climate change (Revi, 2008; Birkmann *et al.*, 2010; Garschagen and Kraas, 2011).

24.4.6. Human Health, Security, Livelihoods, and Poverty

24.4.6.1. Sub-Regional Diversity

Although rapidly urbanizing, Asia is still predominantly an agrarian society, with 57.28% of its total population living in rural areas, of which 81.02% are dependent on agriculture for their livelihoods (FAOSTAT, 2011). Rural poverty is higher than urban poverty, reflecting the heavy dependence on natural resources that are directly influenced by changes in weather and climate (Haggblade *et al.*, 2010; IFAD, 2010). Rural poverty is expected to remain more prevalent than urban poverty for decades to come (Ravallion *et al.*, 2007). However, climate change will also affect urbanizing Asia, where the urban poor will be impacted indirectly, as evident from the food price rises in the Middle East and other areas in 2007-2008. Certain categories of urban dwellers, such as urban wage labor households, are particularly vulnerable (Hertel *et al.*, 2010).

Agriculture has been identified as a key driver of economic growth in Asia (World Bank, 2007). Although economic growth was impressive in recent decades, there are still gaps in development compared to the rest of the world (World Bank, 2011). Southeast Asia is the third poorest performing region after Sub-Saharan Africa and Southern Asia in terms of the Human Development Indicators (UN, 2009). Impacts on human security in Asia will primarily manifest through impacts on water resources, agriculture, coastal areas, resource-dependent livelihoods, and urban settlements and infrastructure, with implications for human health and well-being. Regional disparities on account of socioeconomic context and geographical characteristics largely define the differential vulnerabilities and impacts within countries in Asia (Thomas, 2008; Sivakumar and Stefanski, 2011).

24.4.6.2. Observed Impacts

Floods and Health. Epidemics have been reported after floods and storms (Bagchi, 2007) as a result of decreased drinking water quality (Harris *et al.*, 2008; Hashizume *et al.*, 2008; Solberg, 2010; Kazama *et al.*, 2012), mosquito proliferation (Pawar *et al.*, 2008), and exposure to rodent-borne pathogens (Kawaguchi *et al.*, 2008; Zhou *et al.*, 2011) and the intermediate snail hosts of *Schistosoma* (Wu *et al.*, 2008). Contaminated urban flood waters have caused exposure to pathogens and toxic compounds, for example in India and Pakistan (Sohan *et al.*, 2008; Warraich *et al.*, 2011). Mental disorders and posttraumatic stress syndrome have also been observed in disaster prone areas (Udomratn, 2008) and, in India, have been linked to age and gender (Telles *et al.*, 2009). See also Chapter 11.4.2. for flood-attributable deaths.

Heat and Health. The effects of heat on mortality and morbidity have been studied in many countries, with a focus on the elderly and people with cardiovascular and respiratory disorders (Kan *et al.*, 2007; Guo *et al.*, 2009; Huang *et al.*, 2010). Associations between high temperatures and mortality have been shown for populations in India and Thailand (McMichael *et al.*, 2008) and in several cities in East Asia (Kim *et al.*, 2006; Chung *et al.*, 2009). Several studies have analyzed the health effects of air pollution in combination with increased temperatures (Lee *et al.*, 2007; Qian *et al.*, 2010; Wong *et al.*, 2010; Yi *et al.*, 2010). Intense heat waves have been shown to affect outdoor workers in South and East Asia (Nag *et al.*, 2007; Hyatt *et al.*, 2010).

Drought and Health. Dust storms in Southwest, Central and East Asia result in increased hospital admissions and worsen asthmatic conditions, as well as causing skin and eye irritations (Griffin, 2007; Hashizume *et al.*, 2010; Kan *et al.*, 2012). Droughts may also lead to wildfires and smoke exposure, with increased morbidity and mortality, as observed in Southeast Asia (Johnston *et al.*, 2012). Drought can also disrupt food security, increasing malnutrition (Kumar *et al.*, 2005) and thus susceptibility to infectious diseases.

Water-borne Diseases. Many pathogens and parasites multiply faster at higher temperatures. Temperature increases have been correlated with increased incidence of diarrheal diseases in East Asia (Huang *et al.*, 2008; Zhang *et al.*, 2008; Onozuka *et al.*, 2010). Other studies from South and East Asia have shown an association between diarrheal outbreaks and a combination of higher temperatures and heavy rainfall (Hashizume *et al.*, 2007; Majra and Gur, 2009; Chou *et al.*, 2010). Increasing coastal water temperatures correlated with outbreaks of systemic *Vibrio vulnificus* infection in Israel (Paz *et al.*, 2007) and South Korea (Kim and Jang, 2010). Cholera outbreaks in coastal populations in South Asia have been associated with increased water temperatures and algal blooms (Huq *et al.*, 2005). The ENSO cycle and Indian Ocean Dipole have been associated with cholera epidemics in Bangladesh (Pascual, 2000; Rodó *et al.*, 2002; Hashizume *et al.*, 2011).

Vector-borne Diseases. Increasing temperatures affect vector-borne pathogens during the extrinsic incubation period and shorten vector life-cycles, facilitating larger vector populations and enhanced disease transmission, whilst the vector's ability to acquire and maintain a pathogen tails off (Paaijmans *et al.*, 2012). Dengue outbreaks in South and Southeast Asia are correlated with temperature and rainfall with varying time lags (Su, 2008; Hii *et al.*, 2009; Hsieh and Chen, 2009; Shang *et al.*, 2010; Sriprom *et al.*, 2010; Hashizume *et al.*, 2012). Outbreaks of vaccine-preventable Japanese encephalitis have been linked to rainfall in studies from the Himalayan region (Partridge *et al.*, 2007; Bhattachan *et al.*, 2009), and to rainfall and temperature in South and East Asia (Bi *et al.*, 2007; Murty *et al.*, 2010). Malaria prevalence is often influenced by non-climate variability factors, but studies from India and Nepal have found correlations with rainfall (Devi and Jauhari, 2006; Dev and Dash, 2007; Dahal, 2008; Laneri *et al.*, 2010). Temperature was linked to distribution and seasonality of malaria mosquitoes in Saudi Arabia (Kheir *et al.*, 2010). The re-emergence of malaria in central China has been attributed to rainfall and increases in temperature close to water bodies (Zhou *et al.*, 2010). In China, temperature, precipitation, and the virus-carrying index among rodents have been found to correlate with the prevalence of hemorrhagic fever with renal syndrome (Guan *et al.*, 2009).

Livelihoods and Poverty. An estimated 51% of total income in rural Asia comes from non-farm sources (Haggblade *et al.*, 2009, 2010), mostly local non-farm business and employment. The contribution of remittances to rural income has grown steadily (Estudillo and Otsuka, 2010). Significant improvements have been made in poverty eradication over the past decade (World Bank, 2008), with rapid reductions in poverty in East Asia, followed by South Asia (IFAD, 2010). A significant part of the reduction has come from population shifts, rapid growth in agriculture, and urban contributions (Janvry and Sadoulet, 2010). Climate change negatively impacts livelihoods (see Table 24-SM-4) and these impacts are directly related to natural resources affected by changes in weather and climate. Factors that have made agriculture less sustainable in the past include input non-responsive yields, soil erosion, natural calamities, and water and land quality related problems (Dev, 2011). These have predisposed rural livelihoods to climate change vulnerability. Livelihoods are impacted by droughts (Harshita, 2013; Selvaraju *et al.*, 2006), floods (Nuorteva *et al.*, 2010; Dun, 2011; Nguyen, 2007; Keskinen *et al.*, 2010) and typhoons (Huigen and Jens, 2006; Gaillard *et al.*, 2007; Uy *et al.*, 2011). Drought disproportionately impacts small farmers, agricultural laborers, and small businessmen (Selvaraju *et al.*, 2006), who also have least access to rural safety net mechanisms, including financial services (IFAD, 2010), despite recent developments in microfinance services in parts of Asia. Past floods have exposed conditions such as lack of access to alternative livelihoods, difficulty in maintaining existing livelihoods, and household debts leading to migration in the Mekong region (Dun, 2011). Similar impacts of repeated floods leading to perpetual vulnerability were found in the Tonle Sap Lake area of Cambodia (Nuorteva *et al.*, 2010; Keskinen *et al.*, 2010). Typhoon impacts are mainly through damage to the livelihood assets of coastal populations in the Philippines and the level of ownership of livelihood assets has been a major determinant of vulnerability (Uy *et al.*, 2011).

24.4.6.3. Projected Impacts

Health Effects. An emerging public health concern in Asia is increasing mortality and morbidity due to heat waves. An ageing population will increase the number of people at risk, especially those with cardiovascular and respiratory disorders. Urban heat island effects have increased (Tan *et al.*, 2010), although local adaptation of the built environment and urban planning will determine the impacts on public health. Heat stress disorders among workers and consequent productivity losses have also been reported (Lin *et al.*, 2009; Langkulsen *et al.*, 2010). The relationship between temperature and mortality is often U-shaped (Guo *et al.*, 2009), with increased mortality also during cold events, particularly in rural environments, even if temperatures do not fall below 0°C (Hashizume *et al.*, 2009). However, some studies in developing areas suggest that factors other than climate can be important, so warming may not decrease cold-related deaths much in these regions (Honda and Ono, 2009).

Climate change will affect the local transmission of many climate-sensitive diseases. Increases in heavy rain and temperature are projected to increase the risk of diarrheal diseases in, for example, China (Zhang *et al.*, 2008). However, the impact of climate change on malaria risk will differ between areas, as projected for West and South Asia (Husain and Chaudhary, 2008; Garg *et al.*, 2009; Majra and Gur, 2009), while a study suggested that the impact of socioeconomic development will be larger than that of climate change (Béguin *et al.*, 2011).
Climate change is also expected to affect the spatiotemporal distribution of dengue fever in the region, although the level of evidence differs across geographical locations (Banu *et al.*, 2011). Some studies have developed climate change-disease prevalence models, for example one for schistosomiasis in China shows an increased northern distribution of the disease with climate change (Zhou *et al.*, 2008; Kan *et al.*, 2012). Impacts of climate change on fish production (Qiu *et al.*, 2010) are being studied, along with impacts on chemical pathways in the marine environment and consequent impacts on food safety (Tirado *et al.*, 2010), including seafood safety (Marques *et al.*, 2010).

Livelihood and Poverty. Floods, droughts and changes in seasonal rainfall patterns are expected to negatively impact crop yields, food security and livelihoods in vulnerable areas (Dawe *et al.*, 2008; Kelkar *et al.*, 2008; Douglas, 2009). Rural poverty in parts of Asia could be exacerbated (Skoufias *et al.*, 2011) due to impacts on the rice crop and increases in food prices and the cost of living (Hertel *et al.*, 2010; Rosegrant, 2011). The poverty impacts of climate change will be heterogeneous among countries and social groups (see Table 24-SM-5). In a low crop productivity scenario, producers in food exporting countries, such as Indonesia, the Philippines and Thailand, would benefit from global food price rises and reduce poverty, while countries such as Bangladesh would experience a net increase in poverty of 15% by 2030 (Hertel *et al.*, 2010). These impacts will also differ within food exporting countries, with disproportionate negative impacts on farm laborers and the urban poor. Skoufias *et al.* (2011) project significant negative impacts of a rainfall shortfall on the welfare of rice farmers in Indonesia, compared to a delay in rainfall onset. These impacts may lead to global mass migration and related conflicts (Laczko and Aghazarm, 2009; Barnett and Webber, 2010; Warner, 2010; World Bank, 2010). In North Asia, climate-driven changes in tundra and forest-tundra biomes may influence indigenous peoples who depend on nomadic tundra pastoralism, fishing and hunting (Kumpula *et al.*, 2011).

24.4.6.4. Vulnerabilities to Key Drivers

Key vulnerabilities vary widely within the region. Climate change can exacerbate current socio-economic and political disparities and add to the vulnerability of Southeast Asia and Central Asia to security threats that may be transnational in nature (Jasparro and Taylor, 2008; Lioubimtseva and Henebry, 2009). Apart from detrimental impacts of extreme events, vulnerability of livelihoods in agrarian communities also arises from geographic settings, demographic trends, socio-economic factors, access to resources and markets, unsustainable water consumption, farming practices and lack of adaptive capacity (Mulligan *et al.*, 2011; Acosta-Michlik and Espaldon, 2008; Allison *et al.*, 2009; Knox *et al.*, 2011; Lioubimtseva and Henebry, 2009; Byg and Salick, 2009; Salick and Ross, 2009; Salick *et al.*, 2009; Xu *et al.*, 2009; UN, 2009). Urban wage laborers were found to be more vulnerable to cost of living related poverty impacts of climate change than those who directly depend on agriculture for their livelihoods (Hertel *et al.*, 2010). In Indonesia, drought-associated fires increase vulnerability of agriculture, forestry and human settlements, particularly in peatland areas (Murdiyarso and Lebel, 2007). Human health is also a major area of focus for Asia (Munslow and O'Dempsey, 2010), where the magnitude and type of health effects from climate change depend on differences in socioeconomic and demographic factors, health systems, the natural and built environment, land use changes, and migration, in relation to local resilience and adaptive capacity. The role of institutions is also critical, particularly in influencing vulnerabilities arising from gender (Ahmed and Fajber, 2009), caste and ethnic differences (Jones and Boyd, 2011), and securing climate-sensitive livelihoods in rural areas (Agrawal and Perrin, 2008).

24.4.6.5. Adaptation Options

Disaster preparedness on a local community level could include a combination of indigenous coping strategies, early-warning systems, and adaptive measures (Paul and Routray, 2010). Heat warning systems have been successful in preventing deaths among risk groups in Shanghai (Tan *et al.*, 2007). New work practices to avoid heat stress among outdoor workers, in Japan and the UAE have also been successful (Morioka *et al.*, 2006; Joubert *et al.*, 2011). Early warning models have been developed for haze exposure from wildfires, in for example Thailand (Kim Oanh and Leelasakultum, 2011), and are being tested in infectious disease prevention and vector control programs, as for malaria in Bhutan (Wangdi *et al.*, 2010) and Iran (Haghdoost *et al.*, 2008), or are being developed, as for dengue fever region-wide (Wilder-Smith *et al.*, 2012).

Some adaptation practices provide unexpected livelihood benefits, as with the introduction of traditional flood mitigation measures in China which could positively impact local livelihoods, leading to reductions in both the physical and economic vulnerabilities of communities (Xu *et al.*, 2009). A greater role of local communities in decision making is also proposed (Alauddin and Quiggin, 2008) and in prioritization and adoption of adaptation options (Prabhakar *et al.*, 2010; Prabhakar and Srinivasan, 2011). Defining adequate community property rights, reducing income disparity, exploring market-based and off-farm livelihood options, moving from production-based approaches to productivity and efficiency decision-making based approaches, and promoting integrated decision-making approaches, have also been suggested (Merrey *et al.*, 2005; Brouwer *et al.*, 2007; Paul *et al.*, 2009; Niino, 2011; Stucki and Smith, 2011).

Climate resilient livelihoods can be fostered through the creation of bundles of capitals (natural, physical, human, financial and social capital) and poverty eradication (Table 24-SM-8). Greater emphasis on agricultural growth has been suggested as an effective means of reducing rural poverty (Janvry and Sadoulet, 2010; Rosegrant, 2011). Bundled approaches are known to facilitate better adaptation than individual adaptation options (Acosta-Michlik and Espaldon, 2008; Fleischer *et al.*, 2011). Community-based approaches have been suggested to identify adaptation options that address poverty and livelihoods, as these techniques help capture information at the grassroots (Huq and Reid, 2007; van Aalst *et al.*, 2008), and help integration of disaster risk reduction, development, and climate change adaptation (Heltberg *et al.*, 2010), connect local communities and outsiders (van Aalst *et al.*, 2008), address the location-specific nature of adaptation (Iwasaki *et al.*, 2009; Rosegrant, 2011), help facilitate community learning processes (Bass and Ramasamy, 2008), and help design location-specific solutions (Ensor and Berger, 2009). Some groups can become more vulnerable to change after being 'locked into' specialized livelihood patterns, as with fish farmers in India (Coulthard, 2008).

Livelihood diversification, including livelihood assets and skills, has been suggested as an important adaptation option for buffering climate change impacts on certain kinds of livelihoods (Selvaraju *et al.*, 2006; Nguyen, 2007; Agrawal and Perrin, 2008; IFAD, 2011; Keskinen *et al.*, 2010; Uy *et al.*, 2011). The diversification should occur across assets, including productive assets, consumption strategies and employment opportunities (Agrawal and Perrin, 2008). Ecosystem-based adaptation has been suggested to secure livelihoods in the face of climate change (Jones *et al.*, 2012), integrating the use of biodiversity and ecosystem services into an overall strategy to help people adapt (IUCN, 2009). Among financial means, low-risk liquidity options such as microfinance programs and risk transfer products can help lift the rural poor from poverty and accumulate assets (Barrett *et al.*, 2007; Jarvis *et al.*, 2011).

24.4.7 Valuation of Impacts and Adaptation

Economic valuation in Asia generally covers impacts and vulnerabilities of disperse sectors such as food production, water resources and human health (Aydinalp and Cresser, 2008; Kelkar *et al.*, 2008; Lioubimtseva and Henebry, 2009; Su *et al.*, 2009; Srivastava *et al.*, 2010). Multi-sector evaluation that unpacks the relationships between and across sectors, particularly in a context of resource scarcity and competition, is very limited. Information is scarce especially for North, Central and West Asia.

Generally, annual losses from drought are expected to increase based on various projection under diverse scenarios, but such losses are expected to be reduced if adaptation measures are implemented (ADB, 2009; Sutton *et al.*, 2013). It is also stressed that there are great uncertainties associated with the economic aspects of climate change. In China, the total loss due to drought projected in 2030 is expected to range from $1.1-1.7 billion for regions in northeast China and about $0.9 billion for regions in north China (CWF *et al.*, 2009), with adaptation measures having the potential to avert half of the losses. In India, the estimated countrywide agricultural loss in 2030 of over $7 billion that will severely affect the income of 10% of the population could be reduced by 80% if cost-effective climate resilience measures are implemented (CWF *et al.*, 2009).

In Indonesia, the Philippines, Thailand and Vietnam, under the A2 scenario, the PAGE2002 integrated assessment model projects a mean loss of 2.2% of gross domestic product (GDP) by 2100 on an annual basis, if only the market impact (mainly related to agriculture and coastal zones) is considered (ADB, 2009). This is well above the world's projected mean GDP loss of 0.6% each year by 2100 due to market impact alone. In addition, the mean cost for the four countries could reach 5.7% of the GDP if non-market impacts related to health and ecosystems are included and 6.7% of the GDP if catastrophic risks are also taken into account. The cost of adaptation for agriculture and coastal zones is expected to be about $5 billion/year by 2020 on average. Adaptation that is complemented with global mitigation measures is expected to be more effective in reducing the impacts of climate change (IPCC, 2007; ADB, 2009; UNFCCC, 2009; MNRE, 2010; Begum *et al.*, 2011).

24.5. Adaptation and Managing Risks

24.5.1. Conservation of Natural Resources

Natural resources are already under severe pressure from land-use change and other impacts in much of Asia. Deforestation in Southeast Asia has received most attention (Sodhi *et al.*, 2010; Miettinen *et al.*, 2011a), but ecosystem degradation, with the resulting loss of natural goods and services, is also a major problem in other ecosystems. Land-use change is also a major source of regional greenhouse gas emissions, particularly in Southeast Asia (see WGI AR5 Section 6.3.2.2 and Table 6.3). Projected climate change is expected to intensify these pressures in many areas (see Sections 24.4.2.3 and 24.4.3.3), most clearly for coral reefs, where increases in sea surface temperature and ocean acidification are a threat to all reefs in the region and the millions of people who depend on them (see Section 5.4.2.4 and Boxes CC-CR and CC-OA). Adaptation has so far focused on minimizing non-climate pressures on natural resources and restoring connectivity to allow movements of genes and species between fragmented populations (see Section 24.4.2.5). Authors have also suggested a need to identify and protect areas that will be subject to the least damaging climate change ('climate refugia') and to identify additions to the protected area network that will allow for expected range shifts, for example by extending protection to higher altitudes or latitudes. Beyond the intrinsic value of wild species and ecosystems, ecosystem-based approaches to adaptation aim to use the resilience of natural systems to buffer human systems against climate change, with potential social, economic and cultural co-benefits for local communities (see Box CC-EA).

24.5.2. Flood Risks and Coastal Inundation

Many coasts in Asia are exposed to threats from floods and coastal inundation (see also 24.4.5.3). Responding to a large number of climate change impact studies for each Asian country over the past decade (e.g. Karim and Mimura, 2008; Pal and Al-Tabbaa, 2009), various downscaled tools to support, formulate and implement climate change adaptation policy for local governments are under development. One of the major tools is vulnerability assessment and policy option identification with Geographical Information Systems (GIS). These tools are expected to be of assistance in assessing city-specific adaptation options by examining estimated impacts and identified vulnerability for some coastal cities and areas in Asian countries (e.g. Brouwer *et al.*, 2007; Taylor, 2011; Storch and Downs, 2011). These tools and systems sometimes take the form of integration of top down approaches and bottom-up (community-based) approaches (see Section 14.5). Whereas top-down approaches give scientific knowledge to local actors, community-based approaches are built on existing knowledge and expertise to strengthen coping and adaptive capacity by involving local actors (van Aalst *et al.*, 2008). Community-based approaches may have a limitation in that they place greater responsibility on the shoulders of local people without necessarily increasing their capacity proportionately (Allen, 2006). As the nature of adaptive capacity varies depending on the formulation of social capital and institutional context in the local community, it is essential for the approaches to be based on an understanding of local community structures (Adger, 2003).

24.5.3. Economic Growth and Equitable Development

Climate change challenges fundamental elements in social and economic policy goals such as prosperity, growth, equity and sustainable development (Mearns and Norton, 2010). Economic, social, and environmental equity is an enduring challenge in many parts of Asia. Generally, the level of wealth (typically GDP) has been used as a measure of human vulnerability of a country but this approach has serious limitations (Mattoo and Subramanian, 2012; Dellink *et al.*, 2009). In many cases, social capital, an indicator of equity in income distribution within countries, is a more important factor in vulnerability and resilience than GDP per capita (Lioubimtseva and Henebry, 2009; Islam *et al.*, 2006). Furthermore, political and institutional instabilities can undermine the influence of economic development (Lioubimtseva and Henebry, 2009). Poor and vulnerable countries are at greater risk of inequity and loss of livelihoods from the impacts of climate extremes as their options for coping with such events are limited. Many factors contribute to this limitation, including poverty, illiteracy, weak institutions and infrastructures, poor access to resources, information and technology, poor health care, and low investment and management capabilities. The overexploitation of land resources including forests, increases in population, desertification and land degradation pose additional threats (UNDP, 2006). This is particularly true for developing countries in Asia with a high level of natural resource dependency. Provision of adequate resources based on the burden sharing and the equity principle will serve to strengthen appropriate adaptation policies and measures in such countries (Su *et al.*, 2009).

24.5.4. Mainstreaming and Institutional Barriers

Mainstreaming climate change adaptation into sustainable development policies offers a potential opportunity for good practice to build resilience and reduce vulnerability, depending on effective, equitable and legitimate actions to overcome barriers and limits to adaptation (ADB, 2005; Lim *et al.*, 2005; Lioubimtseva and Henebry, 2009). The level of adaptation mainstreaming is most advanced in the context of official development assistance, where donor agencies and international financial institutions have made significant steps towards taking climate change adaptation into account in their loan and grant making processes (Gigli and Agrawala, 2007; Klein *et al.*, 2007). While some practical experiences of adaptation in Asia at the regional, national and local level are emerging, there can be barriers that impede or limit adaptation. These include challenges related to competing national priorities, awareness and capacity, financial resources for adaptation implementation, institutional barriers, biophysical limits to ecosystem adaptation, and social and cultural factors (Lasco *et al.*, 2009; Moser and Ekstrom, 2010; Lasco *et al.*, 2012). Issues with resource availability might not only result from climate change, but also from weak governance mechanisms and the breakdown of policy and regulatory structures, especially with common-pool resources (Moser and Ekstrom, 2010). Furthermore, the impact of climate change depends on the inherent vulnerability of the socio-ecological systems in a region as much as on the magnitude of the change (Evans, 2010). Recent studies linking climate-related resource scarcities and conflict call for enhanced regional cooperation (Gautam, 2012).

24.5.5. Role of Higher Education in Adaptation and Risk Management

To enhance the development of young professionals in the field of climate change adaptation, the topic could be included in higher education, especially in formal education programs. Shaw *et al.* (2011) mentioned that higher education in adaptation and disaster risk reduction in the Asia-Pacific region can be done through environment disaster linkage, focus on hydro-meteorological disasters, and emphasizing synergy issues between adaptation and risk reduction. Similar issues are also highlighted by other authors (Chhokar, 2010; Niu *et al.*, 2010; Nomura and Abe, 2010; Ryan *et al.*, 2010). Higher education should be done through lectures and course work, field studies, internships, and establishing education-research link by exposing the students to field realities. In this regard, guiding principles could include: an inclusive curriculum, focus on basic theory, field orientation, multidisciplinary courses and practical skill enhancement. Bilateral or multilateral practical research programs on adaptation and risk management by the graduate students and young faculty members would expose them to the real field problems.

24.6. Adaptation and Mitigation Interactions

Integrated mitigation and adaptation responses focus on either land-use changes or technology development and use. Changes in land use, such as agroforestry, may provide both mitigation and adaptation benefits (Verchot *et al.*, 2007), or otherwise, depending on how they are implemented. Agroforestry practices provide carbon storage and may decrease soil erosion, increase resilience against floods, landslides and drought, increase soil organic matter, reduce the financial impact of crop failure, as well as have biodiversity benefits over other forms of agriculture, as shown, for example, in Indonesia (Clough *et al.*, 2011). Integrated approaches are often needed when developing mitigation-adaptation synergies, as seen in waste-to-compost projects in Bangladesh (Ayers and Huq, 2009). Other adaptation measures that increase biomass and/or soil carbon content, such as ecosystem protection and reforestation, will also contribute to climate mitigation by carbon sequestration. However, exotic monocultures may fix more carbon than native mixtures while supporting less biodiversity and contributing less to ecological services, calling for compromises that favor biodiversity-rich carbon storage (Diaz *et al.*, 2009). The potential for both adaptation and mitigation through forest restoration is greatest in the tropics (Sasaki *et al.*, 2011). At higher latitudes (>45^{o}N), reforestation can have a net warming influence by reducing surface albedo (Anderson-Teixeira *et al.*, 2012). Expansion of biofuel crops on abandoned and marginal agricultural lands could potentially make a large contribution to mitigation of carbon emissions from fossil fuels, but could also have large negative consequences for both carbon and biodiversity if it results directly or indirectly in the conversion of carbon-rich ecosystems to cropland (Fargione *et al.*, 2010; Qin *et al.*, 2011). Mechanisms, such as REDD+, that put an economic price on land-use emissions, could reduce the risks of such negative consequences (Thomson *et al.*, 2010), but the incentive structures need to be worked out very carefully (Busch *et al.*, 2012).

Forests and their management are also often emphasized for providing resilient livelihoods and reducing poverty (Chhatre and Agrawal, 2009; Noordwijk, 2010; Persha *et al.*, 2010; Larson, 2011). Securing rights to resources is essential for greater livelihood benefits for poor indigenous and traditional people (Macchi *et al.*, 2008) and the need for REDD+ schemes to respect and promote community forest tenure rights has been emphasized (Angelsen, 2009). It has been suggested that indigenous people can provide a bridge between biodiversity protection and climate change adaptation (Salick and Ross, 2009): a point that appears to be missing in the current discourse on ecosystem-based adaptation. There are arguments against REDD+ supporting poverty reduction due to its inability to promote productive use of forests, which may keep communities in perpetual poverty (Campbell, 2009), but there is a contrasting view that REDD+ can work in forests managed for timber production (Putz *et al.*, 2012; Guariguata *et al.*, 2008), especially through reduced impact logging (Guariguata *et al.*, 2008) and other approaches such as assuring the legality of forest products, certifying responsible management, and devolving control over forests to empowered local communities (Putz *et al*., 2012).

On rivers and coasts, the use of hard defenses (e.g. sea-walls, channelization, bunds, dams) to protect agriculture and human settlements from flooding may have negative consequences for both natural ecosystems and carbon sequestration by preventing natural adjustments to changing conditions (see 24.4.3.5). Conversely, setting aside landward buffer zones along coasts and rivers would be positive for both. The very high carbon sequestration potential of the organic-rich soils in mangroves (Donato *et al.*, 2011) and peat swamp forests (Page *et al.*, 2011) provides opportunities for combining adaptation with mitigation through restoration of degraded areas.

Mitigation measures can also result in public health benefits (Bogner *et al.*, 2008; Haines *et al.*, 2009). For example, sustainable cities with fewer fossil-fuel driven vehicles (mitigation) and more trees and greenery (carbon storage and adaptation to the urban heat island effect) would have a number of co-benefits, including public health – a promising strategy for “triple win” interventions (Romero-Lankao *et al.*, 2011). Other examples include efforts to decarbonize electricity production in India and China that are projected to decrease mortality due to reduced PM5 and PM2.5 particulates (Markandya *et al.*, 2009); policies to increase public transportation, promote walking and cycling, and reduce private cars that will increase air quality and decrease the health burden, particularly in urban environments as projected in India (Woodcock *et al.*, 2009) ; and abandoning the use of biomass fuel or coal for indoor cooking and heating to improve indoor air quality and respiratory and cardiac health among, in particular, women and children in India and China (Wilkinson *et al.*, 2009). Conversely, actions to reduce current environmental-public health issues may often have beneficial mitigation effects, like traffic emissions reduction programs in China (Wu *et al.*, 2011) and India (Reynolds and Kandikar, 2008).

24.7. Intra-regional and Inter-regional Issues

24.7.1. Trans-boundary Pollution

Many Asian countries and regions face long-distance and trans-boundary air pollution problems. In eastern China, Japan and the Korean Peninsula, these include dust storms that originate in the arid and semi-arid regions upwind, with impacts on climate, human health and ecosystems (Huang *et al.*, 2013). The susceptibility of the land surface to wind erosion is strongly influenced by vegetation cover, which is in turn sensitive to climate change and other human impacts. In the humid tropics of Southeast Asia, in contrast, the major trans-boundary pollution issue involves smoke aerosols from burning of biomass and peatlands, mostly during clearance for agriculture (Miettinen *et al.*, 2011b; Gautam *et al.*, 2013). Apart from the large impact on human health, these aerosols may be having a significant effect on rainfall in equatorial regions, leading to the possibility of climate-feedbacks, with fires reducing rainfall and promoting further fires (Tosca *et al.*, 2012). Pollutants of industrial origin are also a huge problem in many parts of the region, with well-documented impacts on human health (see Section 24.4.6) and the climate (see WGI AR5 Chapters 7 and 8).

24.7.2. Trade and Economy

The ASEAN Free Trade Agreement (AFTA) and the Indonesia–Japan Economic Partnership Agreement (IJEPA) have positively impacted the Indonesian economy and reduced water pollution, but increased CO_2 emissions by 0.46% compared to the business-as-usual situation, mainly due to large emission increases in the transportation sector (Gumilang *et al.*, 2011). Full liberalization of tariffs and GDP growth concentrated in China and India has led to transport emissions growing much faster than the value of trade, due to a shift towards distant trading partners (Cristea *et al.*, 2013). China's high economic growth and flourishing domestic and international trade has resulted in increased consumption and pollution of water resources (Guan and Hubacek, 2007). Japanese imports from the ASEAN region are negatively correlated with per capita carbon emissions (Atici, 2012) due to strict regulations in Japan that prevent import from polluting sectors. Export-led growth is central to the economic progress and well-being of Southeast Asian countries. Generally, as exports rise, carbon emissions tend to rise. International trading systems that help address the challenge of climate change need further investigation.

24.7.3. Migration and Population Displacement

Floods and droughts are predominant causes for internal displacement (Internal Displacement Monitoring Center, 2011). In 2010 alone, 38.3 million people were internally displaced; 85% because of hydrological hazards and 77% in Asia. Floods are increasingly playing a role in migration in the Mekong Delta (Warner, 2010). Often some migrants return to the vulnerable areas (Piguet, 2008) giving rise to ownership, rights of use, and other issues (Kolmannskog, 2008). Increasing migration has led to increasing migration-induced remittances contributing to Asian economies, but has had negligible effect on the poverty rate (Vargas-Silva *et al.*, 2009). In Bangladesh, migrant workers live and work under poor conditions, such as crowded shelters, inadequate sanitation, conflict and competition with the local population, and exploitation (Penning-Rowsell *et al.*, 2011). Forced migration can result from adaptation options such as construction of dams, but the negative outcomes could be allayed by putting proper safeguards in place (Penning-Rowsell *et al.*, 2011). Managed retreat of coastal communities is a suggested option to address projected sea-level rise (Alexander *et al.*, 2012). A favorable approach to deal with migration is within a development framework and through adaptation strategies (Penning-Rowsell *et al.*, 2011; ADB, 2012).

24.8. Research and Data Gaps

Studies of observed climate changes and their impacts are still inadequate for many areas, particularly in North, Central and West Asia (Table 24-2). Improved projections for precipitation, and thus water supply, are most urgently needed. Another priority is developing water management strategies for adaptation to changes in demand and supply. More research is also needed on the health effects of changes in water quality and quantity. Understanding of climate change impacts on ecosystems and biodiversity in Asia is currently limited by the poor quality and low accessibility of biodiversity information (UNEP, 2012). National biodiversity inventories are incomplete and few sites have the baseline information needed to identify changes. For the tropics, major research gaps include the temperature dependence of carbon fixation by tropical trees, the thermal tolerances and acclimation capacities of both plants and animals, and the direct impacts of rising CO_2 (Corlett, 2011; Zuidema *et al.*, 2013). Rising CO_2 is also expected to be important in cool-arid ecosystems, where lack of experimental studies currently limits our ability to make predictions (Poulter *et al.*, 2013). Boreal forest dynamics will be influenced by complex interactions between rising temperatures and CO_2, permafrost thawing, forest fires, and insect outbreaks (Osawa *et al.*, 2010; Zhang *et al.*, 2011), and understanding this complexity will require enhanced monitoring of biodiversity and species ranges, improved modeling, and greater knowledge of species biology (Meleshko and Semenov, 2008).

Rice is the most studied crop but there are still significant uncertainties in model accuracy, CO_2-fertilization effects, and regional differences (Masutomi *et al.*, 2009; Zhang *et al.*, 2010; Shuang-He *et al.*, 2011). For other crops, there is even greater uncertainty. Studies are also needed of the health effects of interactions between heat and air pollution in urban and rural environments. More generally, research is needed on impacts, vulnerability and adaptation in urban settlements, especially cities with populations under 500,000, which share half the region's urban population. Greater understanding is required of the linkages between local livelihoods, ecosystem functions, and land resources for creating a positive impact on livelihoods in areas with greater dependence on natural resources (Paul *et al.*, 2009). Increasing regional collaboration in scientific research and policy making has been suggested for reducing climate change impacts on water, biodiversity and livelihoods in the Himalayan region (Xu *et al.*, 2009) and could be considered elsewhere. The literature suggests that work must begin now on building understanding of the impacts of climate change and moving forward with the most cost-effective adaptation measures (ADB, 2007; Cai *et al.*, 2008; Mathy and Guivarch, 2010; Stage, 2010). For devising mitigation policies, the key information needed is again the most cost-effective measures (Nguyen, 2007; Cai *et al.*, 2008; Mathy and Guivarch, 2010).

[INSERT TABLE 24-2 HERE
Table 24-2: The amount of information supporting conclusions regarding observed and projected impacts in Asia.

24.9. Case Studies

24.9.1. Transboundary Adaptation Planning and Management – Lower Mekong River Basin

The *Lower Mekong River Basin (LMB)* covers an area of approximately 606,000 sq. km across the countries of Thailand, Laos, Cambodia and Vietnam. More than 60 million people are heavily reliant on natural resources, in particular agriculture and fisheries, for their well-being (MRC, 2009; Dugan *et al.*, 2010; Figure 24-SM-2). Thailand and Vietnam produced 51% of the world's rice exports in 2008, mostly in the LMB (Mainuddin *et al.*, 2011).

Observations of climate change over the past 30-50 years in the LMB include: an increase in temperature, an increase in rainfall in the wet season and decreases in the dry season, intensified flood and drought events, and sea-level rise (ICEM, 2010; IRG, 2010). Agricultural output has been noticeably impacted by intensified floods and droughts which caused almost 90% of rice production losses in Cambodia during 1996-2001 (Brooks and Adger, 2003; MRC, 2009).Vietnam and Cambodia are two of the countries most vulnerable to climate impacts on fisheries (Allison *et al.*, 2009; Halls, 2009).

Existing studies about future climate impacts in the Mekong Basin broadly share a set of common themes (MRC, 2009; Murphy and Sampson, 2013): increased temperature and annual precipitation; increased depth and duration of flood in the Mekong Delta and Cambodia floodplain; prolonged agricultural drought in the south and the east of the basin; and sea-level rise and salinity intrusion in the Mekong delta. Hydropower dams along the Mekong River and its tributaries will also have severe impacts on fish productivity and biodiversity, by blocking critical fish migration routes, altering the habitat of non-migratory fish species, and reducing nutrient flows downstream (Costanza *et al.*, 2011; Baran and Guerin, 2012; Ziv *et al.*, 2012). Climate impacts, though less severe than the impact of dams, will exacerbate these changes (Wyatt and Baird, 2007; Grumbine *et al.*, 2012; Orr *et al.*, 2012; Räsänen *et al.*, 2012; Ziv *et al.*, 2012).

National climate change adaptation plans have been formulated in all four LMB countries, but transboundary adaptation planning across the LMB does not exist to date. Effective future transboundary adaptation planning and management will benefit from: a shared climate projection across the LMB for transboundary adaptation planning; improved coordination among adaptation stakeholders and sharing of best practices across countries; mainstreaming climate change adaptation into national and sub-national development plans with proper translation from national adaptation strategies into local action plans; integration of transboundary policy recommendations into national climate change plans and policies; integration of adaptation strategies on a landscape scale between ministries and different levels of government within a country (MRC, 2009; Lian and Bhullar, 2011; Lebel *et al.*, 2012; Kranz *et al.*, 2010)

A study of the state-of-adaptation practice in the LMB showed that only 11% (45 of 417) of climate-change related projects in the LMB were on-the-ground adaptation efforts driven by climate risks (Ding, 2012; Neo, 2012; Schaffer and Ding, 2012). Common features of 'successful' projects include: robust initial gap assessment, engagement of local stakeholders, and a participatory process throughout (Brown, 2012; Khim, 2012; Mondal, 2012; Panyakul, 2012; Roth and Grunbuhel, 2012). A multi-stakeholder Regional Adaptation Action Network has been proposed with the intent of scaling up and improving mainstreaming of adaptation through tangible actions following the theory and successful examples of the Global Action Networks (GANs) (Waddell, 2005; Waddell and Khagram, 2007; WCD, 2000; GAVI, 2011; Schaffer and Ding, 2012) .

24.9.2. Glaciers of Central Asia

In the late 20th century, central Asian glaciers occupied 31,628 km^2 (Dolgushin and Osipova). All recent basin-scale studies document multidecadal area loss (Figure 24-3); where multiple surveys are available, most show accelerating loss. The rate of glacier area change varies (Table 24-SM-9). Rates between –0.05%/yr and –0.76%/yr have been reported in the Altai (Surazakov *et al.*, 2007; Shahgedanova *et al.*, 2010; Yao *et al.*, 2012b) and Tien Shan (Lettenmaier *et al.*, 2009; Sorg *et al.*, 2012), and between –0.13%/yr and–0.30%/yr in the Pamir (Konovalov and Desinov, 2007; Aizen, 2011a, 2011b, 2011c; Yao *et al.*, 2012b). These ranges reflect varying sub-regional distributions of glacier size (smaller glaciers shrink faster) and debris cover (which retards shrinkage), but also varying proportions of ice at high altitudes, where as yet warming has produced little increase in melt (Narama *et al.*, 2010). Most studies also document mean-annual (e.g. Glazyrin and Tadzhibaeva, 2011, for 1961-1990) and summertime (e.g. Shahgedanova *et al.*, 2010) warming, with slight cooling in the central and eastern Pamir (Aizen, 2011b). Precipitation increases have been observed more often than decreases (e.g. Braun *et al.*, 2009; Glazyrin and Tadzhibaeva, 2011).

[INSERT FIGURE 24-3 HERE
Figure 24-3: Losses of glacier area in the Altai-Sayan, Pamir and Tien Shan. Remote sensing data analysis from 1960s (Corona) through 2008 (Landsat, ASTER and Alos Prism).]

Aizen *et al.* (2007) calculated 21st-century losses of 43% of the volume of Tien Shan glaciers for an 8^{o}C temperature increase accompanied by a 24% precipitation increase, but probable complete disappearance of glaciers if precipitation decreased by 16%; a more moderate 2^{o}C increase led to little loss, but only if accompanied by a 24% precipitation increase. Drawing on CMIP5 simulations, (Radić *et al.*, 2013) simulated losses by 2100 of between 25% and 90% of 2006 ice volume (including Tibet but excluding the Altai and Sayan; range of all single-model simulations); the 14-GCM model mean losses are 55% for RCP4.5 and 75% for RCP8.5. Similarly, Marzeion *et al.* (2012) found 21st-century volume losses of 50% for RCP2.6, about 57% for both RCP4.5 and RCP6.0, and 67% for RCP8.5.

The glaciers have therefore been a diminishing store of water, and the diminution is projected to continue. Paradoxically, this implies more meltwater, possibly explaining limited observations of increased runoff (Sorg *et al*., 2012), but also an eventual decrease of meltwater yield (see Section 3.4.4). More immediately, it entails a hazard due to the formation of moraine-dammed glacial lakes (Bolch *et al.*, 2011).

Frequently Asked Questions

FAQ 24.1: What will the projected impact of future climate change be on freshwater resources in Asia?
[to be placed in Section 24.4.1]
Asia is a huge and diverse region, so both climate change and the impact on freshwater resources will vary greatly depending on location. But throughout the region, adequate water resources are particularly important because of the massive population and heavy dependence of the agricultural sector on precipitation, river runoff and groundwater. Overall, there is *low confidence* in the projections of specifically how climate change will impact future precipitation on a subregional scale, and thus in projections of how climate change might impact the availability of water resources. However, water scarcity is expected to be a big challenge in many Asian regions because of increasing water demand from population growth and consumption per capita with higher standards of living. Shrinkage of glaciers in central Asia is expected to increase due to climate warming, which will influence downstream river runoff in these regions. Better water management strategies could help ease water scarcity. Examples include developing water saving technologies in irrigation, building reservoirs, increasing water productivity, changing cropping systems and water reuse.

FAQ 24.2: How will climate change affect food production and food security in Asia?
[to be placed in Section 24.4.4]
Climate change impacts on temperature and precipitation will affect food production and food security in various ways in specific areas throughout this diverse region. Climate change will have a generally negative impact on crop production Asia, but with diverse possible outcomes [*medium confidence*]. For example most simulation models show that higher temperatures will lead to lower rice yields as a result of a shorter growing period. But some studies indicate that increased atmospheric CO_2 that leads to those higher temperatures could enhance photosynthesis and increase rice yields. This uncertainty on the overall effects of climate change and CO_2 fertilization is generally true for other important food crops such as wheat, sorghum, barley, and maize among others.

Yields of some crops will increase in some areas (e.g. cereal production in north and east Kazakhstan) and decrease in others (e.g. wheat in the Indo-Gangetic Plain of South Asia). In Russia, climate change may lead to a food production shortfall, defined as an event in which the annual potential production of the most important crops falls 50% or more below it's normal average. Sea-level rise is projected to decrease total arable areas and thus food supply in many parts of Asia. A diverse mix of potential adaptation strategies, such as crop breeding, changing crop varieties, adjusting planting time, water management, diversification of crops and a host of indigenous practices will all be applicable within local contexts.

FAQ 24.3: Who is most at risk from climate change in Asia? *[to be placed in Section 24.4.6]*
People living in low-lying coastal zones and flood plains are probably most at risk from climate change impacts in Asia. Half of Asia's urban population lives in these areas. Compounding the risk for coastal communities, Asia has more than 90% of the global population exposed to tropical cyclones. The impact of such storms, even if their frequency or severity remains the same, is magnified for low lying and coastal zone communities because of rising sea level [*medium confidence*]. Vulnerability of many island populations is also increasing due to climate change impacts. Settlements on unstable slopes or landslide prone-areas, common in some parts of Asia, face increased likelihood of rainfall-induced landslides.

Asia is predominantly agrarian, with 58% of its population living in rural areas, of which 81% are dependent on agriculture for their livelihoods. Rural poverty in parts of Asia could be exacerbated due to negative impacts from climate change on rice production, and a general increase in food prices and the cost of living [*high confidence*].

Climate change will have widespread and diverse health impacts. More frequent and intense heatwaves will increase mortality and morbidity in vulnerable groups in urban areas [*high confidence*]. The transmission of infectious disease, such as cholera epidemics in coastal Bangladesh, and schistosomiasis in inland lakes in China, and diarrheal outbreaks in rural children will be affected due to warmer air and water temperatures and altered rain patterns and water flows [*medium confidence*]. Outbreaks of vaccine-preventable Japanese encephalitis in the Himalayan region and malaria in India and Nepal have been linked to rainfall. Changes in the geographical distribution of vector-borne diseases, as vector species that carry and transmit diseases migrate to more hospitable environments, will occur [*medium confidence*]. These effects will be most noted close to the edges of the current habitats of these species.

Cross-Chapter Box

Box CC-TC. Building Long-Term Resilience from Tropical Cyclone Disasters

[Yoshiki Saito (Japan), Kathleen McInnes (Australia)]

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

About 90 tropical cyclones occur globally each year (Seneviratne et al., 2012) although interannual variability is large. Changes in observing techniques particularly after the introduction of satellites in the late 1970s, confounds the assessment of trends in tropical cyclone frequencies and intensities. Therefore, IPCC (2012) "Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)" concluded that there is *low confidence* that any observed long-term (i.e. 40 years or more) increases in tropical cyclone activity are robust, after accounting for past changes in observing capability (Seneviratne et al., 2012; Chapter 2). There is also *low confidence* in the detection and attribution of century scale trends in tropical cyclones. Future changes to tropical cyclones arising from climate change are *likely* to vary by region. This is because there is *medium confidence* that for certain regions, shorter-term forcing by natural and anthropogenic aerosols has had a measurable effect on tropical cyclones. Tropical cyclone frequency is *likely* to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is *likely* to increase (AR5 WG1 Ch 14.6). Regionally specific projections have *lower confidence* (see AR5 WG1 Box 14.2).

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

Densely populated Asian deltas are particularly vulnerable to tropical cyclones due to their large population density in expanding urban areas (Nicholls et al., 2007). Extreme cyclones in Asia since 1970 caused over 0.5 million fatalities (Murray et al., 2012) e.g., cyclones Bhola in 1970, Gorky in 1991, Thelma in 1998, Gujarat in 1998, Orissa in 1999, Sidr in 2007, and Nargis in 2008. Tropical cyclone Nargis hit Myanmar on 2 May 2008 and caused over 138,000 fatalities. Several-meter high storm surges widely flooded densely populated coastal areas of the Irrawaddy Delta and surrounding areas (Revenga et al., 2003; Brakenridge et al., 2013). The flooded areas were captured by a NASA MODIS image on 5 May 2008 (see Figure TC-1).

[INSERT FIGURE TC-1 HERE
Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. Source: Brakenridge et al., 2013.]

Murray et al. (2012) compared the response to cyclone Sidr in Bangladesh in 2007 and Nargis in Myanmar in 2008 and demonstrated how disaster risk reduction methods could be successfully applied to climate change adaptation.

Sidr, despite being of similar strength to Nargis, caused far fewer fatalities (3,400 compared to over 138000) and this was attributed to advancement in preparedness and response in Bangladesh through experience in previous cyclones such as Bhola and Gorky. The responses included the construction of multistoried cyclone shelters, improvement of forecasting and warning capacity, establishing a coastal volunteer network, and coastal reforestation of mangroves. The strategies of disaster risk management for tropical cyclones in coastal areas, that create protective measures, anticipate and plan for extreme events, increase the resilience of potentially exposed communities. The integration of activities relating to education, training, and awareness-raising into relevant ongoing processes and practices is important for the long-term success of disaster risk reduction and management (Murray et al., 2012). Birkmann and Teichman (2010) caution that while the combination of risk reduction and climate change adaptation strategies may be desirable, different spatial and temporal scales, norm systems, and knowledge types and sources between the two goals can confound their effective combination.

Box CC-TC References

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Table 24-1: Key risks from climate change and the potential for risk reduction through mitigation and adaptation in Asia. Key risks are identified based on assessment of the literature and expert judgments, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation (Very low – Medium – Very high)
Increased risk of crop failure and lower crop production could lead to food insecurity in Asia (*medium confidence*)	Autonomous adaptation of farmers on-going in many parts of Asia.		24.4.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Water shortage in arid areas of Asia (*medium confidence*)	Limited capacity for water resource adaptation; options include developing water saving technology, changing drought-resilient crops, building more water reservoirs.		24.4.1.3, 24.4.1.4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased flooding leading to widespread damage to infrastructure and settlements in Asia (*medium confidence*)	Adaptation measures include extreme weather exposure reduction via effective land-use planning, selective relocation and structural measures; reduction in the vulnerability of lifeline infrastructure and services (water, energy, waste management, food, biomass, mobility, local ecosystems and telecommunications) and measures to assist vulnerable sectors and households.		24.4.5.1, 24.4.5.2, 24.4.5.3, 24.4.5.5,	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased risk of flood-related deaths, injuries, infectious diseases and mental disorders (*medium confidence*)	Disaster preparedness including early-warning systems and local coping strategies.		24.4.6.2, 24.4.6.3, 24.4.6.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	
Increased risk of heat-related mortality (*high confidence*)	Heat health-warning systems, urban planning to reduce heat islands and improvement of built environment.		24.4.6.2, 24.4.6.3, 24.4.6.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	

Climatic drivers of impacts

Warming trend	Extreme temperature	Drying trend	Extreme precipitation	Damaging cyclone	Storm surge	Sea level	Ocean acidification

Risk & potential for adaptation

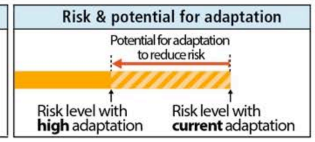

Table 24-1 (continued)

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Increased risk of drought-related water and food shortage causing malnutrition (*high confidence*)	Disaster preparedness including early-warning systems and local coping strategies.		24.4.6.2, 24.4.6.3, 24.4.6.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Increased risk of water and vector-borne diseases (*medium confidence*)	Early-warning systems, vector control programs, water management and sanitation programs.		24.4.6.2, 24.4.6.3, 24.4.6.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Exacerbated poverty, inequalities and new vulnerabilities (*high confidence*)	Insufficient emphasis and limited understanding on urban poverty, interaction between livelihoods, poverty and climate change.		24.4.5 24.4.6	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Coral reef decline in Asia (*high confidence*)	The limited adaptation options include minimizing additional stresses in marine protected areas sited where sea surface temperatures are expected to change least and reef resilience is expected to be highest.		24.4.3.3, 24.4.3.5, CC-CR, CC-OA	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high
Mountain-top extinctions in Asia (*high confidence*)	Adaptation options are limited. Reducing non-climate impacts and maximizing habitat connectivity will reduce risks to some extent, while assisted migration may be practical for some species.		24.4.2.4, 24.4.2.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	Very low – Medium – Very high

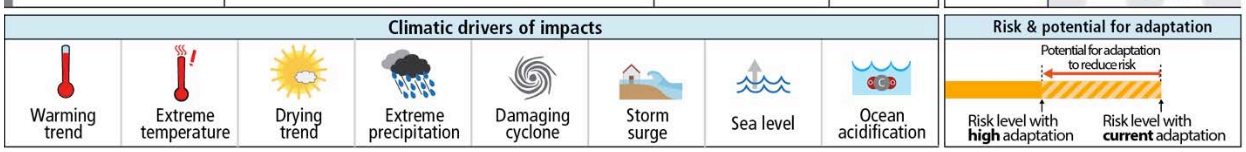

Table 24-2: The amount of information supporting conclusions regarding observed and projected impacts in Asia.

/ = Relatively abundant/sufficient information; knowledge gaps need to be addressed but conclusions can be drawn based on existing information
X = Limited information/no data; critical knowledge gaps, difficult to draw conclusions
NR = Not relevant

Region	Topics/Issues	North Asia		East Asia		Southeast Asia		South Asia		Central Asia		West Asia	
	O= Observed impacts; P= Projected Impacts	O	P	O	P	O	P	O	P	O	P	O	P
Freshwater Resources	Major river runoff	/	x	/	/	/	/	/	x	x	x	x	x
	Water supply	x	x	x	x	x	x	x	x	x	x	x	x
Terrestrial and Inland Water Systems	Phenology and growth rates	/	/	/	/	x	x	x	x	x	x	x	x
	Distributions of species and biomes	/	/	/	/	x	x	x	/	x	x	x	x
	Permafrost	/	/	/	/	/	x	/	/	/	/	/	x
	Inland waters	x	x	/	x	x	x	x	x	x	x	x	x
Coastal Systems and Low-Lying Areas	Coral reefs	NR	NR	/	/	/	/	/	/	NR	NR	/	/
	Other coastal ecosystems	x	x	/	/	x	x	x	x	NR	NR	x	x
	Arctic coast erosion	/	/	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR
Food Production Systems and Food Security	Rice yield	x	x	/	/	x	/	x	/	x	x	X	/
	Wheat yield	x	x	x	x	x	x	x	/	x	x	/	/
	Corn yield	x	x	x	/	x	x	x	x	x	x	x	x
	Other crops (e.g. barley, potato)	x	x	/	/	x	x	x	x	x	X	/	/
	Vegetables	x	x	/	x	x	x	x	x	x	x	x	x
	Fruits	x	x	/	x	x	x	x	x	x	x	x	x
	Livestock	x	x	/	x	x	x	x	x	x	x	x	x
	Fisheries and aquaculture production	x	/	x	/	x	/	x	x	x	x	x	x
	Farming area	x	/	x	/	x	x	x	/	x	/	x	x
	Water demand for irrigation	x	/	x	/	x	x	x	/	x	x	x	x
	Pest and disease occurrence	x	x	x	x	x	x	x	/	x	x	x	x
Human Settlements, Industry, and Infrastructure	Floodplains	x	x	/	/	/	/	/	/	x	x	x	x
	Coastal areas	x	x	/	/	/	/	/	/	NR	NR	x	x
	Population and assets	x	x	/	/	/	/	/	/	x	x	x	x
	Industry and infrastructure	x	x	/	/	/	/	/	/	x	x	x	x
Human Health, Security, Livelihoods and Poverty	Health effects of floods	x	x	x	x	x	x	/	x	x	x	x	x
	Health effects of heat	x	x	/	x	x	x	x	x	x	x	x	x
	Health effects of drought	x	x	x	x	x	x	x	x	x	x	x	x
	Water-borne diseases	x	x	x	x	/	x	/	x	x	x	x	x
	Vector-borne diseases	x	x	x	x	/	x	/	x	x	x	x	x
	Livelihoods and poverty	x	x	/	x	x	x	/	x	x	x	x	x
	Economic valuation	x	x	x	x	/	/	/	/	x	x	x	x

Sub-region	Countries/Regions	
Central Asia (5)	• Kazakhstan • Kyrgyzstan • Tajikistan	• Turkmenistan • Uzbekistan
East Asia (7)	• China, Hong Kong Special Administrative Region (Hong Kong SAR) • China, Macao Special Administrative Region • Japan	• North Korea • People's Republic of China (China) • South Korea • Taiwan Province of China (Taiwan POC)
North Asia (2)	• Mongolia	• Russia (East of Urals)
South Asia (8)	• Afghanistan • Bangladesh • Bhutan • India	• Maldives • Nepal • Pakistan • Sri Lanka
Southeast Asia (12)	• Brunei • Indonesia • Lao People's Democratic • Malaysia • Myanmar • Papua New Guinea	• The Philippines • Republic Cambodia • Singapore • Thailand • Timor-Leste • Vietnam
West Asia (17)	• Armenia • Azerbaijan • Bahrain • Georgia • Iran • Iraq • Israel • Jordan	• Kuwait • Lebanon • Palestine • Oman • Qatar • Saudi Arabia • Syria • United Arab Emirates • Yemen

Figure 24-1: The land and territories of 51 countries in Asia.
NOTE: Currently in production and will be brought to specification using the current UN-accepted maps.
[Illustration to be redrawn to conform to IPCC publication specifications.]

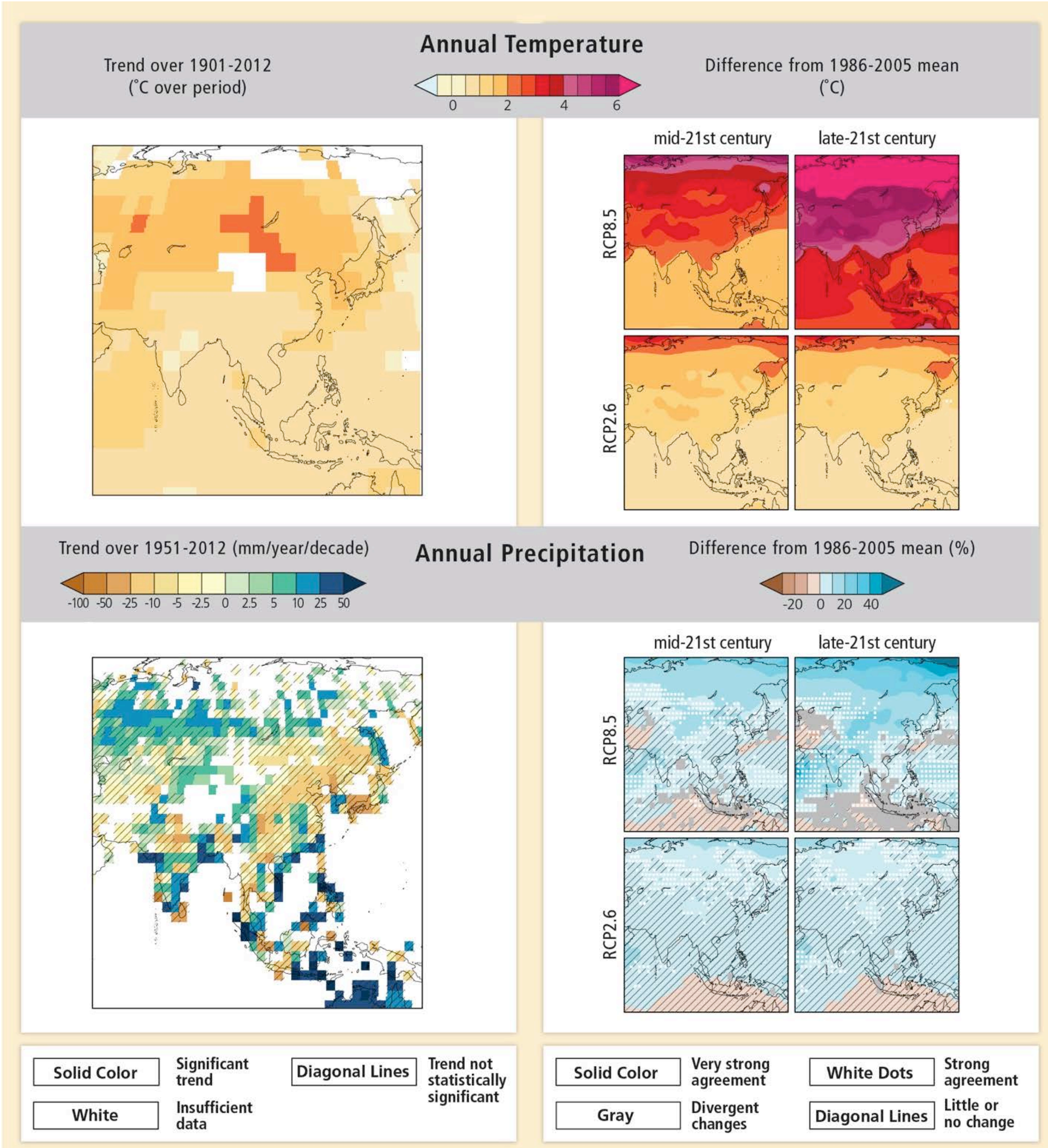

Figure 24-2: Observed and projected changes in annual average temperature and precipitation in Asia. (Top panel, left) Observed temperature trends from 1901-2012 determined by linear regression. [WGI AR5 Figures SPM.1 and 2.21] (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression. [WGI AR5 Figure SPM.2] For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-3 and CC-RC]

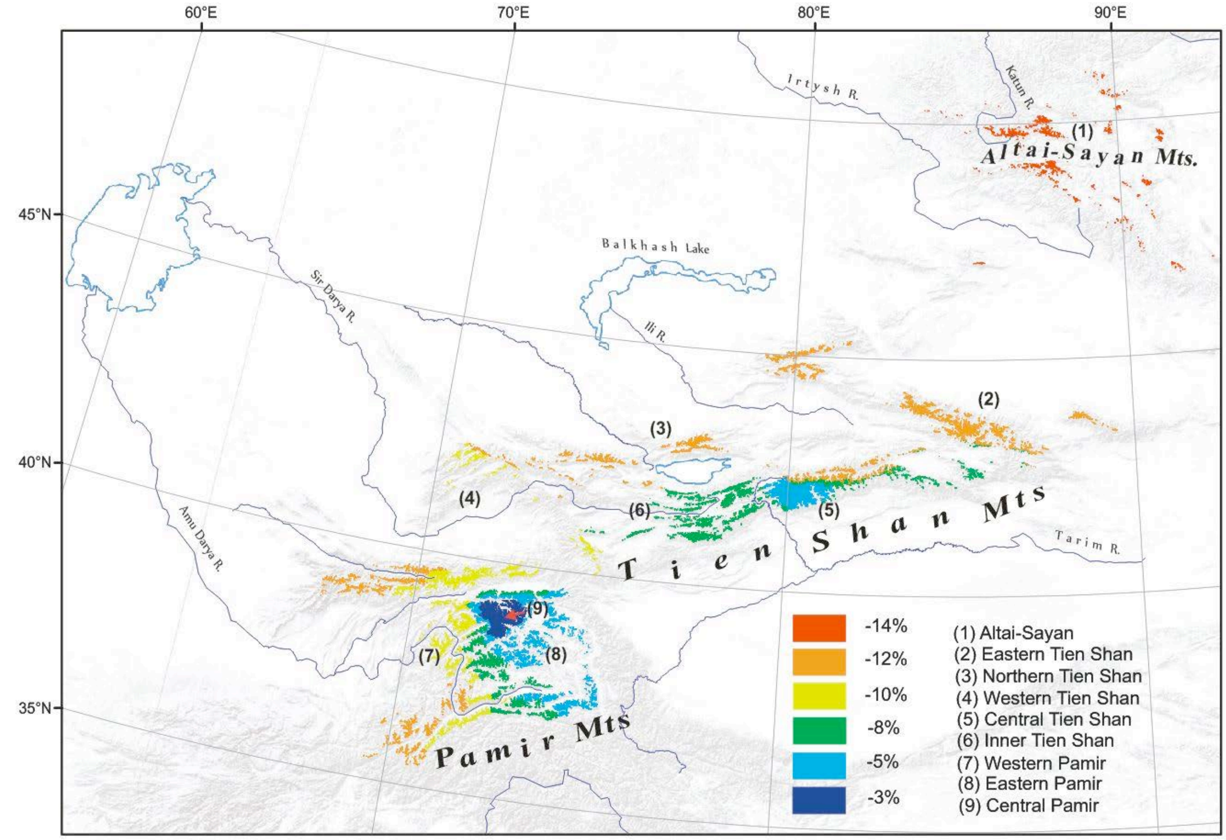

Figure 24-3: Losses of glacier area in the Altai-Sayan, Pamir and Tien Shan. Remote sensing data analysis from 1960s (Corona) through 2008 (Landsat, ASTER and Alos Prism).
[Illustration to be redrawn to conform to IPCC publication specifications.]

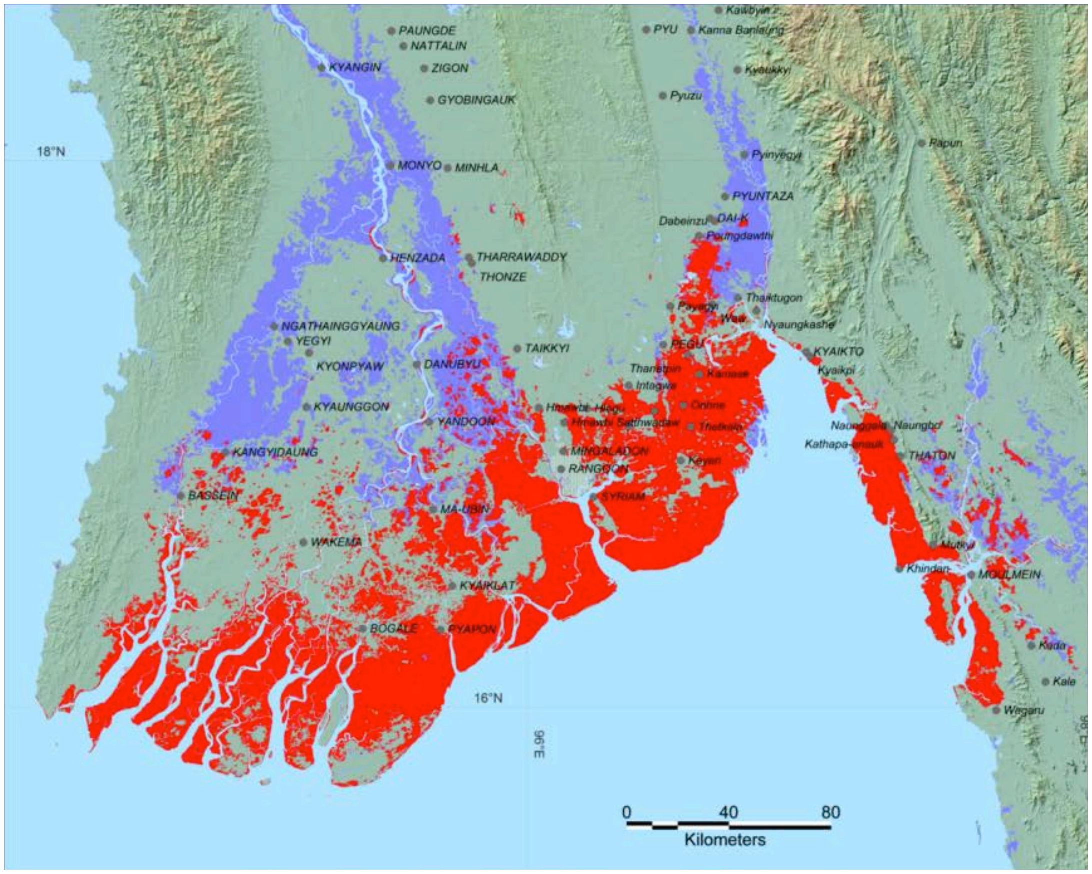

Figure TC-1: The intersection of inland and storm surge flooding. Red shows May 5, 2008 MODIS mapping of the tropical cyclone Nargis storm surge along the Irrawaddy Delta and to the east, Myanmar. The blue areas to the north were flooded by the river in prior years. Source: Brakenridge et al., 2013.

Chapter 25. Australasia

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Frequently Asked Questions

Executive Summary

The regional climate is changing (*very high confidence*). The region continues to demonstrate long term trends toward higher surface air and sea-surface temperatures, more hot extremes and fewer cold extremes, and changed rainfall patterns. Over the past 50 years, increasing greenhouse gas concentrations have contributed to rising average temperature in Australia *(high confidence)* and New Zealand (*medium confidence*) and decreasing rainfall in south-western Australia (*high confidence*). [25.2, Table 25-1]

Warming is projected to continue through the 21st century (*virtually certain*) along with other changes in climate. Warming is expected to be associated with rising snow lines (*very high confidence*), more frequent hot extremes, less frequent cold extremes (*high confidence*), and increasing extreme rainfall related to flood risk in many locations (*medium confidence*). Annual average rainfall is expected to decrease in south-western Australia (*high confidence*) and elsewhere in most of far southern Australia and the north-east South Island and northern and eastern North Island of New Zealand (*medium confidence*), and to increase in other parts of New Zealand (*medium confidence*). Tropical cyclones are projected to increase in intensity but remain similar or decrease in numbers (*low confidence*), and fire weather is projected to increase in most of southern Australia (*high confidence*) and many parts of New Zealand (*medium confidence*). Regional sea level rise will *very likely* exceed the historical rate (1971-2010), consistent with global mean trends. [25.2, Table 25-1, Box 25-6; WGI 13.5, 13.6]

Uncertainty in projected rainfall changes remains large for many parts of Australia and New Zealand, which creates significant challenges for adaptation. For example, projections for average annual runoff in far south-eastern Australia range from little change to a 40% decline for 2°C global warming above current levels. The dry end of these scenarios would have severe implications for agriculture, rural livelihoods, ecosystems and urban water supply, and would increase the need for transformational adaptation (*high confidence*). [25.2, 25.5.1, 25.6.1, 25.7.2, Box 25-2, Box 25-5]

Recent extreme climatic events show significant vulnerability of some ecosystems and many human systems to current climate variability (*very high confidence*), and the frequency and/or intensity of such events is projected to increase in many locations (*medium* to *high confidence*). For example, high sea surface temperatures have repeatedly bleached coral reefs in north-eastern Australia (since the late 1970s) and more recently in western Australia. Recent floods in Australia and New Zealand caused severe damage to infrastructure and settlements and 35 deaths in Queensland alone (2011); the Victorian heat wave (2009) increased heat-related morbidity and was associated with more than 300 excess deaths, while intense bushfires destroyed over 2,000 buildings and led to 173 deaths; and widespread drought in south-east Australia (1997-2009) and many parts of New Zealand (2007-2009; 2012-13) resulted in substantial economic losses (e.g. regional GDP in the southern Murray Darling Basin was below forecast by about 5.7% in 2007/08, and New Zealand lost about NZ$3.6b in direct and off-farm output in 2007-09). [Table 25-1, 25.6.2, 25.8.1, Box 25-5, Box 25-6, Box 25-8]

Without adaptation, further changes in climate, atmospheric CO_2 and ocean acidity are projected to have substantial impacts on water resources, coastal ecosystems, infrastructure, health, agriculture and biodiversity (*high confidence*). Freshwater resources are projected to decline in far south-west and far south-east mainland Australia (*high confidence*) and for rivers originating in the north-east of the South Island and east and north of the North Island of New Zealand (*medium confidence*). Rising sea levels and increasing heavy rainfall are projected to increase erosion and inundation, with consequent damages to many low-lying ecosystems, infrastructure and housing; increasing heat waves will increase risks to human health; rainfall changes and rising temperatures will shift agricultural production zones; and many native species will suffer from range contractions and some may face local or even global extinction. [25.5.1, 25.6.1, 25.6.2, 25.7.2, 25.7.4, Box 25-1, Box 25-5, Box 25-8]

Some sectors in some locations have the potential to benefit from projected changes in climate and increasing atmospheric CO_2 (*high confidence*). Examples include reduced winter mortality (*low confidence*), reduced energy demand for winter heating in New Zealand and southern parts of Australia, and forest growth in cooler regions except where soil nutrients or rainfall are limiting. Spring pasture growth in cooler regions would also increase and be beneficial for animal production if it can be utilized. [25.7.1, 25.7.2, 25.7.4, 25.8.1]

Adaptation is already occurring and adaptation planning is becoming embedded in some planning processes, albeit mostly at the conceptual rather than implementation level (*high confidence*). Many solutions for reducing energy and water consumption in urban areas with co-benefits for climate change adaptation (e.g. greening cities and recycling water) are already being implemented. Planning for reduced water availability in southern Australia and for sea-level rise in both countries is becoming adopted widely, although implementation of specific policies remains piecemeal, subject to political changes, and open to legal challenges. [25.4, Box 25-1, Box 25-2, Box 25-9]

Adaptive capacity is generally high in many human systems, but implementation faces major constraints especially for transformational responses at local and community levels (*high confidence*). Efforts to understand and enhance adaptive capacity and adaptation processes have increased since the AR4, particularly in Australia. Constraints on implementation arise from: absence of a consistent information base and uncertainty about projected impacts; limited financial and human resources to assess local risks and to develop and implement effective policies and rules; limited integration of different levels of governance; lack of binding guidance on principles and priorities; different attitudes towards the risks associated with climate change, and different values placed on objects and places at risk. [25.4, 25.10.3, Box 25-1, Table 25-2]

Indigenous peoples in both Australia and New Zealand have higher than average exposure to climate change due to a heavy reliance on climate-sensitive primary industries and strong social connections to the natural environment, and face particular constraints to adaptation (*medium confidence*). Social status and representation, health, infrastructure and economic issues, and engagement with natural resource industries constrain adaptation and are only partly offset by intrinsic adaptive capacity (*high confidence*). Some proposed responses to climate change may provide economic opportunities, particularly in New Zealand related to forestry. Torres Strait communities are vulnerable even to small sea level rises (*high confidence*). [25.3, 25.8.2]

We identify eight *regional key risks* during the 21st century based on the severity of potential impacts for different levels of warming, uniqueness of the systems affected, and adaptation options (*high confidence*). These risks differ in the degree to which they can be managed via adaptation and mitigation, and some are more likely to be realized than others, but all warrant attention from a risk-management perspective.

- Some potential impacts can be delayed but now appear very difficult to avoid entirely, even with globally effective mitigation and planned adaptation:
  - ***significant change in community composition and structure of coral reef systems in Australia***, driven by increasing sea-surface temperatures and ocean acidification; the ability of corals to adapt naturally to rising temperatures and acidification appears limited and insufficient to offset the detrimental effects [25.6.2, 30.5, Box CC-CR]
  - ***loss of montane ecosystems and some native species in Australia***, driven by rising temperatures and snow lines, increased fire risk and drying trends; fragmentation of landscapes, limited dispersal and limited rate of evolutionary change constrain adaptation options [25.6.1]
- Some impacts have the potential to be severe but can be reduced substantially by globally effective mitigation combined with adaptation, with the need for transformational adaptation increasing with the rate and magnitude of climate change:
  - ***increased frequency and intensity of flood damage to settlements and infrastructure in Australia and New Zealand***, driven by increasing extreme rainfall although the amount of change remains uncertain; in many locations, continued reliance on increased protection alone would become progressively less feasible [Table 25-1, 25.4.2, Box 25-8, 25.10.3]
  - ***constraints on water resources in southern Australia***, driven by rising temperatures and reduced cool-season rainfall; integrated responses encompassing management of supply, recycling, water conservation and increased efficiency across all sectors are available and some are being implemented in areas already facing shortages [25.2, 25.5.2, Box 25-2]
  - ***increased morbidity, mortality and infrastructure damages during heat waves in Australia***, resulting from increased frequency and magnitude of extreme high temperatures; vulnerable populations include

the elderly and those with existing chronic diseases; population increases and ageing trends constrain effectiveness of adaptation responses [25.8.1]

- o ***increased damages to ecosystems and settlements, economic losses and risks to human life from wildfires in most of southern Australia and many parts of New Zealand***, driven by rising temperatures and drying trends; local planning mechanisms, building design, early warning systems and public education can assist with adaptation and are being implemented in regions that have experienced major events [25.2, Table 25-1, 25.6.1, 25.7.1, Box 25-6]

- For some impacts, severity depends on changes in climate variables that span a particularly large range, even for a given global temperature change. The most severe changes would present major challenges if realized:
  - o ***increasing risks to coastal infrastructure and low-lying ecosystems in Australia and New Zealand from continuing sea level rise, with widespread damages towards the upper end of projected changes***; managed retreat is a long-term adaptation strategy for human systems but options for some natural ecosystems are limited due to the rapidity of change and lack of suitable space for landward migration. Risks from sea level rise continue to increase beyond 2100 even if temperatures are stabilised. [Table 25-1, 25.4.2, Box 25-1, 25.6.1, 25.6.2; WGI 13.5]
  - o ***significant reduction in agricultural production in the Murray-Darling Basin and far south-eastern and south-western Australia if scenarios of severe drying are realised;*** more efficient water use, allocation and trading would increase the resilience of systems in the near term but cannot prevent significant reductions in agricultural production and severe consequences for ecosystems and some rural communities at the dry end of the projected changes [25.2, 25.5.2, 25.7.2, Box 25-2, Box 25-5]

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

Understanding of future vulnerability of human and mixed human-natural systems to climate change remains limited due to incomplete consideration of socio-economic dimensions (*very high confidence*). Future vulnerability will depend on factors such as wealth and its distribution across society, patterns of ageing, access to technology and information, labour force participation, societal values, and mechanisms and institutions to resolve conflicts. These dimensions have received only limited attention and are rarely included in vulnerability assessments, and frameworks to integrate social, psychological and cultural dimensions of vulnerability with bio-physical impacts and economic losses are lacking. In addition, conclusions for New Zealand in many sectors, even for bio-physical impacts, are based on limited studies that often use a narrow set of assumptions, models and data and hence have not explored the full range of potential outcomes. [25.3, 25.4, 25.11]

25.1. Introduction and Major Conclusions from Previous Assessments

Australasia is defined here as lands, territories, offshore waters and oceanic islands of the exclusive economic zones of Australia and New Zealand. Both countries are relatively wealthy with export-led economies. Both have Westminster-style political systems and have a relatively recent history of non-indigenous settlement (Australia in the late 18th, New Zealand in the early 19th century). Both retain significant indigenous populations.

Principal findings from the IPCC Fourth Assessment Report (AR4) for the region were (Hennessy *et al.*, 2007):

- Consistent with global trends, Australia and New Zealand had experienced warming of 0.4 to 0.7°C since 1950 with changed rainfall patterns and sea-level rise of about 70 mm across the region; there had also been a greater frequency and intensity of droughts and heat waves, reduced seasonal snow cover and glacial retreat.

- Impacts from recent climate changes were evident in increasing stresses on water supply and agriculture, and changed natural ecosystems; some adaptation had occurred in these sectors but vulnerability to extreme events such as fire, tropical cyclones, droughts, hail and floods remained high.
- The climate of the 21st century would be warmer (*virtually certain*), with changes in extreme events including more intense and frequent heat waves, fire, floods, storm surges and droughts but less frequent frost and snow (*high confidence*), reduced soil moisture in large parts of the Australian mainland and eastern New Zealand but more rain in western New Zealand (*medium confidence*).
- Significant advances had occurred in understanding future impacts on water, ecosystems, Indigenous people and health together with an increased focus on adaptation; potential impacts would be substantial without further adaptation, particularly for water security, coastal development, biodiversity, and major infrastructure, but impacts on agriculture and forestry would be variable across the region, including potential benefits in some areas.
- Vulnerability would increase mainly due to an increase in extreme events; human systems were considered to have a higher adaptive capacity than natural systems.
- Hotspots of high vulnerability by 2050 under a medium emissions scenario included:
  - significant loss of biodiversity in areas such as alpine regions, the Wet Tropics, the Australian south-west, Kakadu wetlands, coral reefs and sub-Antarctic islands;
  - water security problems in the Murray-Darling basin, south-western Australia and eastern New Zealand;
  - potentially large risks to coastal development in south-eastern Queensland and in New Zealand from Northland to the Bay of Plenty.

25.2. Observed and Projected Climate Change

Australasia exhibits a wide diversity of climates, such as moist tropical monsoonal, arid and moist temperate, including alpine conditions. Key climatic processes are the Asian-Australian monsoon and the southeast trade winds over northern Australia, and the subtropical high pressure belt and the mid-latitude storm tracks over southern Australia and New Zealand. Tropical cyclones also affect northern Australia, and, more rarely, ex-tropical cyclones affect some parts of New Zealand. Natural climatic variability is very high in the region, especially for rainfall and over Australia, with the El Nino-Southern Oscillation (ENSO) being the most important driver (McBride and Nicholls, 1983; Power *et al.*, 1998; Risbey *et al.*, 2009). The southern annular mode, Indian Ocean Dipole and the Interdecadal Pacific Oscillation are also important regional drivers (Thompson and Wallace, 2000; Salinger *et al.*, 2001; Cai *et al.*, 2009b). This variability poses particular challenges for detecting and projecting anthropogenic climate change and its impacts in the region. For example, changes in ENSO in response to anthropogenic climate change are uncertain (AR5 WGI Ch14) but, given current ENSO impacts, any changes would have the potential to significantly influence rainfall and temperature extremes, droughts, tropical cyclones, marine conditions and glacial mass balance (Mullan, 1995; Chinn *et al.*, 2005; Holbrook *et al.*, 2009; Diamond *et al.*, 2012; Min *et al.*, 2013).

Understanding of observed and projected climate change has received much attention since AR4, particularly in Australia, with a focus on the causes of observed rainfall changes and more systematic analysis of projected changes from different models and approaches. Climatic extremes have also been a research focus. Table 25-1 presents an assessment of this body of research for observed trends and projected changes for a range of climatic variables (including extremes) relevant for regional impacts and adaptation, including examples of the magnitude of projected change, and attribution, where possible. Most studies are based on CMIP3 models and SRES scenarios, but CMIP5 model results are considered where available (see also AR5 WGI Chap 14 & Atlas; WGII Chapter 21).

The region has exhibited warming to the present (*very high confidence*) and is *virtually certain* to continue to do so (Table 25-1). Observed and CMIP5-modelled past and projected future annual average surface temperatures are shown in Figures 25-1 and 25-2. For further details see WGI Atlas, AI.68-69. Changes in precipitation have been observed with *very high confidence* in some areas over a range of time scales, such as increases in north-western Australia since the 1950s, the autumn/winter decline since 1970 in south-western Australia and, since the 1990s, in south-eastern Australia, and over 1950-2004 increases in annual rainfall in the south and west of the South Island and west of the North Island of New Zealand, and decreases in the north-east of the South Island and east and north of the North Island. Based on multiple lines of evidence, annual average rainfall is projected to decrease with *high* *confidence* in south-western Australia. For New Zealand, annual average rainfall is projected to decrease in the north-eastern South Island and eastern and northern North Island, and increase in other parts of the country (*medium confidence*). The direction and magnitude of rainfall change in eastern and northern Australia remains a key uncertainty (Table 25-1).

This pattern of projected rainfall change is reflected in annual average CMIP5 model results (Figure 25-1), but with important additional dimensions relating to seasonal changes and spread across models (see also WGI Atlas, AI.70-71). Examples of the magnitude of projected annual change from 1990 to 2090 (percent model mean change +/- intermodel standard deviation) under RCP8.5 from CMIP5 are -20±13% in south-western Australia, -2±21% in the Murray Darling Basin, and -5±22% in southeast Queensland (Irving *et al.*, 2012). Projected changes during winter and spring are more pronounced and/or consistent across models than the annual changes, e.g. drying in south-western Australia (-32±11%, June to August), the Murray Darling Basin (-16±22%, June to August), and southeast Queensland (-15±26%, September to November), whereas there are increases of 15% or more in the west and south of the South Island of New Zealand (Irving *et al.*, 2012). Downscaled CMIP3 model projections for New Zealand indicate a stronger drying pattern in the south-east of the South Island and eastern and northern regions of the North Island in winter and spring (Reisinger *et al.*, 2010) than seen in the raw CMIP5 data; based on similar broader scale changes this pattern is expected to hold once CMIP5 data are also downscaled (Irving *et al.*, 2012).

Other projected changes of at least *high confidence* include regional increases in sea surface temperature, the occurrence of hot days, fire weather in southern Australia, mean and extreme sea level, and ocean acidity (see WGI 6.4.4 for projections); and decreases in cold days and snow extent and depth. Although changes to tropical cyclone occurrence and that of other severe storms are potentially important for future vulnerability, regional changes to these phenomena cannot be projected with at least *medium confidence* as yet (see Table 25-1).

[INSERT FIGURE 25-1 HERE
Figure 25-1: Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Observed temperature trends from 1901-2012 determined by linear regression [WGI AR5 Figures SPM.1 and 2.21]. (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression [WGI AR5 Figure SPM.2]. For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5 [Boxes 21-3 and CC-RC].]

[INSERT FIGURE 25-2 HERE
Figure 25-2: Observed and simulated variations in past and projected future annual average near-surface air temperature over land areas of Australia (left) and New Zealand (right). Black lines show various estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with 'historical' changes in anthropogenic and natural drivers (63 simulations), historical changes in 'natural' drivers only (34), the 'RCP2.6' emissions scenario (63), and the 'RCP8.5' (63). Data are anomalies from the 1986-2005 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

[INSERT TABLE 25-1 HERE
Table 25-1: Observed and projected changes in key climate variables, and (where assessed) the contribution of human activities to observed changes. For further relevant information see WGI Chapters 3, 6 (ocean changes, including acidification), 11, 12 (projections), 13 (sea level) and 14 (regional climate phenomena).]

25.3. Socio-Economic Trends Influencing Vulnerability and Adaptive Capacity

25.3.1. Economic, Demographic and Social Trends

The economies of Australia and New Zealand rely on natural resources, agriculture, minerals, manufacturing and tourism, but the relative importance of these sectors differs between the two countries. Agriculture and mineral/energy resources accounted, respectively, for 11% and 55% (Australia) and 56% and 5% (New Zealand) of the value of total exports in 2010/2011 (ABS, 2012c; SNZ, 2012b). Water abstraction per capita in both countries is in the top half of the OECD, decreasing since 1990 in Australia but increasing in New Zealand; more than half is used for irrigation (OECD, 2010, 2013a). Between 1970 and 2011, GDP grew by an average of 3.2% p.a. in Australia and 2.4% p.a. in New Zealand, with annual GDP per capita growth of 1.8% and 1.2%, respectively (SNZ, 2011; ABS, 2012d). GDP is projected to grow on average by 2.5-3.5% p.a. in Australia and about 1.9% p.a. in New Zealand to 2050 (Australian Treasury, 2010; Bell *et al.*, 2010) but subject to significant shorter-term fluctuations.

The populations of Australia and New Zealand are projected to grow significantly over at least the next several decades (*very high confidence*; ABS, 2008; SNZ, 2012a); Australia's population from 22.3 million in 2011 to 31-43 million by 2056 and 34-62 million by 2101 (ABS, 2008, 2013); New Zealand's population from 4.4 million in 2011 to 5.1-7.1 million by 2061 (SNZ, 2012a). The number of people aged 65 and over is projected to almost double in the next two decades (ABS, 2008; SNZ, 2012a). More than 85% of the Australasian population lives in urban areas and their satellite communities, mostly in coastal areas (DCC, 2009; SNZ, 2010b; UN, 2012; see Box 25-9). Urban concentration and depletion of remote rural areas is expected to continue (Mendham and Curtis, 2010; SNZ, 2010c; Box 25-5), but some coastal non-urban spaces also face increasing development pressure (Freeman and Cheyne, 2008; Gurran, 2008; Box 25-1). More than 20% of Australasian residents were born overseas (OECD, 2013a).

Poverty rates and income inequality in Australia and New Zealand are in the upper half of OECD countries, and both measures increased significantly in both countries between the mid-1980s and the late-2000s (OECD, 2013a). Measurement of poverty and inequality, however, is highly contested, and it remains difficult to anticipate future changes and their effects on adaptive capacity (Peace, 2001; Scutella *et al.*, 2009; 25.3.2). Indigenous peoples constitute about 2.5% and 15% of the Australian and New Zealand populations, respectively, but in Australia, their national share is growing and they constitute a much higher percentage of the population in remote and very remote regions (ABS, 2009, 2010b; SNZ, 2010a). Indigenous peoples in both countries have lower than average life expectancy, income and education, implying that changes in socio-economic status and social inclusion could strongly influence their future adaptive capacity (see 25.8.2).

25.3.2. Use and Relevance of Socio-Economic Scenarios in Adaptive Capacity/Vulnerability Assessments

Demographic, economic and socio-cultural trends influence the vulnerability and adaptive capacity of individuals and communities (see Chapters 2, 11-13, 16, 20). A limited but growing number of studies in Australasia have attempted to incorporate such information, e.g. changes in the number of people and percentage of elderly people at risk (Preston *et al.*, 2008; Baum *et al.*, 2009; Preston and Stafford-Smith, 2009; Roiko *et al.*, 2012), the density of urban settlements and exposed infrastructure (Preston and Jones, 2008; Preston *et al.*, 2008; Baynes *et al.*, 2012), population-driven pressures on water demand (Jollands *et al.*, 2007; CSIRO, 2009), and economic and social factors affecting individual coping, planning and recovery capacity (Dwyer *et al.*, 2004; Khan, 2012; Roiko *et al.*, 2012).

Socio-economic considerations are used increasingly to understand adaptive capacity of communities (Preston *et al.*, 2008; Smith *et al.*, 2008; Fitzsimons *et al.*, 2010; Soste, 2010; Brunckhorst *et al.*, 2011) and to construct scenarios to help build regional planning capacity (Energy Futures Forum, 2006; Frame *et al.*, 2007; Pride *et al.*, 2010; Pettit *et* *al.*, 2011; Taylor *et al.*, 2011). Such scenarios, however, are only beginning to be used to quantify vulnerability to climate change (except e.g. Bohensky *et al.*, 2011; Baynes *et al.*, 2012; Low Choy *et al.*, 2012).

Apart from these emerging efforts, most vulnerability studies from Australasia make no or very limited use of socio-economic factors, consider only current conditions, and/or rely on postulated correlations between generic socio-economic indicators and climate change vulnerability. In many cases this limits confidence in conclusions regarding future vulnerability to climate change and adaptive capacity of human and mixed natural-human systems.

25.4. Cross-Sectoral Adaptation: Approaches, Effectiveness, and Constraints

25.4.1. Frameworks, Governance, and Institutional Arrangements

Adaptation responses depend heavily on institutional and governance arrangements (see Chapters 2, 14, 15, 16, 20). Responsibility for development and implementation of adaptation policy in Australasia is largely devolved to local governments and, in Australia, to State governments and Natural Resource Management bodies. Federal/central government supports adaptation mostly via provision of information, tools, legislation, policy guidance and (in Australia) support for pilot projects. A standard risk management paradigm has been promoted to embed adaptation into decision-making practices (AGO, 2006; MfE, 2008b; Standards Australia, 2013), but broader systems and resilience approaches are used increasingly for natural resource management (Clayton *et al.*, 2011; NRC, 2012).

The Council of Australian Governments agreed a national adaptation policy framework in 2007 (COAG, 2007). This included establishing the collaborative National Climate Change Adaptation Research Facility (NCCARF) in 2008, which complemented CSIRO's Climate Adaptation Flagship. The federal government supported a first-pass national coastal risk assessment (DCC, 2009; DCCEE, 2011), is developing indicators and criteria for assessing adaptation progress and outcomes (DIICCSRT, 2013), and commissioned targeted reports addressing impacts and management options for natural and managed landscapes (Campbell, 2008; Steffen *et al.*, 2009; Dunlop *et al.*, 2012), National and World Heritage areas (ANU, 2009; BMT WBM, 2011), and indigenous and urban communities (Green *et al.*, 2009; Norman, 2010). Most State and Territory governments have also developed adaptation plans (e.g. DSE, 2013).

In New Zealand, the central government updated and expanded tools to support impact assessments and adaptation responses consistent with regulatory requirements (MfE, 2008b, c, d, 2010b), and revised key directions for coastal management (Minister of Conservation, 2010). No cross-sectoral adaptation policy framework or national-level risk assessments exist, but some departments commissioned high-level impacts and adaptation assessments after the AR4 (e.g. on agriculture and on biodiversity; Wratt *et al.*, 2008; McGlone and Walker, 2011; Clark *et al.*, 2012).

Public and private sector organisations are potentially important adaptation actors but exhibit large differences in preparedness, linked to knowledge about climate change, economic opportunities, external connections, size, and scope for strategic planning (Gardner *et al.*, 2010; Taylor *et al.*, 2012a; Johnston *et al.*, 2013; Kuruppu *et al.*, 2013; see also Chapters 10, 16). This creates challenges for achieving holistic societal outcomes (see also 25.7-25.9).

Several recent policy initiatives in Australia, while responding to broader socio-economic and environmental pressures, include goals to reduce vulnerability to climate variability and change. These include establishing the Murray-Darling Basin Authority to address over-allocation of water resources (Connell and Grafton, 2011; MDBA, 2011), removal of the interest rate subsidy during exceptional droughts (Productivity Commission, 2009), and management of bush fire and flood risk (VBRC, 2010; QFCI, 2012). These may be seen as examples of mainstreaming adaptation (Dovers, 2009), but they also demonstrate lag times in policy design and implementation, windows of opportunity presented by crises (e.g. the Millennium Drought 1997-2009, the Victorian bushfires 2009 and Queensland floods of 2011), and the challenges arising from competing interests in managing finite and changing water resources (Botterill and Dovers, 2013; Pittock, 2013; Box 25-2).

25.4.2. Constraints on Adaptation and Emerging Leading Practice Models

A rapidly growing literature since the AR4 confirms, with *high confidence*, that while the adaptive capacity of society in Australasia is generally high, there are formidable environmental, economic, informational, social, attitudinal and political constraints, especially for local governments and small or highly fragmented industries. Reviews of public- and private-sector adaptation plans and strategies in Australia demonstrate strong efforts in institutional capacity building, but differences in assessment methods and weaknesses in translating goals into specific policies (White, 2009; Gardner *et al.*, 2010; Measham *et al.*, 2011; Preston *et al.*, 2011; Kay *et al.*, 2014). Similarly, local governments in New Zealand to date have focused mostly on impacts and climate-related hazards; some have developed adaptation plans, but few have committed to specific policies and steps to implementation (e.g. O'Donnell, 2007; Britton, 2010; Fitzharris, 2010; HRC, 2012; KCDC, 2012; Lawrence *et al.*, 2013b).

Table 25-2 summarises key constraints and corresponding enabling factors for effective institutional adaptation processes identified in Australia and New Zealand. Scientific uncertainty and resource limitations are reported consistently as important constraints, particularly for smaller councils. Ultimately more powerful constraints arise, however, from current governance and legislative arrangements and the lack of consistent tools to deal with dynamic risks and uncertainty or to evaluate the success of adaptation responses (*high agreement, robust evidence*; Britton, 2010; Barnett *et al.*, 2013; Lawrence *et al.*, 2013b; Mukheibir *et al.*, 2013; Webb *et al.*, 2013; see also Chapter 16).

[INSERT TABLE 25-2 HERE
Table 25-2: Constraints and enabling factors for institutional adaptation processes in Australasia.]

Some constraints exacerbate others. There is *high confidence* that the absence of a consistent information base and binding guidelines that clarify governing principles and liabilities is a challenge particularly for small and resource-limited local authorities, which need to balance special interest advocacy with longer term community resilience. This heightens reliance on individual leadership subject to short-term political change and can result in piecemeal and inconsistent risk assessments and responses between levels of government and locations, and over time (Smith *et al.*, 2008; Brown *et al.*, 2009; Norman, 2009; Britton, 2010; Rouse and Norton, 2010; Abel *et al.*, 2011; McDonald, 2011; Rive and Weeks, 2011; Corkhill, 2013; Macintosh *et al.*, 2013). In these situations, planners tend to rely more on single numbers for climate projections that can be argued in court (Reisinger *et al.*, 2011; Lawrence *et al.*, 2013b), which increases the risk of maladaptation given the uncertain and dynamic nature of climate risk (McDonald, 2010; Stafford-Smith *et al.*, 2011; Gorddard *et al.*, 2012; McDonald, 2013; Reisinger *et al.*, 2014).

Vulnerability assessments that take mid- to late-century impacts as their starting point can inhibit actors from implementing adaptation actions, as distant impacts are easily discounted and difficult to prioritise in competition with near-term non-climate change pressures (Productivity Commission, 2012). Emerging leading practice models in Australia (Balston, 2012; HCCREMS, 2012; SGS, 2012) and New Zealand (MfE, 2008a; Britton *et al.*, 2011) recommend a high-level scan of sectors and locations at risk and emphasise a focus on near-term decisions that influence current and future vulnerability (which could range from early warning systems to strategic and planning responses). More detailed assessment can then focus on this more tractable subset of issues, based on explicit and iterative framing of the adaptation issue (Webb *et al.*, 2013) and taking into account the full lifetime (lead- and consequence time) of the decision/asset in question (Stafford-Smith *et al.*, 2011).

Participatory processes help balance societal preferences with robust scientific information and ensure ownership by affected communities but rely on human capital and political commitment (*high confidence*; Hobson and Niemeyer, 2011; Rouse and Blackett, 2011; Weber *et al.*, 2011; Leitch and Robinson, 2012). Realising widespread and equitable participation is challenging where policies are complex, debates polarised, legitimacy of institutions contested and potential transformational changes threaten deeply held values (Gardner *et al.*, 2009a; Gorddard *et al.*, 2012; Burton and Mustelin, 2013; see also 25.4.3). Regional approaches that engage diverse stakeholders, government and science providers and support the co-production of knowledge can help overcome some of these problems but require long-term institutional and financial commitments (e.g. Britton *et al.*, 2011; DSEWPC, 2011; CSIRO, 2012; IOCI, 2012; Low Choy *et al.*, 2012; Webb and Beh, 2013).

There is active debate about the extent to which incremental adjustments of existing planning instruments, institutions and decision-making processes can deal adequately with the dynamic and uncertain nature of climate change and support transformational responses (Kennedy *et al.*, 2010; Preston *et al.*, 2011; Park *et al.*, 2012; Dovers, 2013; Lawrence *et al.*, 2013b; McDonald, 2013; Stafford-Smith, 2013). Recent studies suggest a greater focus on flexibility and matching decision-making frameworks to specific problems (Hertzler, 2007; Nelson *et al.*, 2008; Dobes, 2010; Howden and Stokes, 2010; Randall *et al.*, 2012). Limitations of mainstreamed and autonomous adaptation and the case for more proactive government intervention are being explored in Australia (Productivity Commission, 2012; Johnston *et al.*, 2013), but have not yet resulted in new policy frameworks.

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Box 25-1. Coastal Adaptation – Planning and Legal Dimensions

Sea level rise is a significant risk for Australia and New Zealand (*very high confidence*) due to intensifying coastal development and the location of population centres and infrastructure (see 25.3). Under a high emissions scenario (RCP8.5), global mean sea level would *likely* rise by 0.53 to 0.97 m by 2100, relative to 1986-2005, whereas with stringent mitigation (RCP2.6), the *likely* rise by 2100 would be 0.28 to 0.6 m (*medium confidence*). Based on current understanding, only instability of the Antarctic Ice Sheet, if initiated, could lead to a rise substantially above the *likely* range; evidence remains insufficient to evaluate its probability, but there is *medium confidence* that this additional contribution would not exceed several tenths of a metre during the 21st century (AR5 WGI 13.5). Local case studies in New Zealand (Fitzharris, 2010; Reisinger *et al.*, 2014) and national reviews in Australia (DCC, 2009; DCCEE, 2011) demonstrate risks to large numbers of residential and commercial assets as well as key services, with widespread damages at the upper end of projected ranges (*high confidence*). In Australia, sea level rise of 1.1 m would affect over A$226 billion of assets, including up to 274,000 residential and 8,600 commercial buildings (DCCEE, 2011), with additional intangible costs related to stress, health effects and service disruption (HCCREMS, 2010) and ecosystems (DCC, 2009; BMT WBM, 2011). Under expected future settlement patterns, exposure of the Australian road and rail network will increase significantly once sea level rises above about 0.5 m (Baynes *et al.*, 2012). Even if temperatures peak and decline, sea level is projected to continue to rise beyond 2100 for many centuries, at a rate dependent on future emissions (AR5 WGI 13.5).

Responsibility for adapting to sea level rise in Australasia rests principally with local governments through spatial planning instruments. Western Australia, South Australia and Victoria have mandatory State planning benchmarks for 2100, with local governments determining how they should be implemented. Long-term benchmarks in New South Wales and Queensland have either been suspended or revoked, so local authorities now have broad discretion to develop their own adaptation plans. The New Zealand Coastal Policy Statement (Minister of Conservation, 2010) mandates a minimum 100-year planning horizon for assessing hazard risks, discourages hard protection of existing development and recommends avoidance of new development in vulnerable areas. Non-binding government guidance recommends a risk based approach, using a base value of 0.5 m sea level rise by the 2090s and considering the implications of at least 0.8 m and, for longer term planning, an additional 0.1 m per decade (MfE, 2008d).

The incorporation of climate change impacts into local planning has evolved considerably over the past 20 years, but remains piecemeal and shows a diversity of approaches (Gibbs and Hill, 2012; Kay *et al.*, 2014). Governments have invested in high-resolution digital elevation models of coastal and flood prone areas in some regions, but many local governments still lack the resources for hazard mapping and policy design. Political commitment is variable, and legitimacy of approaches and institutions is often strongly contested (Gorddard *et al.*, 2012), including pressure on State governments to modify adaptation policies and on local authorities to compensate developers for restrictions on current or future land uses (LGNZ, 2008; Berry and Vella, 2010; McDonald, 2010; Reisinger *et al.*, 2011). Incremental adaptation responses can entrench existing rights and expectations about on-going protection and development, which limit options for more transformational responses such as accommodation and retreat (*high agreement, medium evidence*; Gorddard *et al.*, 2012; Barnett *et al.*, 2013; Fletcher *et al.*, 2013; McDonald, 2013). Strategic regional-scale planning initiatives in rapidly growing regions, like south-east Queensland, allow climate change adaptation to be addressed in ways not typically achieved by locality- or sector-specific plans, but require effective coordination across different scales of governance (Serrao-Neumann *et al.*, 2013; Smith *et al.*, 2014).

Courts in both countries have played an important role in evaluating planning measures. Results of litigation have varied and, in the absence of clearer legislative guidance, more litigation is expected as rising sea levels affect existing properties and adaptation responses constrain development on coastal land (MfE, 2008d; Kenderdine, 2010; Rive and Weeks, 2011; Verschuuren and McDonald, 2012; Corkhill, 2013; Macintosh, 2013).

In addition to raising minimum floor levels and creating coastal set-backs to limit further development in areas at risk, several councils in Australia and New Zealand have consulted on or attempted to implement managed retreat policies (ECAN, 2005; BSC, 2010; HDC, 2012; KCDC, 2012). These policies remain largely untested in New Zealand, but experience in Australia has shown high litigation potential and opposing priorities at different levels of government, undermining retreat policies (SCCCWEA, 2009; DCCEE, 2010; Abel *et al.*, 2011). Mandatory disclosure of information about future risks, community engagement and policy stability are critical to support retreat, but existing-use rights, liability concerns, special interests, community resources, place attachment and divergent priorities at different levels of government present powerful constraints (*high confidence*; Hayward, 2008b; Berry and Vella, 2010; McDonald, 2010; Abel *et al.*, 2011; Alexander *et al.*, 2012; Leitch and Robinson, 2012; Macintosh *et al.*, 2013; Reisinger *et al.*, 2014).

_____ END BOX 25-1 HERE _____

25.4.3. Psychological and Socio-cultural Factors Influencing Impacts of and Adaptation to Climate Change

Adapting to climate change relies on individuals accepting and understanding changing risks and opportunities, and responding to these changes both psychologically and behaviourally (see Chapters 2, 16). The majority of Australasians accept the reality of climate change and less than 10% fundamentally deny its existence (*high confidence*; ShapeNZ, 2009; Leviston *et al.*, 2011; Lewandowsky, 2011; Milfont, 2012; Reser *et al.*, 2012b). Australians perceive themselves to be at higher risk from climate change than New Zealanders and citizens of many other countries, which may reflect recent experiences of climatic extremes (Gifford *et al.*, 2009; Agho *et al.*, 2010; Ashworth *et al.*, 2011; Milfont *et al.*, 2012; Reser *et al.*, 2012c). However, beliefs about climate change and its risks vary over time, are uneven across society and reflect media coverage and bias, political preferences and gender (ShapeNZ, 2009; Bacon, 2011; Leviston *et al.*, 2012; Milfont, 2012), which can influence attitudes to adaptation (Gardner *et al.*, 2010; Gifford, 2011; Reser *et al.*, 2011; Alexander *et al.*, 2012; Raymond and Spoehr, 2013).

Surveys in Australia between 2007 and 2011 show moderate to high levels of climate change concern, distress, frustration, resolve, psychological adaptation, and carbon-reducing behaviour (*high agreement, medium evidence*; Agho *et al.*, 2010; Reser *et al.*, 2012b, c). About two thirds of respondents expected global warming to worsen, with about half very or extremely concerned that they or their family would be affected directly. Direct experience with environmental changes or events attributed to climate change, reported by 45% of respondents, was particularly influential, but the extent to which resulting distress and concern translate into support for planned adaptation has not been fully assessed (Reser *et al.*, 2012a, b).

Perceived risks and potential losses from climate change depend on values associated by individuals with specific places, activities and objects. Examples from Australia include the value placed on snow cover in the Snowy Mountains (Gorman-Murray, 2008, 2010), risks to biodiversity and recreational values in coastal South Australia (Raymond and Brown, 2011), conflicts between human uses and environmental priorities in national parks (Wyborn, 2009; Roman *et al.*, 2010), and trade-offs between alternative water supplies and relocation in rural areas (Hurlimann and Dolnicar, 2011). These and additional studies in Australasia confirm that the more individuals identify with particular places and their natural features, the stronger the perceived potential loss but also the greater the motivation to address environmental threats (e.g. Rogan *et al.*, 2005; McCleave *et al.*, 2006; Collins and Kearns, 2010; Gosling and Williams, 2010; Raymond *et al.*, 2011; Russell *et al.*, 2013). This indicates that ecosystem-based climate change adaptation (see Box CC-EA) can provide co-benefits for subjective well-being and mental health, especially for disadvantaged and indigenous communities (Berry *et al.*, 2010; see also 25.8.2).

At the same time, social and cultural values and norms can constrain adaptation options for communities by limiting the range of acceptable responses and processes (e.g. place attachment, differing values relating to near- versus long-term, private versus public, and economic versus environmental or social costs and benefits, and perceived legitimacy of institutions). Examples of this are particularly prominent in Australasia in the coastal zone (e.g. Hayward, 2008a; King *et al.*, 2010; Gorddard *et al.*, 2012; Hofmeester *et al.*, 2012) and acceptance of water recycling or pricing (e.g. Pearce *et al.*, 2007; Kouvelis *et al.*, 2010; Mankad and Tapsuwan, 2011).

Overall, these studies give *high confidence* that the experience and threat of climate change and extreme climatic events are having appreciable psychological impacts, resulting in psychological and subsequent behavioural adaptations, reflected in high levels of acceptance and realistic concern, motivational resolve, self-reported changes in thinking, feeling and understanding of climate change and its implications, and behavioural engagement (Reser and Swim, 2011; Reser *et al.*, 2012a, b, c). However, adequate strategies and systems to monitor trends in psychological and social impacts, adaptation and vulnerability are lacking, and such perspectives remain poorly integrated with and dominated by bio-physical and economic characterisations of climate change impacts.

25.5. Freshwater Resources

25.5.1. Observed Impacts

Climate change impacts on water represent a cross-cutting issue affecting people, agriculture, industries and ecosystems. The challenge of satisfying multiple demands with a limited resource is exacerbated by the high inter-annual and inter-decadal variability of river flows (Chiew and McMahon, 2002; Peel *et al.*, 2004; Verdon *et al.*, 2004; McKerchar *et al.*, 2010) particularly in Australia. Declining river flows since the mid-1970s in far south-western Australia have led to changed water management (see Box 11.2 in Hennessy *et al.*, 2007). The unprecedented decline in river flows during the 1997-2009 ‘Millennium’ drought in south-eastern Australia resulted in low irrigation water allocations, severe water restrictions in urban centres, suspension of water sharing arrangements and major environmental impacts (Chiew and Prosser, 2011; Leblanc *et al.*, 2012).

25.5.2. Projected Impacts

Figure 25-4 shows estimated changes to mean annual runoff across Australia for a 1°C global average warming above current levels (Chiew and Prosser, 2011; Teng *et al.*, 2012). The range of estimates arises mainly from uncertainty in projected precipitation (Table 25-1). Hydrological modelling with CMIP3 future climate projections indicates that freshwater resources in far south-eastern and far south-west Australia will decline (*high confidence;* by 0-40% and 20-70%, respectively, for 2°C warming) due to the reduction in winter precipitation (Table 25-1) when most of the runoff in southern Australia occurs. The percent change in mean annual precipitation in Australia is generally amplified as a 2–3 times larger percent change in mean annual streamflow (Chiew, 2006; Jones *et al.*, 2006). This can vary, however, with unprecedented declines in flow in far south-eastern Australia in the 1997–2009 drought (Cai and Cowan, 2008; Potter and Chiew, 2011; Chiew *et al.*, 2013). Higher temperatures and associated evaporation, tree re-growth following more frequent bushfires (Kuczera, 1987; Cornish and Vertessy, 2001; Marcar *et al.*, 2006; Lucas *et al.*, 2007), interceptions from farm dams (van Dijk *et al.*, 2006; Lett *et al.*, 2009) and reduced surface-groundwater connectivity in long dry spells (Petrone *et al.*, 2010; Hughes *et al.*, 2012) can further accentuate declines. In the longer-term, water availability will also be affected by changes in vegetation and surface-atmosphere feedbacks in a warmer and higher CO_2 environment (Betts *et al.*, 2007; Donohue *et al.*, 2009; McVicar *et al.*, 2010).

[INSERT FIGURE 25-4 HERE
Figure 25-4: Estimated changes in mean annual runoff for 1°C global average warming above current levels. Maps show changes in annual runoff (percentage change; top row) and runoff depth (millimetres; bottom row), for dry, median and wet (10^{th} to 90^{th} percentile) range of estimates, based on hydrological modelling using 15 CMIP3 climate projections (Chiew *et al.*, 2009; CSIRO, 2009; Petheram *et al.*, 2012; Post *et al.*, 2012). Projections for 2°C global average warming are about twice that shown in the maps (Post *et al.*, 2011). (Figure adapted from Chiew and Prosser, 2011; Teng *et al.*, 2012).]

In New Zealand, precipitation changes (Table 25-1) are projected to lead to increased runoff in the west and south of the South Island and reduced runoff in the north-east of the South Island, and the east and north of the North Island (*medium confidence*). Annual flows of eastward flowing rivers with headwaters in the Southern Alps (Clutha, Waimakariri, Rangitata) are projected to increase by 5-10 % (median projection) by 2040 (Bright *et al.*, 2008; Poyck *et al.*, 2011; Zammit and Woods, 2011) in response to higher alpine precipitation. Most of the increases occur in winter and spring, as more precipitation falls as rain and snow melts earlier (Hendrikx *et al.*, 2013). In contrast, the Ashley River, slightly north of this region, is projected to have little change in annual flows, with the increase in winter flows offset by reduced summer flows (Woods *et al.*, 2008). The retreat of glaciers is expected to have only a minor impact on river flows in the first half of the century (Chinn, 2001; Anderson *et al.*, 2008).

Climate change will affect groundwater through changes in recharge rates and the relationship between surface waters and aquifers. Dryland diffuse recharge in most of western, central and southern Australia is projected to decrease because of the decline in precipitation, with increases in the north and some parts of the east because of projected increase in extreme rainfall intensity (*medium confidence*; Crosbie *et al.*, 2010; McCallum *et al.*, 2010; Crosbie *et al.*, 2012). In New Zealand, a single study projects groundwater recharge in the Canterbury Plains to decrease by about 10% by 2040 (Bright *et al.*, 2008). Climate change will also degrade water quality, particularly through increased material washoff following bushfires and floods (Box 25-6, Box 25-8).

25.5.3. Adaptation

The 1997–2009 drought in south-eastern Australia and projected declines in future water resources in southern Australia are already stimulating adaptation (Box 25-2). In New Zealand, there is little evidence of water resources adaptation specifically to climate change. Water in New Zealand is not as scarce generally and water policy reform is driven more by pressure to maintain water quality while expanding agricultural activities, with an increasing focus on collaborative management (Memon and Skelton, 2007; Memon *et al.*, 2010; Lennox *et al.*, 2011; Weber *et al.*, 2011) within national guidelines (LWF, 2010; MfE, 2011). Impacts of climate change on water supply, demand and infrastructure have been considered by several New Zealand local authorities and consultancy reports (Jollands *et al.*, 2007; Williams *et al.*, 2008; Kouvelis *et al.*, 2010), but no explicit management changes have yet resulted.

_____ START BOX 25-2 HERE _____

Box 25-2. Adaptation through Water Resources Policy and Management in Australia

Widespread drought and projections of a drier future in south-eastern and far south-west Australia (Bates *et al.*, 2010; CSIRO, 2010; Potter *et al.*, 2010; Chiew *et al.*, 2011) saw extensive policy and management change in both rural and urban water systems (Hussey and Dovers, 2007; Bates *et al.*, 2008; Melbourne Water, 2010; DSE, 2011; MDBA, 2011; NWC, 2011; Schofield, 2011). These management changes provide examples of adaptations, building on previous policy reforms (Botterill and Dovers, 2013). The broad policy framework is set out in the 2004 National Water Initiative and 2007 Commonwealth Water Act. The establishment of the National Water Commission (2004) and the Murray-Darling Basin Authority (2008) were major institutional reforms. The National Water Initiative explicitly recognises climate change as a constraint on future water allocations. Official assessments (NWC, 2009, 2011) and critiques (Connell, 2007; Grafton and Hussey, 2007; Byron, 2011; Crase, 2011; Pittock and Finlayson, 2011) have discussed progress and shortcomings of the initiative, but assessment of its overall success is made difficult by other factors such as on-going revisions to allocation plans and time lags to observable impacts.

Rural water reform in south-eastern Australia, focused on the Murray-Darling Basin, is currently being implemented. The Murray-Darling Basin Plan (MDBA, 2011, 2012) will return 2750 GL/year of consumptive water (about one fifth of current entitlements) to riverine ecosystems and develop flexible and adaptive water sharing mechanisms to cope with current and future climates. In 2012, the Australian Government committed more than A$12 billion nationally to upgrade water infrastructure, improve water use efficiency, and purchase water entitlements for environmental use. The Basin Plan also includes an environmental watering plan to optimise environmental outcomes for the Basin. Water markets are a key policy instrument, allowing water use patterns to adapt to shifting availability and water to move toward higher value uses (NWC, 2010; Kirby *et al.*, 2012). For example, the two-thirds reduction in irrigation water use over 2000–2009 in the Basin resulted in only 20% reduction in gross agricultural returns, mainly because water use shifted to more valuable enterprises (Kirby *et al.*, 2012). Elsewhere, catchment management authorities and state agencies throughout south-eastern Australia develop water management strategies to cope with prolonged droughts and climate change (e.g. DSE, 2011). Nevertheless, if the extreme dry end of future water projections is realised (25.5.2, Figure 25-4), agriculture and ecosystems across south-eastern and south-western Australia would be threatened even with comprehensive adaptation (see 25.6.1, 25.7.1, 25.7.2; Connor *et al.*, 2009; Kirby *et al.*, 2013).

Climate change and population growth are the two major factors that influence water planning in Australian capital cities. In Melbourne, for example, planning has centred on securing new supplies that are more resilient to major climate shocks; increasing use of alternative sources like sewage recycling and stormwater for non-potable water; programs to reduce demand; water sensitive urban design; and integrated planning that considers climate change impact on water supply, flood risk and stormwater and wastewater infrastructures (DSE, 2007; Skinner, 2010; DSE, 2011; Rhodes *et al.*, 2012). Melbourne's water augmentation program includes a desalinisation plant with a 150 GL/year capacity (about one third of the current demand), following the lead of Perth where a desalinisation plant was established in 2006 because of declining inflows since the mid-1970s (Rhodes *et al.*, 2012). Melbourne's water conservation strategies include water efficiency and rebate programs for business and industry, water smart gardens, dual flush toilets, grey water systems, rainwater tank rebates, free water-efficient showerheads and voluntary residential use targets. These conservation measures, together with water use restrictions since the early 2000s, have reduced Melbourne's total per capita water use by 40% (Fitzgerald, 2009; Rhodes *et al.*, 2012). Similar programs reduced Brisbane's per capita water use by about 50% (Shearer, 2011), while adoption of water recycling and rainwater harvesting resulted in up to 60% water savings in some parts of Adelaide (Barton and Argue, 2009).

The success of urban water reforms in the face of drought and climate change can be variously interpreted. Increasing supply through desalinisation plants and water reuse schemes reduces the risk of future water shortages and helps cities cope with increasing population. Uptake of household-scale adaptation options has been locally significant but their long-term sustainability or reversibility in response to changing drivers and societal attitudes needs further research (Troy, 2008; Brown and Farrelly, 2009; Mankad and Tapsuwan, 2011). Desalinisation plants can be maladaptive due to their energy demand, and the enhancement of mass supply could create a disincentive for reducing demand or increasing resilience through diversifying supply (Barnett and O'Neill, 2010; Taptiklis, 2011).

_____ END BOX 25-2 HERE _____

25.6. Natural Ecosystems

25.6.1. Inland Freshwater and Terrestrial Ecosystems

Terrestrial and freshwater ecosystems have suffered high rates of habitat loss and species extinctions since European settlement in both Australia and New Zealand (Kingsford *et al.*, 2009; Bradshaw *et al.*, 2010; McGlone *et al.*, 2010; Lundquist *et al.*, 2011; SoE, 2011); many reserves are small and isolated, and some key ecosystems and species under-represented (Sattler and Taylor, 2008; MfE, 2010a; SoE, 2011). Many freshwater ecosystems are pressured from over-allocation and pollution, especially in southern and eastern coastal regions in Australia (e.g. Ling, 2010). Additional stresses include erosion, changes in nutrients and fire regimes, mining, invasive species, grazing and salinity (Kingsford *et al.*, 2009; McGlone *et al.*, 2010; SoE, 2011). These increase vulnerability to rapid climate change and provide challenges for both autonomous and managed adaptation (Steffen *et al.*, 2009).

25.6.1.1. Observed Impacts

In Australian terrestrial systems, some recently observed changes in the distribution, genetics and phenology of individual species, and in the structure and composition of some ecological communities, can be attributed to recent climatic trends (*medium* to *high confidence*; see Box 25-3). Uncertainty remains regarding the role of non-climatic drivers, including changes in atmospheric CO_2, fire management, grazing and land-use. The 1997-2009 drought had severe impacts in freshwater systems in the eastern States and the Murray Darling Basin (Pittock and Finlayson, 2011) but in many freshwater systems, direct climate impacts are difficult to detect above the strong signal of over-allocation, pollution, sedimentation, exotic invasions and natural climate variability (Jenkins *et al.*, 2011). In New Zealand, few if any impacts on ecosystems have been directly attributed to climate change rather than variability (Box 25-3; McGlone *et al.*, 2010; McGlone and Walker, 2011). Alpine treelines in New Zealand have remained roughly stable for several hundred years (*high confidence*) despite 0.9°C average warming over the past century (McGlone and Walker, 2011; Harsch *et al.*, 2012).

25.6.1.2. Projected Impacts

Existing environmental stresses will interact with, and in many cases be exacerbated by, shifts in mean climatic conditions and associated change in the frequency or intensity of extreme events, especially fire, drought and floods (*high confidence*; Steffen *et al.*, 2009; Bradstock, 2010; Murphy *et al.*, 2012). Recent drought-related mortality has been observed for amphibians in south-east Australia (Mac Nally *et al.*, 2009), savannah trees in north-east Australia (Fensham *et al.*, 2009; Allen *et al.*, 2010), mediterranean-type eucalypt forest in southwest Western Australia (Matusik *et al.*, 2013), and, eucalypts in sub-alpine regions in Tasmania (Calder and Kirkpatrick, 2008). Mass die-offs of flying foxes and cockatoos have been observed during heatwaves (Welbergen *et al.*, 2008; Saunders *et al.*, 2011). These examples provide *high confidence* that extreme heat and reduced water availability, either singly or in combination, will be significant drivers of future population losses and will increase the risk of local species extinctions in many areas (e.g. McKechnie and Wolf, 2010; see also Figure 25-5).

Species distribution modelling (SDM) consistently indicates future range contractions for Australia's native species even assuming optimistic rates of dispersal, e.g. Western Australian *Banksia* spp. (Fitzpatrick *et al.*, 2008), koalas (Adams-Hosking *et al.*, 2011), northern macropods (Ritchie and Bolitho, 2008), native rats (Green *et al.*, 2008b), greater gliders (Kearney *et al.*, 2010b), quokkas (Gibson *et al.*, 2010), platypus (Klamt *et al.*, 2011), birds (Garnett *et al.*, 2013; van der Wal *et al.*, 2013), and fish (Bond *et al.*, 2011). In some studies, complete loss of climatically suitable habitat is projected for some species within a few decades, and therefore increased risk of local and, perhaps, global extinction (*medium confidence*). SDM has limitations (e.g. Elith *et al.*, 2010; McGlone and Walker, 2011) but is being improved through integration with physiological (Kearney *et al.*, 2010b) and demographic models (Keith *et al.*, 2008; Harris *et al.*, 2012), genetic estimates of dispersal capacity (Duckett *et al.*, 2013), and incorporation into broader risk assessments (e.g. Williams *et al.*, 2008; Crossman *et al.*, 2012).

In Australia, assessments of ecosystem vulnerability have been based on observed changes, coupled with projections of future climate in relation to known biological thresholds and assumptions about adaptive capacity (e.g. Laurance *et al.*, 2011; Murphy *et al.*, 2012). There is *very high confidence* that one of the most vulnerable Australian ecosystems is the alpine zone due to loss of snow cover, invasions by exotic species, and changed species interactions (reviewed in Pickering *et al.*, 2008). There is also *high confidence* in substantial risks to coastal wetlands such as Kakadu National Park subject to saline intrusion (BMT WBM, 2011); tropical savannas subject to changed fire regimes (Laurance *et al.*, 2011); inland freshwater and groundwater systems subject to drought, over-allocation and altered timing of floods (Pittock *et al.*, 2008; Jenkins *et al.*, 2011; Pratchett *et al.*, 2011); peat-forming wetlands along the east coast subject to drying (Keith *et al.*, 2010); and biodiversity-rich regions such as southwest Western Australia (Yates *et al.*, 2010a; Yates *et al.*, 2010b) and tropical and sub-tropical rainforests in Queensland subject to drying and warming (Stork *et al.*, 2007; Shoo *et al.*, 2011; Murphy *et al.*, 2012; Hagger *et al.*, 2013).

The very few studies of climate change impacts on biodiversity in New Zealand suggest that on-going impacts of invasive species (Box 25-4) and habitat loss will dominate climate change signals in the short- to medium-term (McGlone *et al.*, 2010), but that climate change has the potential to exacerbate existing stresses (McGlone and Walker, 2011). There is *limited evidence but high agreement* that the rich biota of the alpine zone is at risk through increasing shrubby growth and loss of herbs, especially if combined with increased establishment of invasive species (McGlone *et al.*, 2010; McGlone and Walker, 2011). Some cold water-adapted freshwater fish and invertebrates are vulnerable to warming (August and Hicks, 2008; Winterbourn *et al.*, 2008; Hitchings, 2009; McGlone and Walker, 2011) and increased spring flooding may increase risks for braided-river bird species (MfE, 2008b). For some restricted native species, suitable habitat may increase with warming (e.g. native frogs; Fouquet *et* *al.*, 2010) although limited dispersal ability will limit range expansion. Tuatara populations are at risk as warming increases the ratio of males to females (Mitchell *et al.*, 2010), although the lineage has persisted during higher temperatures in the geological past (McGlone and Walker, 2011).

25.6.1.3. Adaptation

High levels of endemism in both countries (Lindenmayer, 2007; Lundquist *et al.*, 2011) are associated with narrow geographic ranges and associated climatic vulnerability, although there is greater scope for adaptive dispersal to higher elevations in New Zealand than in Australia. Anticipated rates of climate change, together with fragmentation of remaining habitat and limited migration options in many regions (Steffen *et al.*, 2009; Morrongiello *et al.*, 2011), will limit *in situ* adaptive capacity and distributional shifts to more climatically suitable areas for many species (*high confidence*). Significant local and global losses of species, functional diversity, and ecosystem services, and large scale changes in ecological communities, are anticipated (e.g. Dunlop *et al.*, 2012; Gallagher *et al.*, 2012b; Murphy *et al.*, 2012).

There is increasing recognition in Australia that rapid climate change has fundamental implications for traditional conservation objectives (e.g. Steffen *et al.*, 2009; Prober and Dunlop, 2011; Dunlop *et al.*, 2012; Murphy *et al.*, 2012). Research on impacts and adaptation in terrestrial and freshwater systems has been guided by the National Adaptation Research Plans (Hughes *et al.*, 2010; Bates *et al.*, 2011) and by research undertaken within the CSIRO Climate Adaptation Flagship. Climate change adaptation plans developed by many levels of government and Natural Resource Management (NRM) bodies, supported by substantial Australian government funding, have identified priorities that include: identification and protection of climatic refugia (Davis *et al.*, 2013; Reside *et al.*, 2013); restoration of riparian zones to reduce stream temperatures (Davies, 2010; Jenkins *et al.*, 2011); construction of levees to protect wetlands from saltwater intrusion (Jenkins *et al.*, 2011); reduction of non-climatic threats such as invasive species to increase ecosystem resilience (Kingsford *et al.*, 2009); ecologically-appropriate fire regimes (Driscoll *et al.*, 2010); restoration of environmental flows in major rivers (Kingsford and Watson, 2011; Pittock and Finlayson, 2011); protecting and restoring habitat connectivity in association with expansion of the protected area network (Dunlop and Brown, 2008; Mackey *et al.*, 2008; Taylor and Philp, 2010; Prowse and Brook, 2011; Maggini *et al.*, 2013); and, active interventionist strategies such as assisted colonisation to reduce probability of species extinctions (Burbidge *et al.*, 2011; McIntyre, 2011) or restore ecosystem services (Lunt *et al.*, 2013). Few specific measures have been implemented and thus their effectiveness cannot yet be assessed. Biodiversity research and management in New Zealand to date has taken little account of climate change-related pressures and continues to focus largely on managing pressures from invasive species and predators, freshwater pollution, exotic diseases, and halting the decline in native vegetation, although a number of specific recommendations have been made to improve ecosystem resilience to future climate threats (McGlone *et al.*, 2010; McGlone and Walker, 2011).

Climate change responses in other sectors may have beneficial as well as adverse impacts on biodiversity, but few tools to assess risks from an integrated perspective have been developed (25.9.1, Box 25-10). Assessments of the impacts of climate change on the provision of ecosystem services (such as pollination and erosion control) via impacts on terrestrial and freshwater ecosystems are generally lacking. Similarly, the concept of Ecosystem-based Adaptation, the role of healthy, well-functioning ecosystems in increasing the resilience of human sectors to the impacts of climate change (see Chapters 4 and 5, and Box CC-EA), is relatively unexplored.

25.6.2. Coastal and Ocean Ecosystems

Australia's 60,000 km coastline spans tropical waters in the north to cool temperate waters off Tasmania and the sub-Antarctic islands with sovereign rights over ~8.1 million km^2, excluding the Australian Antarctic Territory (Richardson and Poloczanska, 2009). New Zealand has ~18,000 km of coastline, spanning subtropical to sub-Antarctic waters, and the world's fifth largest Exclusive Economic Zone at 4.2 million km^2 (Gordon *et al.*, 2010). The marine ecosystems of both countries are considered hotspots of global marine biodiversity with many rare, endemic and commercially important species (Hoegh-Guldberg *et al.*, 2007; Blanchette *et al.*, 2009; Gordon *et al.*, 2010; Gillanders *et al.*, 2011; Lundquist *et al.*, 2011). The increasing density of coastal populations (see 25.3) and stressors such as pollution and sedimentation from settlements and agriculture will intensify non-climate stressors in coastal areas (*high confidence*; e.g. Russell *et al.*, 2009). Coastal habitats provide many ecosystem services including coastal protection (Arkema *et al.*, 2013) and carbon storage, particularly in seagrass, saltmarsh and mangroves, which could become increasingly important for mitigation (e.g. Irving *et al.*, 2011). Coastal ecosystems occupy <1% of the land mass but may account for 39% of Australia's average national annual carbon burial (estimated total: 466 millions tonnes CO_2-eq per year; Lawrence *et al.*, 2012).

25.6.2.1. Observed Impacts

There is *high confidence* that climate change is already affecting the oceans around Australia (Pearce and Feng, 2007; Poloczanska *et al.*, 2007; Lough and Hobday, 2011) and warming the Tasman sea in northern New Zealand (Sutton *et al.*, 2005; Lundquist *et al.*, 2011); average climate zones have shifted south by more than 200 km along the northeast and about 100 km along the northwest Australian coasts since 1950 (Lough, 2008). The rate of warming is even faster in southeast Australia, with a poleward advance of the East Australia Current of ~350 km over the past 60 years (Ridgway, 2007). Based on elevated rates of ocean warming, southwest and southeast Australia are recognized as global warming hotspots (Wernberg *et al.*, 2011). It is *virtually certain* that the increased storage of carbon by the ocean will increase acidification in the future, continuing the observed trends of the past decades in Australia as elsewhere (Howard *et al.*, 2012; see also WGI 3.8, 6.44).

Recently observed changes in marine systems around Australia are consistent with warming oceans (*high confidence*; Box 25-3). Examples include changes in phytoplankton productivity (Thompson *et al.*, 2009; Johnson *et al.*, 2011); species abundance of macroalgae (Johnson *et al.*, 2011); growth rates of abalone (Johnson *et al.*, 2011), southern rock lobster (Pecl *et al.*, 2009; Johnson *et al.*, 2011), coastal fish (Neuheimer *et al.*, 2011) and coral (De'ath *et al.*, 2009); life cycles of southern rock lobster (Pecl *et al.*, 2009) and seabirds (Cullen *et al.*, 2009; Chambers *et al.*, 2011); and, distribution of subtidal seaweeds (Johnson *et al.*, 2011; Wernberg *et al.*, 2011; Smale and Wernberg, 2013), plankton (Mcleod *et al.*, 2012), fish (Figueira *et al.*, 2009; Figueira and Booth, 2010; Last *et al.*, 2011; Madin *et al.*, 2012), sea urchins (Ling *et al.*, 2009) and intertidal invertebrates (Pitt *et al.*, 2010).

Habitat-related impacts are more prevalent in northern Australia (Pratchett *et al.*, 2011), while distribution changes are reported more often in southern waters (Madin *et al.*, 2012), particularly south-east Australia, where warming has been greatest. The 2011 marine heat wave in Western Australia caused the first-ever reported bleaching at Ningaloo reef (Abdo *et al.*, 2012; Feng *et al.*, 2013) resulting in coral mortality (Moore *et al.*, 2012; Depczynski *et al.*, 2013) and changes in community structure and composition (Smale and Wernberg, 2013; Wernberg *et al.*, 2013). About 10% of the observed 50% decline in coral cover on the Great Barrier Reef since 1985 has been attributed to bleaching, the remainder to cyclones and predators (De'ath *et al.*, 2012). Changes in distribution and abundance of marine species in New Zealand are primarily linked to ENSO-related variability that dominates in many time series (Clucas, 2011; Lundquist *et al.*, 2011; McGlone and Walker, 2011; Schiel, 2011), although water temperature is also important (e.g. Beentjes and Renwick, 2001). New Zealand fisheries exported over $1.5 billion worth of product in 2012 (SNZ, 2013) and variability in ocean circulation and temperature plays an important role in local fish abundance (e.g. Chiswell and Booth, 2005; Dunn *et al.*, 2009); no climate change impacts have been reported at this stage (Dunn *et al.*, 2009), although this may be due to insufficient monitoring.

25.6.2.2. Projected Impacts

Even though evidence of climate impacts on coastal habitats is limited to date, *confidence* is *high* that negative impacts will arise with continued climate change (Lovelock *et al.*, 2009; McGlone and Walker, 2011; Traill *et al.*, 2011; Chapter 6). Some coastal habitats such as mangroves are projected to expand further landward, driven by sea-level rise and exacerbated by soil subsidence if rainfall declines (*medium confidence*; Traill *et al.*, 2011), although this may be at the expense of saltmarsh and constrained in many regions by the built environment (DCC, 2009; Lovelock *et al.*, 2009; Rogers *et al.*, 2012). Estuarine habitats will be affected by changing rainfall or sediment discharges, as well as connectivity to the ocean (*high confidence*; Gillanders *et al.*, 2011). Loss of coastal habitats and declines in iconic species will result in substantial impacts on coastal settlements and infrastructure from direct impacts such as storm surge, and will affect tourism (*medium confidence*; 25.7.5).

Changes in temperature and rainfall, and sea level rise, are expected to lead to secondary effects, including erosion, landslips, and flooding, affecting coastal habitats and their dependent species, e.g. loss of habitat for nesting birds (*high confidence*; Chambers *et al.*, 2011). Increasing ocean acidification is expected to affect many taxa (*medium confidence*; see also Box CC-OA, Chapters 6, 30) including corals (Fabricius *et al.*, 2011), coralline algae (Anthony *et al.*, 2008), calcareous plankton (Richardson *et al.*, 2009; Thompson *et al.*, 2009; Hallegraeff, 2010), reef fishes (Munday *et al.*, 2009; Nilsson *et al.*, 2012), bryozoans, and other benthic calcifiers (Fabricius *et al.*, 2011). Deep-sea scleractinian corals are also expected to decline with ocean acidification (Miller *et al.*, 2011).

The AR4 identified the Great Barrier Reef (GBR) as highly vulnerable to both warming and acidification (Hennessy *et al.*, 2007). Recent observations of bleaching (GBRMPA, 2009a) and reduced calcification in both the GBR and other reef systems (Cooper *et al.*, 2008; De'ath *et al.*, 2009; Cooper *et al.*, 2012), along with model and experimental studies (Hoegh-Guldberg *et al.*, 2007; Anthony *et al.*, 2008; Veron *et al.*, 2009) confirm this vulnerability (see also Box CC-CR). The combined impacts of warming and acidification associated with atmospheric CO_2 concentrations in excess of 450-500 ppm are projected to be associated with increased frequency and severity of coral bleaching, disease incidence and mortality, in turn leading to changes in community composition and structure including increasing dominance by macroalgae (*high confidence*; Hoegh-Guldberg *et al.*, 2007; Veron *et al.*, 2009). Other stresses, including rising sea levels, increased cyclone intensity, and nutrient-enriched and freshwater runoff, will exacerbate these impacts (*high confidence*; Hoegh-Guldberg *et al.*, 2007; Veron *et al.*, 2009; GBRMPA, 2011). Thermal thresholds and the ability to recover from bleaching events vary geographically and between species (e.g. Diaz-Pulido *et al.*, 2009) but evidence of the ability of corals to adapt to rising temperatures and acidification is limited and appears insufficient to offset the detrimental effects of warming and acidification (*robust evidence, medium agreement*; Hoegh-Guldberg, 2012; Howells *et al.*, 2013; Box CC-CR).

Under all SRES scenarios and a range of CMIP3 models, pelagic fishes such as sharks, tuna and billfish are projected to move further south on the east and west coasts of Australia (*high confidence*; Hobday, 2010). These changes depend on sensitivity to water temperature, and may lead to shifts in species-overlap with implications for by-catch management (Hartog *et al.*, 2011). Poleward movements are also projected for coastal fish species in Western Australia (Cheung *et al.*, 2012) and a complex suite of impacts are expected for marine mammals (Schumann *et al.*, 2013). A strengthening East Auckland Current in northern New Zealand is expected to promote establishment of tropical or sub-tropical species that currently occur as vagrants in warm La Niña years (Willis *et al.*, 2007). Such shifts suggest potentially substantial changes in production and profit of both wild fisheries (Norman-Lopez *et al.*, 2011) and aquaculture species such as salmon, mussels and oysters (*medium confidence*; Hobday *et al.*, 2008; Hobday and Poloczanska, 2010). Ecosystem models also project changes to habitat and fisheries production (*low confidence*; Fulton, 2011; Watson *et al.*, 2012).

25.6.2.3. Adaptation

In Australia, research on marine impacts and adaptation has been guided by the National Adaptation Research Plan for Marine Biodiversity and Resources (Mapstone *et al.*, 2010), programs within the CSIRO Climate Adaptation Flagship and the Great Barrier Reef Marine Park Authority (GBRMPA, 2007). Limits to autonomous adaptation are unknown for almost all species, although limited experiments suggests capacity for response on a scale comparable to projected warming for some species (e.g. coral reef fish; Miller *et al.*, 2012) and not others (e.g. Antarctic krill; Kawaguchi *et al.*, 2013). Planned adaptation options include removal of human barriers to landward migration of species, beach nourishment, management of environmental flows to maintain estuaries (Jenkins *et al.*, 2010), habitat provision (Hobday and Poloczanska, 2010), assisted colonisation of seagrass and species such as turtles (e.g. Fuentes *et al.*, 2009) and burrow modification for nesting seabirds (Chambers *et al.*, 2011). For southern species on the continental shelf, options are more limited because suitable habitat will not be present – the next shallow water to the south is Macquarie Island. There is *low confidence* about the adequacy of autonomous rates of adaptation by species, although recent experiments with coral reef fish suggest that some species may adapt to the projected climate changes (Miller *et al.*, 2012).

Management actions to increase coral reef resilience include reducing fishing pressure on herbivorous fish, protecting top predators, managing runoff quality, and minimizing other human disturbances, especially through marine protected areas (Hughes *et al.*, 2007; Veron *et al.*, 2009; Wooldridge *et al.*, 2012). Such actions will slow, but not prevent, long-term degradation of reef systems once critical thresholds of ocean temperature and acidity are exceeded (*high confidence*), and so novel options, including assisted colonisation and shading critical reefs, have been proposed but remain untested at scale (Rau *et al.*, 2012). Seasonal forecasting can also prepare managers for bleaching events (Spillman, 2011).

Adaptation by the fishing industry to shifting distributions of target species is considered possible by most stakeholders (e.g. southern rock lobster fishery; Pecl *et al.*, 2009). Assisted colonisation to maintain production in the face of declining recruitment may also be possible for some high value species, and has been trialled for the southern rock lobster (Green *et al.*, 2010a). Options for aquaculture include disease management, alternative site selection, and selective breeding (Battaglene *et al.*, 2008), but implementation is only preliminary. Marine protected area planning is not explicitly considering climate change in either country, but reserve performance will be affected by projected environment shifts and novel combinations of species, habitats and human pressures (Hobday, 2011).

_____ START BOX 25-3 HERE _____

Box 25-3. Impacts of a Changing Climate in Natural and Managed Ecosystems

Observed changes in species, and in natural and managed ecosystems (25.6.1, 25.6.2, 25.7.2) provide multiple lines of evidence of the impacts of a changing climate[1]. Examples of observations published since the AR4 are shown in Table 25-3.

[INSERT TABLE 25-3 HERE
Table 25-3: Examples of detected changes in species, natural and managed ecosystems, consistent with a climate change[1] signal, published since the AR4. Confidence in detection of change is based on the length of study, and the type, amount and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate as a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change.]

[FOOTNOTE 1: Consistent with the IPCC definition, a change in climate refers to any statistically detectable signal; it does not necessarily imply a human cause. See Glossary, Table 25-1 and 25.2.]

_____ END BOX 25-3 HERE _____

25.7. Major Industries

25.7.1. Production Forestry

Australia has about 149 Mha forests, including woodlands. Two Mha are plantations and 9.4 Mha multiple-use native forests, and forestry contributes around $7 billion annually to GDP (ABARES, 2012). New Zealand's plantation estate in production forests comprises about 1.7 Mha (90% *Pinus radiata*), with recent contractions due to increased profitability of dairying (FOA and MPI, 2012; MfE, 2013).

25.7.1.1. Observed and Projected Impacts

Existing climate variability and other confounding factors have so far prevented the detection of climate change impacts on forests. Modelled projections are based on ecophysiological responses of forests to CO_2, water and temperatures. In Australia, potential changes in water availability will be most important (*very high confidence*; e.g.

reviews by Battaglia *et al.*, 2009; Medlyn *et al.*, 2011b). Modelling future distributions or growth rates indicate that plantations in south-west Western Australia are most at risk due to declining rainfall, and there is *high confidence* that plantation growth will be reduced by temperature increases in hotter regions, especially where species are grown at the upper range of their temperature tolerances (Medlyn *et al.*, 2011a). Moderate reductions in rainfall and increased temperature could be offset by fertilisation from increasing CO_2 (*limited evidence, medium agreement*; Simioni *et al.*, 2009). In cool regions where water is not limiting, higher temperatures could benefit production (Battaglia *et al.*, 2009). In New Zealand, temperatures are mostly sub-optimal for growth of *P. radiata* and water relations are generally less limiting (Kirschbaum and Watt, 2011). Warming is expected to increase *P. radiata* growth in the cooler south (*very high confidence*), whereas in the warmer north, temperature increases can reduce productivity, but CO_2 fertilisation may offset this (*medium confidence*; Kirschbaum *et al.*, 2012).

Modelling studies are limited by their reliance on key assumptions which are difficult to verify experimentally, e.g. the degree to which photosynthesis remains stimulated under elevated CO_2 (Battaglia *et al.*, 2009). Most studies also exclude impacts of pests, diseases, weeds, fire and wind damage that may change adversely with climate. Fire, for instance, poses a significant threat in Australia and is expected to worsen with climate change (see Box 25-6), especially for the commercial forestry plantations in the southern winter-rainfall regions (Williams *et al.*, 2009; Clarke *et al.*, 2011). In New Zealand, changes in biotic factors are particularly important as they already affect plantation productivity. *Dothistroma* blight, for instance, is a serious pine disease with a temperature optimum that coincides with New Zealand's warmer, but not warmest, pine-growing regions; under climate change, its severity is, therefore, expected to reduce in the warm central North Island but increase in the cooler South Island (*high confidence*) where it could offset temperature-driven improved plantation growth (Watt *et al.*, 2011a). There is *medium evidence* and *high agreement* of similar future southward shifts in the distribution of existing plantation weed, insect pest and disease species in Australia (see review in Medlyn *et al.*, 2011b).

25.7.1.2. Adaptation

Depending on the extent of climate changes and plant responses to increasing CO_2, the above studies provide *limited evidence* but *high agreement* of potential net increased productivity in many areas, but only where soil nutrients are not limiting. Adaptation strategies include changes to species or provenance selection towards trees better adapted to warmer conditions, or adopting different silvicultural options to increase resilience to climatic or biotic stresses, such as pest challenges (White *et al.*, 2009; Booth *et al.*, 2010; Singh *et al.*, 2010; Wilson and Turton, 2011a). The greatest barriers to long-term adaptation planning are incomplete knowledge of plant responses to increased CO_2 and uncertainty in regional climate scenarios (*medium evidence, high agreement*; Medlyn *et al.*, 2011b). The rotation time of plantation forests of about 30 years or more makes proactive adaptation important but also challenging.

25.7.2. Agriculture

Australia produces 93% of its domestic food requirements and exports 76% of agricultural production (PMSEIC, 2010a). New Zealand agriculture contributes about 56% of total export value and dairy products 27%; 95% of dairy products are exported (SNZ, 2012b). Agricultural production is sensitive to climate (especially drought; Box 25-5) but also to many non-climate factors such as management, which thus far has limited both detection and attribution of climate-related changes (see Chapters 7 and 18; Webb *et al.*, 2012a; Darbyshire *et al.*, 2013). Because the region is a major exporter – providing, for example, over 40% of the world trade in dairy products – changes in production conditions in the region have a major influence on world supply (OECD, 2011). This implies that climate change impacts could have consequences for food security not just locally but even globally (Qureshi *et al.*, 2013a).

25.7.2.1. Projected Impacts and Adaptation – Livestock Systems

Livestock grazing dominates land use by area in the region. At the Australian national level, the net effect of a 3°C temperature increase (from a 1980-99 baseline) is expected to be a 4% reduction in gross value of the beef, sheep and wool sector (McKeon et al., 2008). Dairy output is projected to decline in all regions of Australia other than

Tasmania under a 1°C increase by 2030 (Hanslow *et al.*, 2013). Projected changes in national pasture production for dairy, sheep and beef pastures in New Zealand range from an average reduction of 4% across climate scenarios for the 2030s (Wratt et al., 2008) to increases of up to 4% for two scenarios in the 2050s (Baisden *et al.*, 2010) when the models included CO_2 fertilisation and nitrogen feedbacks.

Studies modelling seasonal changes in fodder supply show greater sensitivity in animal production to climate change and elevated CO_2 than models using annual average production, with some impacts expected even under modest warming (*high confidence*) in both New Zealand (Lieffering *et al.*, 2012) and Australia (Moore and Ghahramani, 2013). Across 25 sites in southern Australia (an area that produces 85% of sheep and 40% of beef production by value) modelled profitability declined at most sites by the 2050s because of a shorter growing season due to changes in both rainfall and temperature (Moore and Ghahramani, 2013). In New Zealand, projected changes in seasonal pasture growth drove changes in animal production at four sites representing the main areas of sheep production (Lieffering *et al.*, 2012). In Hawke's Bay, changes in stock number and the timing of grazing were able to maintain farm income for a period in the face of variable forage supply but not in the longer term. In Southland and Waikato, projected increases in early spring pasture growth posed management problems in maintaining pasture quality, yet, if these were met, animal production could be maintained or increased. The temperature-humidity index (THI), an indicator of potential heat stress for animals, increased from 1960-2008 in the Murray Dairy region of Australia and further increases and reductions in milk production are projected (Nidumolu *et al.*, 2011). Shading can substantially reduce, but not avoid, the temperature and humidity effects that produce a high THI (Nidumolu *et al.*, 2011).

Rainfall is a key determinant of inter-annual variability in production and profitability of pastures and rangelands (Radcliffe and Baars, 1987; Steffen *et al.*, 2011) yet remains the most uncertain change. In northern Australia, incremental adaptation may be adequate to manage risks of climate change to the grazing industry but an increasing frequency of droughts and reduced summer rainfall will potentially drive the requirement for transformational change (Cobon *et al.*, 2009). Rangelands that are currently water-limited are expected to show greater sensitivity to temperature and rainfall changes than nitrogen-limited ones (Webb *et al.*, 2012b). The 'water-sparing' effect of elevated CO_2 (offsetting reduced water availability from reduced rainfall and increased temperatures) is invoked in many impact studies but does not always translate into production benefits (Kamman *et al.*, 2005; Newton *et al.*, 2006; Stokes and Ash, 2007; Wan *et al.*, 2007). The impacts of elevated CO_2 on forage production, quality, nutrient cycling and water availability remains the major uncertainty in modelling system responses (McKeon *et al.*, 2009; Finger *et al.*, 2010); recent findings of grazing impacts on plant species composition (Newton *et al.*, 2013) and nitrogen fixation (Watanabe *et al.*, 2013) under elevated CO_2 have added to this uncertainty. New Zealand agro-ecosystems are subject to erosion processes strongly driven by climate; greater certainty in projections of rainfall, particularly storm frequency, are needed to better understand climate change impacts on erosion and consequent changes in the ecosystem services provided by soils (Basher *et al.*, 2012).

25.7.2.2. Projected Impacts and Adaptation – Cropping

Experiments with elevated CO_2 at two sites with different temperatures have shown a wide range in the response of current wheat cultivars (Fitzgerald *et al.*, 2010). Modelling suggests there is the potential to increase New Zealand wheat yields under climate change with appropriate choices of cultivars and sowing dates (*high confidence*; Teixeira *et al.*, 2012). In Australia, the selection of appropriate cultivars and sowing times are projected to result in increased wheat yields in high rainfall areas such as southern Victoria under climate change and maintenance of current yields in some areas expected to be drier (e.g. north-western Victoria; O'Leary *et al.*, 2010). However, if extreme low rainfall scenarios are realized in areas such as South Australia then changes in cultivars and fertilizer applications are not expected to maintain current yields by 2080 (Luo *et al.*, 2009). Under the more severe climate scenarios and without adaptation, Australia could become a net importer of wheat (Howden *et al.*, 2010). One caveat to modelling studies is that an intercomparison of 27 wheat models found large differences between model outputs for already dry and hot Australian sites in response to increasing CO_2 and temperature (Asseng *et al.*, 2013; Carter, 2013).

Rice production in Australia is largely dependent on irrigation and climate change impacts will strongly depend on water availability and price (Gaydon *et al.*, 2010). Sugarcane is also strongly water dependent (Carr and Knox, 2011); yields may increase where rainfall is unchanged or increased, but rising temperatures could drive up evapotranspiration and increase water use (*medium confidence*; Park *et al.*, 2010).

Observed trends and modelling for wine-grapes suggest that climate change will lead to earlier budburst, ripening and harvest for most regions and scenarios (*high confidence*; Grace *et al.*, 2009; Sadras and Petrie, 2011; Webb *et al.*, 2012a). Without adaptation, reduced quality is expected in all Australian regions (*high confidence*; Webb *et al.*, 2008). Change in cultivar suitability in specific regions is expected (Clothier *et al.*, 2012), with potential for development of cooler or more elevated sites within some regions (Tait, 2008; Hall and Jones, 2009) and/or expansion to new regions, with some growers in Australia already relocating (e.g. to Tasmania; Smart, 2010).

Climate change and elevated CO_2 impacts on weeds, pests and diseases are highly uncertain (see Box 25.4). Future performance of currently effective plant resistance mechanisms under elevated CO_2 and temperature is particularly important (Melloy *et al.*, 2010; Chakraborty *et al.*, 2011) as is the future efficacy of widely used biocontrol, i.e. the introduction or stimulation of natural enemies to control pests (Gerard *et al.*, 2012). Australia is ranked second and New Zealand fourth in the world in the number of biological control agent introductions (Cock *et al.*, 2010).

25.7.2.3. Integrated Adaptation Perspectives

Future water demand by the sector is critical for planning (Box 25-2). Irrigated agriculture occupies less than 1% of agricultural land in Australia but accounted for 28% of gross agricultural production value in 2010/11; almost half of this was produced the Murray Darling Basin, which used 68% of all irrigation water (ABS, 2012b; DAFF, 2012). Reduced inflow under dry climate scenarios is predicted to reduce substantially the value of agricultural production in the Basin (*high agreement*, *robust evidence*; Garnaut, 2008; Quiggin *et al.*, 2010; Qureshi *et al.*, 2013b), e.g. in one study by 12-44% to 2030 and 49-72% to 2050 (A1F1; Garnaut, 2008).Water availability also constrains agricultural expansion: 17 Mha in northern Australia could support cropping but only 1% has appropriate water availability (Webster *et al.*, 2009). In New Zealand, the irrigated area has risen by 82% since 1999 to over 1 Mha; 76% is on pasture (Rajanayaka *et al.*, 2010). The New Zealand dairy herd doubled between 1980-2009 expanding from high rainfall zones (>2000 mm annual) into drier, irrigation-dependent areas (600-1000 mm annual); this dependence will increase with further expansion (Robertson, 2010), which is being supported by the Government’s Irrigation Acceleration Fund.

Many adaptation options such as flexible water allocation, irrigation and seasonal forecasting support managing risk in the current climate (Howden *et al.*, 2008; Botterill and Dovers, 2013) and adoption is often high (Hogan *et al.*, 2011a; Kenny, 2011). However, incremental on-farm adaptation has limits (Park *et al.*, 2012) and may hinder transformational change such as diversification of land use or relocation (see Box 25-5) if it encourages persistence where climate change may take current systems beyond their response capacity (Marshall, 2010; Park *et al.*, 2012; Rickards and Howden, 2012). In many cases, transformational change requires a greater level of commitment, access to more resources, and greater integration across all levels of decision-making that encompass both on- and off-farm knowledge, processes and values (Marshall, 2010; Rickards and Howden, 2012).

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Box 25-4. Biosecurity

Biosecurity is a high priority for Australia and New Zealand given the economic importance of biologically-based industries and risks to endemic species and iconic ecosystems. The biology and potential risk from invasive and native pathogenic species will be altered by climate change (*high confidence*; Roura-Pascual *et al.*, 2011), but impacts may be positive or negative depending on the particular system.

[INSERT TABLE 25-4 HERE
Table 25-4: Examples of potential consequences of climate change for invasive and pathogenic species relevant to Australia and New Zealand, with consequence categories based on Hellman et al. (2008).]

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Box 25-5. Climate Change Vulnerability and Adaptation in Rural Areas

Rural communities in Australasia have higher proportions of older and unemployed people than urban populations (Mulet-Marquis and Fairweather, 2008). Employment and economic prospects depend heavily on the physical environment and hence are highly exposed to climate (averages, variability and extremes) as well as changing commodity prices. These interact with other economic, social and environmental pressures, such as changing government policies (e.g. on drought, carbon pricing; Productivity Commission, 2009; Nelson *et al.*, 2010) and access to water resources. The vulnerability of rural communities differs within and between countries reflecting differences in financial security, environmental awareness, policy and social support, strategic skills and capacity for diversification (Bi and Parton, 2008; Marshall, 2010; Nelson *et al.*, 2010; Hogan *et al.*, 2011b; Kenny, 2011).

Climate change will affect rural industries and communities through impacts on resource availability and distribution, particularly water. Decreased availability and/or increased demand, or price, in response to climate change will increase tensions among agricultural, mining, urban and environmental water users (*very high confidence*), with implications for governance and participatory adaptation processes to resolve conflicts (see 25.4.2, 25.6.1, 25.7.2, 25.7.3, Box 25-2, Box 25-10). Communities will also be affected through direct impacts on primary production, extraction activities, critical infrastructure, population health and recreational and culturally significant sites (see 25.7, 25.8; Kouvelis *et al.*, 2010; Balston *et al.*, 2012).

Altered production and profitability risks and/or land use will translate into complex and interconnected effects on rural communities, particularly income, employment, service provision, and reduced volunteerism (Stehlik *et al.*, 2000; Bevin, 2007; Kerr and Zhang, 2009). The prolonged drought in Australia during the early 2000s, for example, had many interrelated negative social impacts in rural communities, including farm closures, increased poverty, increased off-farm work and, hence, involuntary separation of families, increased social isolation, rising stress and associated health impacts, including suicide (especially of male farmers), accelerated rural depopulation and closure of key services (*high agreement, robust evidence*; Alston, 2007; Edwards and Gray, 2009; Alston, 2010, 2012; Hanigan *et al.*, 2012; see also Box CC-GC). Positive social change also occurred, however, including increased social capital through interaction with community organisations (Edwards and Gray, 2009). While social and cultural changes have the potential to undermine the adaptive capacity of communities (Smith *et al.*, 2011), robust ongoing engagement between farmers and the local community can contribute to a strong sense of community and enhance potential for resilience (McManus *et al.*, 2012; see also 25.4.3).

The economic impact of droughts on rural communities and the entire economy can be substantial. The most recent drought in Australia (2006/7-2008/9), for example, is estimated to have reduced national GDP by about 0.75% (RBA, 2006) and regional GDP in the southern Murray Darling Basin was about 5.7% below forecast in 2007/08, along with the temporary loss of 6000 jobs (Wittwer and Griffith, 2011). Widespread drought in New Zealand during 2007-2009 reduced direct and off-farm output by about NZ$3.6 billion (Butcher, 2009). The 2012-13 drought in New Zealand is estimated to have reduced national GDP by 0.3-0.6% and contributed to a significant rise in global dairy prices, which tempered even greater domestic economic losses (Kamber *et al.*, 2013). Drought frequency and severity are projected to increase in many parts of the region (Table 25-1).

The decisions of rural enterprise managers have significant consequences for and beyond rural communities (Pomeroy, 1996; Clark and Tait, 2008). Many current responses are incremental, responding to existing climate variability (Kenny, 2011). Transformational change has occurred where industries and individuals are relocating part of their operations in response to recent and/or expectations of future climate or policy change (Kenny, 2011; see also Box 25-10), e.g. rice (Gaydon *et al.*, 2010), wine-grapes (Park *et al.*, 2012), peanuts (Thorburn *et al.*, 2012) or changing and diversifying land use *in situ* (e.g. the recent switch from grazing to cropping in South Australia; Howden *et al.*, 2010). Such transformational changes are expected to become more frequent and widespread with a changing climate (*high confidence*; 25.7.2), with positive or negative implications for the wider communities in origin and destination regions (Kiem and Austin, 2012).

Although stakeholders within rural communities differ in their vulnerabilities and adaptive capacities, they are bound by similar dependence upon critical infrastructure and resources, economic conditions, government policy direction, and societal expectations (Loechel *et al.*, 2013). Consequently, adaptation to climate change will require an approach that devolves decision-making to the level where the knowledge for effective adaptations resides, using open communication, interaction and joint-planning (Nelson *et al.*, 2008; Kiem and Austin, 2013).

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_____ START BOX 25-6 HERE _____

Box 25-6. Climate Change and Fire

Fire during hot, dry and windy summers in southern Australia can cause loss of life and substantial property damage (Cary *et al.*, 2003; Adams and Attiwill, 2011). The 'Black Saturday' bushfires in Victoria in February 2009, for example, burnt over 3,500 km^2, caused 173 deaths, destroyed over 2,000 buildings and caused damages of A$4 billion (Cameron *et al.*, 2009; VBRC, 2010). This fire occurred toward the end of a 13-year drought (CSIRO, 2010) and after an extended period of consecutive days over 30°C (Tolhurst, 2009).

Climate change is expected to increase the number of days with very high and extreme fire weather (Table 25-1), with greater changes where fire is weather-constrained (most of southern Australia; many, in particular eastern and northern, parts of New Zealand) than where it is constrained by fuel load and ignitions (tropical savannas in Australia). Fire season length will be extended in many already high-risk areas (*high confidence*) and so reduce opportunities for controlled burning (Lucas *et al.*, 2007). Higher CO_2 may also enhance fuel loads by increasing vegetation productivity in some regions (Donohue *et al.*, 2009; Williams *et al.*, 2009; Bradstock, 2010; Hovenden and Williams, 2010; King *et al.*, 2011).

Climate change and fire will have complex impacts on vegetation communities and biodiversity (Williams *et al.*, 2009). Greatest impacts in Australia are expected in sclerophyll forests of the south-east and south-west (Williams *et al.*, 2009). Most New Zealand native ecosystems have limited exposure but also limited adaptations to fire (Ogden *et al.*, 1998; McGlone and Walker, 2011). There is *high confidence* that increased fire incidence will increase risk in southern Australia to people, property and infrastructure such as electricity transmission lines (Parsons Brinkerhoff, 2009; O'Neill and Handmer, 2012; Whittaker *et al.*, 2013) and in parts of New Zealand where urban margins expand into rural areas (Jakes *et al.*, 2010; Jakes and Langer, 2012); exacerbate some respiratory conditions such as asthma (Johnston *et al.*, 2002; Beggs and Bennett, 2011); and increase economic risks to plantation forestry (Watt *et al.*, 2008; Pearce *et al.*, 2011). Forest regeneration following wildfires also reduces water yields (Brown *et al.*, 2005; MDBC, 2007), while reduced vegetation cover increases erosion risk and material washoff to waterways with implications for water quality (Shakesby *et al.*, 2007; Wilkinson *et al.*, 2009; Smith *et al.*, 2011a).

In Australia, fire management will become increasingly challenging under climate change, potentially exacerbating conflicting management objectives for biodiversity conservation versus protection of property (*high confidence*; O'Neill and Handmer, 2012; Whittaker *et al.*, 2013). Current initiatives centre on planning and regulations, building design to reduce flammability, fuel management, early warning systems, and fire detection and suppression (Handmer and Haynes, 2008; Preston *et al.*, 2009; VBRC, 2010; O'Neill and Handmer, 2012). Some Australian authorities are taking climate change into account when rethinking approaches to managing fire to restore ecosystems while protecting human life and properties (Preston *et al.*, 2009; Adams and Attiwill, 2011). Improved understanding of climate drivers of fire risk is assisting fire management agencies, landowners and communities in New Zealand (Pearce *et al.*, 2008; Pearce *et al.*, 2011), although changes in management to date show little evidence of being driven by climate change.

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25.7.3. Mining

Australia is the world's largest exporter of coking coal and iron ore and has the world's largest resources of brown coal, nickel, uranium, lead and zinc (ABS, 2012c). Recent events demonstrated significant vulnerability to climate extremes: the 2011 floods reduced coal exports by 25-54 million tonnes and led to A$5-9bn revenue lost in that year (ABARES, 2011; RBA, 2011), and tropical cyclones regularly disrupted mining operations over the past decade (McBride, 2012; Sharma *et al.*, 2013). Flood impacts were exacerbated by regulatory constraints on mine discharges, highlighting tensions among industry, social and ecological management objectives (QRC, 2011), and by flooding affecting road and rail transport to major shipping ports (QRC, 2011; Sharma *et al.*, 2013).

Projected changes in climate extremes imply increasing sector vulnerability without adaptation (*high confidence*; Hodgkinson *et al.*, 2010a; Hodgkinson *et al.*, 2010b). Stakeholders have conducted initial climate risk assessments (Mills, 2009) and perceive the adaptive capacity of the industry to be high (Hodgkinson *et al.*, 2010a; Loechel *et al.*, 2010; QRC, 2011), but costs and broader benefits are yet to be explored along the value-chain and evaluated for community support. On-going challenges include competition for energy and water, climate change scepticism, dealing with contrasting extremes, avoiding maladaptation, and mining-community relations regarding response options, acceptable mine discharges and post-mining rehabilitation (Loechel *et al.*, 2013; Sharma *et al.*, 2013).

25.7.4. Energy Supply, Demand, and Transmission

Energy demand is projected to grow by 0.5-1.3% per annum in Australasia over the next few decades in the absence of major new policies (MED, 2011; Syed, 2012). Australia's predominantly thermal power generation is vulnerable to drought-induced water restrictions, which could require dry-cooling and increased water use efficiency where rainfall declines (Graham *et al.*, 2008; Smart and Aspinall, 2009). Depending on carbon price and technology costs, renewable electricity generation in Australia is projected to increase from 10% in 2010/11 to ~33-50% by 2030 (Hayward *et al.*, 2011; Stark *et al.*, 2012; Syed, 2012), but few studies have explored the vulnerability of these new energy sources to climate change (Bryan *et al.*, 2010; Crook *et al.*, 2011; Odeh *et al.*, 2011).

New Zealand's predominantly hydroelectric power generation is vulnerable to precipitation variability. Increasing winter precipitation and snow melt, and a shift from snowfall to rainfall will reduce this vulnerability (*medium confidence*) as winter/spring inflows to main hydro lakes are projected to increase by 5-10% over the next few decades (McKerchar and Mullan, 2004; Poyck *et al.*, 2011). Further reductions in seasonal snow and glacial melt as glaciers diminish, however, would compromise this benefit (Chinn, 2001; Renwick *et al.*, 2009; Srinivasan *et al.*, 2011). Increasing wind power generation (MED, 2011) would benefit from projected increases in mean westerly winds but face increased risk of damages and shut-down during extreme winds (Renwick *et al.*, 2009).

Climate warming would reduce annual average peak electricity demands by 1-2% per °C across New Zealand and 2(±1)% in New South Wales, but increase by 1.1(±1.4)% and 4.6(±2.7)% in Queensland and South Australia due to air conditioning demand (Stroombergen *et al.*, 2006; Jollands *et al.*, 2007; Thatcher, 2007; Nguyen *et al.*, 2010). Increased summer peak demand, particularly in Australia (see also Figure 25-5), will place additional stress on networks and can result in black-outs (*very high confidence*; Jollands *et al.*, 2007; Thatcher, 2007; Howden and Crimp, 2008; Wang *et al.*, 2010a). During the 2009 Victorian heat wave demand rose by 24% but electrical losses from transmission lines increased by 53% due to higher peak currents (Nguyen *et al.*, 2010), and successive failures of the overloaded network temporarily left more than 500,000 people without power (QUT, 2010). Various adaptation options to limit increasing urban energy demand exist and some are being implemented (see Box 25-9).

There is *limited evidence* but *high agreement* that without additional adaptation, distribution networks in most Australian states will be at high risk of failure by 2031-2070 under non-mitigation scenarios due to increased bushfire risk and potential strengthening and southward shift of severe cyclones in tropical regions (Maunsell and CSIRO, 2008; Parsons Brinkerhoff, 2009). Adaptation costs have been estimated at A$2.5 billion to 2015, with more than half to meet increasing demand for air conditioning and the remainder to increase resilience to climate-related hazards; underground cabling would reduce bushfire risk but has large investment costs that are not included above (Parsons Brinkerhoff, 2009). Decentralised ownership of assets constitutes a significant adaptation constraint

(ATSE, 2008; Parsons Brinkerhoff, 2009). In New Zealand, increasing high winds and temperatures have been identified qualitatively as the most relevant risks to transmission (Jollands *et al.*, 2007; Renwick *et al.*, 2009).

25.7.5. Tourism

Tourism contributes 2.6-4% of GDP to the economies of Australia and New Zealand (ABS, 2010a; SNZ, 2011). The net present value of the Great Barrier Reef alone over the next 100 years has been estimated at A$51.4 billion (Oxford Economics, 2009). Most Australasian tourism is exposed to climate variability and change (see 25.2 for projected trends), and some destinations are highly sensitive to extreme events (Hopkins *et al.*, 2012). The 2011 floods and Tropical Cyclone Yasi, for example, cost the Queensland tourism industry about A$590 million, mainly due to cancellations and damage to the Great Barrier Reef (PWC, 2011); and drought in the Murray-Darling Basin caused an estimated A$70 million loss in 2008 due to reduced visitor days (TRA, 2010).

25.7.5.1. Projected Impacts

Future impacts on tourism have been modelled for several Australian destinations. The Great Barrier Reef is expected to degrade under all climate change scenarios (25.6.2, 30.5, Box CC-CR), reducing its attractiveness (Marshall and Johnson, 2007; Bohensky *et al.*, 2011; Wilson and Turton, 2011b). Ski tourism is expected to decline in the Australian Alps due to snow cover reducing more rapidly than in New Zealand (Pickering *et al.*, 2010; Hendrikx *et al.*, 2013) and greater perceived attractiveness of New Zealand (Hopkins *et al.*, 2012). Higher temperature extremes in the Northern Territory are projected with *high confidence* to increase heat stress and incur higher costs for air conditioning (Turton *et al.*, 2009). Sea level rise places pressures on shorelines and long-lived infrastructure but implications for tourist resorts have not been quantified (Buckley, 2008).

Economic modelling suggests that the Australian alpine region would be most negatively affected in relative terms due to limited alternative activities (Pham *et al.*, 2010), whereas the competitiveness of some destinations (e.g. Margaret River in Western Australia) could be enhanced by higher temperatures and lower rainfall (Jones *et al.*, 2010; Pham *et al.*, 2010). An analogue-based study suggests that, in New Zealand, warmer and drier conditions mostly benefit but wetter conditions and extreme climate events undermine tourism (Wilson and Becken, 2011). *Confidence* in outcomes is *low*, however, due to uncertain future tourist behaviour (Scott *et al.*, 2012; also 25.9.2).

25.7.5.2. Adaptation

Both New Zealand and Australia have formalised adaptation strategies for tourism (Becken and Clapcott, 2011; Zeppel and Beaumont, 2011). In Australia, institutions at various levels also promote preparation for extreme events (Tourism Queensland, 2007, 2010; Tourism Victoria, 2010) and strengthening ecosystem resilience to maintain destination attractiveness (GBRMPA, 2009b). Snow-making is already broadly adopted to increase reliability of skiing (Bicknell and McManus, 2006; Hennessy *et al.*, 2008b), but its future effectiveness depends on location. In New Zealand, even though warming will significantly reduce the number of days suitable for snow-making (Hendrikx and Hreinsson, 2012), sufficient snow could be made in all years until the end of the 21st century to maintain current minimum operational skiing conditions. Options for resorts in Australia's Snowy Mountains are far more limited (Hendrikx *et al.*, 2013), where maintaining skiing conditions until at least 2020 would require A$100 million in capital investment into 700 snow guns and 2.5-3.3 GL of water per month (Pickering and Buckley, 2010).

Short investment horizons, high substitutability and a high proportion of human capital compared with built assets give *high confidence* that the adaptive capacity of the tourism industry is high overall, except for destinations where climate change is projected to degrade core natural assets and diversification opportunities are limited (Evans *et al.*, 2011; Morrison and Pickering, 2011). Strategic adaptation decisions are constrained by uncertainties in regional climatic changes (Turton *et al.*, 2010), limited concern (Bicknell and McManus, 2006), lack of leadership and limited coordinated forward planning (Sanders *et al.*, 2008; Turton *et al.*, 2009; Roman *et al.*, 2010; White and Buultjens, 2012). An integrated assessment of tourism vulnerability in Australasia is not yet possible due to limited understanding of future changes in tourism and community preferences (Scott *et al.*, 2012), including the flow-on effects of changing travel behaviour and tourism preferences in other world regions (see 25.9.2).

25.8.1. Human Health

25.8.1.1. Observed Impacts

Life expectancy in Australasia is high, but shows substantial ethnic and socio-economic inequalities (Anderson *et al.*, 2006). Mortality increases in hot weather in Australia (*high agreement*, *robust evidence*; Bi and Parton, 2008; Vaneckova *et al.*, 2008) with air pollution exacerbating this association. The last four decades have seen a steady increase in the ratio of summer to winter mortality in Australia, indicating a health effect from climatic warming (Bennett *et al.*, 2013). Exceptional heatwave conditions in Australia have been associated with substantial increases in mortality and hospital admissions in several regional towns and capital cities (*high confidence*; Khalaj *et al.*, 2010; Loughnan *et al.*, 2010; Tong *et al.*, 2010a; Tong *et al.*, 2010b). For example, during the heatwave in January and February 2009 in south-eastern Australia (BoM, 2009), total emergency cases increased by 46% over the three hottest days. Direct heat-related health problems increased 34-fold, 61% of these being in people aged 75 years or older, and there were an estimated 374 excess deaths, a 62% increase in all-cause mortality (Victorian Government, 2009a). Mental health admissions increased across all age groups by 7.3% in metropolitan South Australia during heatwaves (1993-2006; Hansen *et al.*, 2008). Mortality attributed to mental and behavioural disorders increased in the 65 to 74-year age group and in persons with existing mental health problems (Hansen *et al.*, 2008). Experience of extreme events also strongly affects psychological well-being (see 25.4.3).

25.8.1.2. Projected Impacts

Projected increases in heatwaves (Figure 25-5) will increase heat-related deaths and hospitalizations, especially among the elderly, compounded by population growth and ageing (*high confidence*; Bambrick *et al.*, 2008; Gosling *et al.*, 2009; Huang *et al.*, 2012). In the southern states of Australia and parts of New Zealand, this may be partly offset by reduced deaths from cold at least for modest rises in temperature (*low confidence*; Bambrick *et al.*, 2008; Kinney, 2012). With strong mitigation, climate change is projected to result in 11% fewer temperature-related deaths in both 2050 and 2100 in Australia, but 14% and 100% more deaths in 2050 and 2100, respectively, without mitigation under a hot, dry A1FI scenario (Bambrick *et al.*, 2008; see Chapter 11 for details on temperature-related health trade-offs). Net results were driven almost entirely by increased mortality in the north, especially Queensland, consistent with Huang *et al.* (2012). In a separate study that accounted for increased daily temperature variability, a threefold increase in heat-related deaths is projected for Sydney by 2100 for the A2 scenario, assuming no adaptation (Gosling *et al.*, 2009). The number of hot days when physical labor in the sun becomes dangerous is also projected to increase substantially in Australia by 2070, leading to economic costs from lost productivity, increased hospitalisations and occasional deaths (*medium confidence*; Hanna *et al.*, 2011; Maloney and Forbes, 2011).

Water- and food-borne diseases are projected to increase, but the complexity of their relationship to climate and non-climate drivers means there is *low confidence* in specific projections. For Australia, 205,000-335,000 new cases of bacterial gastroenteritis by 2050, and 239,000-870,000 cases by 2100, are projected under a range of emission scenarios (Bambrick *et al.*, 2008; Harley *et al.*, 2011). Based on their observed positive relationship with temperature, notifications of salmonellosis notifications are projected to increase 15% for every 1°C increase in average monthly temperatures (Britton *et al.*, 2010a). Water-borne zoonotic diseases such as cryptosporidiosis and giardiasis have more complex relationships with climate and are amenable to various adaptations, making future projections more difficult (Britton *et al.*, 2010b; Lal *et al.*, 2012).

Understanding of the combined effects of climate change and socio-economic development on the distribution of vector-borne diseases has improved since the AR4. Australasia is projected to remain malaria free under the A1B emission scenario until at least 2050 (Béguin *et al.*, 2011) and sporadic cases could be treated effectively. The area climatically suitable for transmission of dengue will expand in Australasia (*high confidence*; Bambrick *et al.*, 2008; Åström *et al.*, 2012), but changes in socio-economic factors, especially domestic water-storage may have a more important influence on disease incidence than climate (Beebe *et al.*, 2009; Kearney *et al.*, 2009). Impacts of climate change on Barmah Forest Virus in Queensland depend on complex interactions between rainfall and temperature changes, together with tidal and socio-economic factors, and thus will vary substantially among different coastal regions (Naish *et al.*, 2013). The effects of climate change combined with frequent travel within and outside the region, and recent incursions of exotic mosquito species, could expand the geographic range of other important arboviruses such as Ross River Virus (*medium confidence*; Derraik and Slaney, 2007; Derraik *et al.*, 2010).

A growing literature since the AR4 has focused on the psychological impacts of climate change, based on impacts of recent climate variability and extremes (Doherty and Clayton, 2011; 25.4.3). These studies indicate significant mental health risks associated with climate-related disasters, in particular persistent and severe drought, floods and storms; climate impacts may be especially acute in rural communities where climate change places additional stresses on livelihoods (*high confidence*; Edwards *et al.*, 2011; see also Box 25-5). Projected population growth and urbanization could further increase health risks indirectly via climate-related stress on housing, transport and energy infrastructure and water supplies (*low confidence*; Howden-Chapman, 2010; see also Box 25-9).

[INSERT FIGURE 25-5 HERE
Figure 25-5: Projected changes in exposure to heat under a high emissions scenario (A1FI). Maps show the average number of days with peak temperatures >40°C, for ~1990 (based on available meteorological station data for the period 1975-2004), ~2050 and ~2100. Bar charts show the change in population heat exposure, expressed as person-days exposed to peak temperatures >40°C, aggregated by State/Territory and including projected population growth for a default scenario. Future temperatures are based on simulations by the GFDL-CM2 global climate model (Meehl *et al.*, 2007), re-scaled to the A1FI scenario; simulations based on other climate models could give higher or lower results. Data from Baynes *et al*. (2012).]

25.8.1.3. Adaptation

Research since the AR4 has mainly focused on climate change impacts, although some adaptation strategies have received attention in Australia. These include improving healthcare services, social support for those most at risk, improving community awareness to reduce adverse exposures, developing early warning and emergency response plans (Wang and McAllister, 2011), and understanding perceptions of climatic risks to health as they affect adaptive behaviours (Akompad *et al.*, 2013). In New Zealand, central Government health policies do not identify specific measures to adapt to climate change (Wilson, 2011). In both countries, policies to reduce risks from extreme events such as floods and fires will have co-benefits for health (see Box 25-6, Box 25-8).

A review of the southern Australian heatwave of 2009 identified a range of issues including communication failures with no clear public information or warning strategy, and no clear thresholds for initiating public information campaigns (Kiem *et al.*, 2010). Emergency services were underprepared and relied on reactive solutions (QUT, 2010). The Victorian government has since developed a heatwave plan to coordinate a state-wide response, maintain consistent community-wide understanding through a Heat Health alert system, build capacity of councils to support communities most at risk, support a Heat Health Intelligence surveillance system, and distribute public health information (Victorian Government, 2009b).

25.8.2. Indigenous Peoples

25.8.2.1. Aboriginal and Torres Strait Islanders

Work since the AR4 includes a national Indigenous adaptation research action plan (Langton *et al.*, 2012), regional risk studies (Green *et al.*, 2009; DNP, 2010; TSRA, 2010; Nursey-Bray *et al.*, 2013) and scrutiny from an Indigenous rights perspective (ATSISJC 2009). Socio-economic disadvantage and poor health (SCRGSP 2011) indicate a disproportionate climate change vulnerability of Indigenous Australians (McMichael *et al.*, 2009) although there are no detailed assessments. In urban and regional areas, where 75% of the Indigenous population lives, assessments have not specifically addressed risks to Indigenous people (e.g. Guillaume *et al.*, 2010). In other regions, all remote, there is limited empirical evidence of vulnerability (Maru *et al.*, 2012). However, there is *high agreement* and *medium evidence* for significant future impacts from increasing heat stress, extreme events and increased disease (Campbell *et al.*, 2008; Spickett *et al.*, 2008; Green *et al.*, 2009).

The Indigenous estate comprises more than 25% of the Australian land area (Altman *et al.*, 2007; NNTT, 2013). There is *high agreement* but *limited evidence* that natural resource dependence (e.g. Bird *et al.*, 2005; Gray *et al.*, 2005a; Kwan *et al.*, 2006; Buultjens *et al.*, 2010) increases Indigenous exposure and sensitivity to climate change (Green *et al.*, 2009); climate change-induced dislocation, attenuation of cultural attachment to place and loss of agency will disadvantage Indigenous mental health and community identity (Fritze *et al.*, 2008; Hunter, 2009; McIntyre-Tamwoy and Buhrich, 2011); and, housing, infrastructure, services and transport, often already inadequate for Indigenous needs especially in remote Australia (ABS 2010c), will be further stressed (Taylor and Philp, 2010). Torres Strait island communities and livelihoods are vulnerable to major impacts from even small sea level rises (*high confidence*; DCC, 2009; Green *et al.*, 2010b; TSRA 2010).

Little adaptation of Indigenous communities to climate change is apparent to date (but see Burroughs, 2010; GETF 2011; Nursey-Bray *et al.*, 2013; Zander *et al.*, 2013). Plans and policies that are imposed on Indigenous communities can constrain their adaptive capacity (Ellemor, 2005; Petheram *et al.*, 2010; Veland *et al.*, 2010; Langton *et al.*, 2012) but participatory development of adaptation strategies is challenged by multiple stressors and uncertainty about causes of observed changes (Leonard *et al.*, 2013b; Nursey-Bray *et al.*, 2013). Adaptation planning would benefit from a robust typology (Maru *et al.*, 2011) across the diversity of Indigenous life experience (McMichael *et al.*, 2009). Indigenous re-engagement with environmental management (e. g. Hunt *et al.*, 2009; Ross *et al.*, 2009) can promote health (Burgess *et al.*, 2009) and may increase adaptive capacity (Berry *et al.*, 2010; Davies *et al.*, 2011). There is emerging interest in integrating Indigenous observations of climate change (Green *et al.*, 2010c; Petheram *et al.*, 2010) and developing inter-cultural communication tools (Woodward *et al.*, 2012; Leonard *et al.*, 2013b). Extensive land ownership in northern and inland Australia and land management traditions mean that Indigenous people are well situated to provide greenhouse gas abatement and carbon sequestration services that may also support their livelihood aspirations (Whitehead *et al.*, 2009; Heckbert *et al.*, 2012).

25.8.2.2. New Zealand Māori

The projected impacts of climate change on Māori society are expected to be highly differentiated, reflecting complex economic, social, cultural, environmental and political factors (*high confidence*). Since the AR4, studies have been either sector-specific (e.g. Insley, 2007; Insley and Meade, 2008; Harmsworth *et al.*, 2010; King *et al.*, 2012) or more general, inferring risk and vulnerability based on exploratory engagements with varied stakeholders and existing social, economic, political and ecological conditions (e.g. MfE, 2007b; Te Aho, 2007; King *et al.*, 2010).

The Māori economy depends on climate-sensitive primary industries with vulnerabilities to climate conditions (*high confidence*; Packman *et al.*, 2001; NZIER, 2003; Cottrell *et al.*, 2004; TPK, 2007; Tait *et al.*, 2008b; Harmsworth *et al.*, 2010; King *et al.*, 2010; Nana *et al.*, 2011a). Much of Māori-owned land is steep (>60%) and susceptible to damage from high intensity rainstorms, while many lowland areas are vulnerable to flooding and sedimentation (Harmsworth and Raynor, 2005; King *et al.*, 2010). Land in the east and north is also drought prone, and this increases uncertainties for future agricultural performance, product quality and investment (*medium confidence*; Cottrell *et al.*, 2004; Harmsworth *et al.*, 2010; King *et al.*, 2010). The fisheries and aquaculture sector faces substantial risks (and uncertainties) from changes in ocean temperature and chemistry, potential changes in species composition, condition and productivity levels (*medium confidence*; King *et al.*, 2010; see also 25.6.2). At the community and individual level, Māori regularly utilize the natural environment for hunting and fishing, recreation, the maintenance of traditional skills and identity, and collection of cultural resources (King and Penny, 2006; King *et al.*, 2012). Many of these activities are already compromised due to resource-competition, degradation and modification (Woodward *et al.*, 2001; King *et al.*, 2012). Climate change driven shifts in natural ecosystems will further challenge the capacities of some Māori to cope and adapt (*medium confidence*; King *et al.*, 2012).

Māori organizations have sophisticated business structures, governance (e.g. trusts, incorporations) and networks (e.g. Iwi leadership groups) across the state and private sectors (Harmsworth *et al.*, 2010; Insley, 2010; Nana *et al.*, 2011b), critical for managing and adapting to climate change risks (Harmsworth *et al.*, 2010; King *et al.*, 2012). Future opportunities will depend on partnerships in business, science, research and government (*high confidence*; Harmsworth *et al.*, 2010; King *et al.*, 2010) as well as innovative technologies and new land management practices to better suit future climates and use opportunities from climate policy, especially in forestry (Carswell *et al.*, 2002; Harmsworth, 2003; Funk and Kerr, 2007; Insley and Meade, 2008; Tait *et al.*, 2008b; Penny and King, 2010).

Māori knowledge of environmental processes and hazards (King *et al.*, 2005; King *et al.*, 2007) as well as strong social-cultural networks are vital for adaptation and on-going risk management (King *et al.*, 2008); however, choices and actions continue to be constrained by insufficient resourcing, shortages in social capital, and competing values (King *et al.*, 2012). Combining traditional ways and knowledge with new and untried policies and strategies will be key to the long-term sustainability of climate-sensitive Māori communities, groups and activities (*high confidence*; Harmsworth *et al.*, 2010; King *et al.*, 2012).

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Box 25-7. Insurance as a Climate Risk Management Tool

Insurance helps spread the risk from extreme events across communities and over time and therefore enhances the resilience of society to disasters (see 10.7). In Australia, insured losses are dominated by meteorological hazards, including the 2011 Queensland floods and the 1999 Sydney hailstorm (ICA, 2012) with estimated claims of A$3 billion p.a. (IAA, 2011b). In New Zealand, floods and storms are the second most costly natural hazards after earthquakes (ICNZ, 2013). The number of damaging insured events (up to a certain loss value) has increased significantly in the Oceania region since 1980 (Schuster, 2013). Normalised insured losses in Australia show no significant trend from 1967 to 2006 (Crompton and McAneney, 2008; Crompton *et al.*, 2010; Table 10.4), though this conclusion rests on a simplified accounting of population growth and may also reflect improved building codes and early warning systems (Nicholls, 2011; IPCC, 2012).

There is *high confidence* that without adaptive measures, projected increases in extremes (Table 25-1) and uncertainties in these projections will lead to increased insurance premiums, exclusions and non-coverage in some locations (IAG, 2011), which will reshape the distribution of vulnerability, e.g., through unaffordability or unavailability of cover in areas at highest risk (IAA, 2011b, a; NDIR, 2011; Booth and Williams, 2012). Restriction of cover occurred in some locations following the 2011 flood events in Queensland (Suncorp, 2013).

Insurance can contribute positively to risk reduction by providing incentives to policy holders to reduce their risk profile (O'Neill and Handmer, 2012), e.g. through resilience ratings given to buildings (TGA, 2009; Edge Environment, 2011; IAG, 2011). Apart from constituting an autonomous private sector response to extreme events, insurance can also be framed as a form of social policy to manage climate risks, similar to New Zealand’s government insurance scheme (Glavovic *et al.*, 2010); government measures to reduce or avoid risks also interact with insurance companies’ willingness to provide cover (Booth and Williams, 2012). Yet insurance can also act as a constraint on adaptation, if those living in climate-risk prone localities pay discounted or cross-subsidised premiums or policies fail to encourage betterment after damaging events by requiring replacement of ‘like for like’, constituting a missed opportunity for risk reduction (NDIR, 2011; QFCI, 2012; Reisinger *et al.*, 2014; see also 10.7). The effectiveness of insurance thus depends on the extent to which it is linked to a broader national resilience approach to disaster mitigation and response (Mortimer *et al.*, 2011).

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Box 25-8. Changes in Flood Risk and Management Responses

Flood damages across eastern Australia and both main islands of New Zealand in 2010 and 2011 revealed a significant adaptation deficit (ICA, 2012; ICNZ, 2013). For example, the Queensland floods in January 2011 resulted in 35 deaths, three quarters of the State including Brisbane declared a disaster zone, and damages to public infrastructure of AUD$5-6 billion (Queensland Government, 2011). These floods were associated with a strong monsoon and the strongest La Niña on record (Cai *et al.*, 2012; CSIRO and BoM, 2012; Evans and Boyer-Souchet, 2012). Flood frequency and severity exhibit strong decadal variability with no significant long-term trend in Australasia to date (Kiem *et al.*, 2003; Smart and McKerchar, 2010; Ishak *et al.*, 2013).

Flood risk is projected to increase in many regions due to more intense extreme rainfall events driven by a warmer and wetter atmosphere (*medium confidence*; Table 25-1). High resolution downscaling (Carey-Smith *et al.*, 2010), and dynamic catchment hydrological and river hydraulic modelling in New Zealand (Gray *et al.*, 2005b; McMillan *et al.*, 2010; MfE, 2010b; Ballinger *et al.*, 2011; Duncan and Smart, 2011; McMillan *et al.*, 2012) indicate that the 50-year and 100-year flood peaks for rivers in many parts of the country will increase by 5–10% by 2050 and more by 2100 (with large variation between models and emissions scenarios), with a corresponding decrease in return periods for specific flood levels. Studies for Queensland show similar results (DERM *et al.*, 2010). In Australia, flood risk is expected to increase more in the north (driven by convective rainfall systems) than in the south (where more intense extreme rainfall may be compensated by drier antecedent moisture conditions), consistent with confidence in heavy rainfall projections (Table 25-1; Alexander and Arblaster, 2009; Rafter and Abbs, 2009).

Flood risk near river mouths will be exacerbated by storm surge associated with higher sea level and potential change in wind speeds (McInnes *et al.*, 2005; MfE, 2010b; Wang *et al.*, 2010b). Higher rainfall intensity and peak flow will also increase erosion and sediment loads in waterways (Prosser *et al.*, 2001; Nearing *et al.*, 2004) and exacerbate problems from aging stormwater and wastewater infrastructure in cities (Howe *et al.*, 2005; Jollands *et al.*, 2007; CCC, 2010; WCC, 2010; see also Box 25-9). However, moderate flooding also has benefits through filling reservoirs, recharging groundwater and replenishing natural environments (Hughes, 2003; Chiew and Prosser, 2011; Oliver and Webster, 2011).

Adaptation to increased flood risk from climate change is starting to happen (Wilby and Keenan, 2012) through updating guidelines for design flood estimation (MfE, 2010b; Westra, 2012), improving flood risk management (O'Connell and Hargreaves, 2004; NFRAG, 2008; Queensland Government, 2011), accommodating risk in flood prone areas (options include raising floor levels, using strong piled foundations, using water-resistant insulation materials and ensuring weather tightness), and risk reduction and avoidance through spatial planning and managed relocation (Trotman, 2008; Glavovic *et al.*, 2010; LVRC, 2012; QFCI, 2012). Adaptation options in urban areas also include ecosystem-based approaches such as retaining floodplains and floodways, restoring wetlands, and retrofitting existing systems to attenuate flows (Box 25.9; Howe *et al.*, 2005; Skinner, 2010; WCC, 2010).

The recent flooding in eastern Australia and the projected increase in future flood risk have resulted in changes to reservoir operations to mitigate floods (van den Honert and McAneney, 2011; QFCI, 2012) and insurance practice to cover flood damages (NDIR, 2011; Phelan, 2011; Box 25-7). However, the magnitude of potential future changes in flood risk and limits to incremental adaptation responses in urban areas suggest that more transformative approaches based on altering land-use and avoidance of exposure to future flooding may be needed in some locations, especially if changes in the upper range of projections are realised (*high confidence*; Lawrence and Allan, 2009; DERM *et al.*, 2010; Glavovic *et al.*, 2010; Wilby and Keenan, 2012; Lawrence *et al.*, 2013a).

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25.9. Interactions among Impacts, Adaptation, and Mitigation Responses

The AR4 found that individual adaptation responses can entail synergies or trade-offs with other adaptation responses and with mitigation, but that integrated assessment tools were lacking in Australasia (Hennessy *et al.*, 2007). Subsequent studies provide detail on such interactions and can inform a balanced portfolio of climate change responses, but evaluation tools remain limited, especially for local decision-making (Park *et al.*, 2011). A review of 25 specific climate change-associated land-use plans from Australia, for example, found that 14 exhibited potential for conflict between mitigation and adaptation (Hamin and Gurran, 2009).

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Box 25-9. Opportunities, Constraints, and Challenges to Adaptation in Urban Areas

Considerable opportunities exist for Australasian cities and towns to reduce climate change impacts and, in some regions, benefit from projected changes such as warmer winters and more secure water supply (Fitzharris, 2010; Australian Government, 2012). Many tools and practices developed for sustainable resource management or disaster risk reduction in urban areas are co-beneficial for climate change adaptation, and vice versa, and can be integrated with mitigation objectives (Hamin and Gurran, 2009). Despite the abundance of potential adaptation options, however, social, cultural, institutional and economic factors frequently constrain their implementation (*high confidence*; see also 25.4.2). The form and longevity of cities and towns, with their concentration of hard and critical infrastructure such as housing, transport, energy, stormwater and wastewater systems, telecommunications and public facilities provide additional challenges (see also Chapters 8 and 10, 25.7.4, 25.8.1, Boxes 25-1, 25-2, 25-8). Transport infrastructure is vulnerable to extreme heat and flooding (QUT, 2010; Taylor and Philp, 2010) but quantification of future risks remains limited (Gardiner *et al.*, 2009; Balston *et al.*, 2012; Baynes *et al.*, 2012). Table 25-5 summarises some adaptation options, co-benefits and constraints on their adoption in Australasia.

Overall, the implementation of climate change adaptation policy for urban settlements in Australia and New Zealand has been mixed. The Australian National Urban Policy encourages adaptation, and many urban plans include significant adaptation policies (e.g. City of Melbourne, 2009; City of Port Phillip, 2010; ACT Government, 2012; City of Adelaide, 2012). New Zealand also promotes urban adaptation through strategies, plans and guidance documents (MfE, 2008b; CCC, 2010; WCC, 2010; Auckland Council, 2012; NIWA *et al.*, 2012). Many examples of incremental urban adaptation exist (Box 25-2, Table 25-5), particularly where these include co-benefits and respond to other stressors, like prolonged drought in southern Australia and recurrent floods. Experience is much scarcer with more flexible land-uses, managed relocation and ecosystem-based adaptation that could transform existing settlement patterns and development trends, and where maintaining flexibility to address long-term climate risks can run against near-term development pressures (see Boxes 25-1, 25-2, 25-8, CC-EA). Decision-making models that support such adaptive and transformative changes (25.4.2, Box 25-1) have not yet been implemented widely in urban contexts; increased coordination among different levels of government may be required to spread costs and balance public and private, near- and long-term and local and regional benefits (Norman, 2009; Britton, 2010; Norman, 2010; Abel *et al.*, 2011; Lawrence *et al.*, 2013a; McDonald, 2013; Palutikof *et al.*, 2013; Reisinger *et al.*, 2014).

[INSERT TABLE 25-5 HERE
Table 25-5: Examples of co-beneficial climate change adaptation options for urban areas and barriers to their adoption. Options in italics are already widely implemented in Australia and New Zealand urban areas.]

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25.9.1. Interactions among Local-Level Impacts, Adaptation, and Mitigation Responses

Table 25-6 shows examples of adaptation responses that are either synergistic or entail trade-offs with other impacts and/or adaptation responses and goals. Adapting proactively to projected climate changes, particularly extremes such as floods or drought, can increase near-term resilience to climate variability and be a motivation for adopting adaptation measures (Productivity Commission, 2012). However, exclusive reliance on near-term benefits can increase trade-offs and result in long-term maladaptation (*high confidence*). For example, enhancing protection measures after major flood events, combined with rapid re-building, accumulates fixed assets that can become increasingly costly to protect as climate change continues, with attendant loss of amenity and environmental values (Glavovic *et al.*, 2010; Gorddard *et al.*, 2012; McDonald, 2013). Similarly, deferring adoption of increased design wind speeds in cyclone-prone areas delays near-term investment costs but also reduces the long-term benefit/cost ratio of the strategy (Stewart and Wang, 2011).

[INSERT TABLE 25-6 HERE
Table 25-6: Examples of interactions between impacts and adaptation measures in different sectors. In each case, impacts or responses in one sector have the potential to cause negative impacts or have co-benefits with impacts or responses in another sector, or with another type of response in the same sector.]

Mitigation actions can contribute to but also counteract local adaptation goals. Energy efficient buildings, for example, reduce network and health risks during heat waves, but urban densification to reduce transport energy demand intensifies urban heat islands and, hence, heat-related health risks (25.7.4, 25.8.1). Specific adaptations can also make achievement of mitigation targets harder or easier. Increased use of air conditioning, for example, increases energy demand, but energy efficiency and building design can reduce heat exposure as well as energy demand (25.7.4, Box 25-9). Table 25-7 gives further examples, and Box 25-10 explores the multiple and complex benefits and trade-offs in changing land-use to simultaneously adapt to and mitigate climate change.

[INSERT TABLE 25-7 HERE
Table 25-7: Examples of interactions between adaptation and mitigation measures (green rows denote synergies where multiple benefits may be realized, orange rows denote potential tradeoffs and conflicts; grey row gives an example of complex, mixed interactions). The primary goal may be adaptation or mitigation.]

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Box 25-10. Land-based Interactions Among Climate, Energy, Water, and Biodiversity

Climate, water, biodiversity, food and energy production and use are intertwined through complex feedbacks and trade-offs (see also Box CC-WE). This could make alternative uses of natural resources within rural landscapes increasingly contested, yet decision support tools to manage competing objectives are limited (PMSEIC, 2010b).

Various policies in Australasia support increased biofuel production and biological carbon sequestration via, for example, mandatory renewable energy targets and incentives to increase carbon storage. Impacts of increased biological sequestration activities on biodiversity depend on their implementation. Benefits arise from reduced erosion, additional habitat, and enhanced ecosystem connectivity, while risks or lost opportunities are associated with large-scale monocultures especially if replacing more diverse landscapes (Brockerhoff *et al.*, 2008; Giltrap *et al.*, 2009; Steffen *et al.*, 2009; Todd *et al.*, 2009; Bradshaw *et al.*, 2013).

Photosynthesis transfers water to the atmosphere, so increased sequestration is projected to reduce catchment yields particularly in southern Australia and affect water quality negatively (CSIRO, 2008; Schrobback *et al.*, 2011; Bradshaw *et al.*, 2013). Accounting for this water use in water allocations for sequestration activities would increase their cost and limit the potential of sequestration-driven land-use change (Polglase *et al.*, 2011; Stewart *et al.*, 2011). Large-scale land-cover changes also affect local and regional climates and soil moisture through changing albedo, evaporation, plant transpiration and surface roughness (McAlpine *et al.*, 2009; Kirschbaum *et al.*, 2011b), but these feedbacks have rarely been included in analyses of changing water demands and availability.

Biological carbon sequestration in New Zealand is less water-challenged than in Australia, except where catchments are projected to become drier and/or are already completely allocated (MfE, 2007a; Rutledge *et al.*, 2011), and would mostly improve water quality through reduced erosion (Giltrap *et al.*, 2009). Policies to protect water quality by limiting nitrogen discharge from agriculture have reduced livestock production and greenhouse gas emissions in the Lake Taupo and Rotorua catchments and supported land-use change towards sequestration (OECD, 2013b).

Trade-offs between biofuel and food production and ecosystem services depend strongly on the type of sequestration activity and their management relies on the use of consistent principles to evaluate externalities and benefits of alternative land-uses (PMSEIC, 2010b). First-generation biofuels have been modelled in Australia as directly competing with agricultural production (Bryan *et al.*, 2010). In contrast, production of woody biofuels in New Zealand is projected to occur on marginal land, not where the most intense agriculture occurs (Todd *et al.*, 2009). Falling costs and increasing efficiency of solar energy may limit future biofuel demand, given the limited efficiency of plants in converting solar energy into usable fuel (e.g. Reijnders and Huijbregts, 2007).

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25.9.2. Intra- and Inter-Regional Flow-On Effects Among Impacts, Adaptation and Mitigation

Recent studies strengthen conclusions from the AR4 (Hennessy *et al.*, 2007) that flow-on effects from climate change impacts occurring in other world regions can exacerbate or counteract projected impacts in Australasia. Modelling suggests Australia's terms of trade would deteriorate by about 0.23% in 2050 and 2.95% in 2100 as climate change impacts without mitigation reduce economic activity and demand for coal, minerals and agricultural products in other world regions (A1FI scenario; Harman *et al.*, 2008). As a result, Australian Gross National Product (GNP) is expected to decline more strongly than GDP due to climate change, especially towards the end of the 21^{st} century (Gunasekera *et al.*, 2008). These conclusions, however, merit only *medium confidence*, because they rely on simplified assumptions about global climate change impacts, economic effects and policy responses.

For New Zealand, there is *limited evidence* but *high agreement* that higher global food prices driven by adverse climate change impacts on global agriculture and some international climate policies would increase commodity prices and hence producer returns. Agriculture and forestry producer returns, for example, are estimated to increase by 14.6% under the A2 scenario by 2070 (Saunders *et al.*, 2010) and real gross national disposable income by 0.6-2.3% under a range of non-mitigation scenarios (Stroombergen, 2010) relative to baseline projections in the absence of global climate change. Some climate policies such as biofuel targets and agricultural mitigation in other regions would also increase global commodity prices and hence returns to New Zealand farmers (Saunders *et al.*, 2009; Reisinger *et al.*, 2012). Depending on global implementation, these could more than offset projected average domestic climate change impacts on agriculture (Tait *et al.*, 2008a). In contrast, higher international agricultural commodity prices appear insufficient to compensate for the more severe effects of climate change on agriculture in Australia (see 25.7.2; Gunasekera *et al.*, 2007; Garnaut, 2008).

Climate change could affect international tourism to Australasia through international destination and activity preferences (Kulendran and Dwyer, 2010; Rosselló-Nadal *et al.*, 2011; Scott *et al.*, 2012), climate policies, and oil prices (Mayor and Tol, 2007; Becken, 2011; Schiff and Becken, 2011). These potentially significant effects remain poorly quantified, however, and are not well integrated into local vulnerability studies (Hopkins *et al.*, 2012).

Climate change has the potential to change migration flows within Australasia, particularly due to coastal changes (e.g. from the Torres Straits islands to mainland Australia), although reliable estimates of such movements do not yet exist (see 12.4; Green *et al.*, 2010b; McNamara *et al.*, 2011; Hugo, 2012). Migration within countries, and from New Zealand to Australia, is largely economically driven and sustained by transnational networks, though the perceived more attractive current climate in Australia is reportedly a factor in migration from New Zealand (Goss and Lindquist, 2000; Green *et al.*, 2008a; Poot, 2009). The impacts of climate change in the Pacific may contribute to an increase in the number of people seeking to move to nearby countries (Bedford and Bedford, 2010; Hugo, 2010; McAdam, 2010; Farbotko and Lazrus, 2012; Bedford and Campbell, 2013) and affect political stability and geopolitical rivalry within the Asia-Pacific region, although there is no clear evidence of this to date and causal theories are scarce (see 12.4, 12.5; Dupont, 2008; Pearman, 2009). Increasing climate-driven disasters, disease and border control will stimulate operations other than war for Australasia's armed forces; integration of security into adaptation and development assistance for Pacific island countries can therefore play a key role in moderating the influence of climate change on forced migration and conflict (*high agreement, robust evidence*; Dupont and Pearman, 2006; Bergin and Townsend, 2007; Dupont, 2008; Sinclair, 2008; Barnett, 2009; Rolfe, 2009).

25.10. Synthesis and Regional Key Risks

25.10.1. Economy-wide Impacts and the Potential of Mitigation to Reduce Risks

Globally effective mitigation could reduce or delay some of the risks associated with climate change and make adaptation more feasible beyond about 2050, when projected climates begin to diverge substantially between mitigation and non-mitigation scenarios (see also 19.7). Literature quantifying these benefits for Australasia has increased since the AR4 but remains very sparse. Economy-wide net costs for Australia are modelled to be substantially greater in 2100 under unmitigated climate change (A1FI; GNP loss 7.6%) than under globally effective mitigation (GNP loss less than 2% for stabilization at 450 or 550 ppm CO2-eq, including costs of mitigation and residual impacts; Garnaut, 2008). These estimates, however, are highly uncertain and depend strongly on valuation of non-market impacts, treatment of potentially catastrophic outcomes, and assumptions about adaptation, global changes and flow-on effects for Australia, and effectiveness and implementation of global mitigation efforts (Garnaut, 2008). No estimates of climate change costs across the entire economy exist for New Zealand.

The benefits of mitigation in terms of reduced risks have been quantified for some individual sectors in Australia, e.g. for irrigated agriculture in the Murray-Darling Basin (Quiggin *et al.*, 2008; Quiggin *et al.*, 2010; Valenzuela and Anderson, 2011; Scealy *et al.*, 2012) and for net health outcomes (Bambrick *et al.*, 2008). Although quantitative estimates from individual studies are highly assumption-dependent, multiple lines of evidence (see 25.7, 25.8) give *very high confidence* that globally effective mitigation would significantly reduce many long-term risks from climate change to Australia. Benefits differ, however, between States for some issues, e.g. heat and cold mortality (Bambrick *et al.*, 2008). Few studies consider mitigation benefits explicitly for New Zealand, but scenario-based studies give *high confidence* that if global emissions were reduced from a high (A2) to a medium-low (B1) emissions scenario, this would markedly lower the projected increase in flood risks (Ballinger *et al.*, 2011; McMillan *et al.*, 2012) and reduce risks to livestock production in the most drought prone regions (Tait *et al.*, 2008a; Clark *et al.*, 2011). Mitigation would also reduce the projected benefits to production forestry, however, though amounts depend on the response to CO_2 fertilization (Kirschbaum *et al.*, 2011a; 25.7.1).

25.10.2. Regional Key Risks as a Function of Mitigation and Adaptation

The Australia/New Zealand Chapter of the AR4 (Hennessy *et al.*, 2007) concluded with an assessment of aggregated vulnerability for a range of sectors as a function of global average temperature. Building on recent additional insights, Table 25-8 shows eight key risks within those sectors that can be identified with *high confidence* for the 21st century, based on the multiple lines of evidence presented in the preceding sections and selected using the framework for identifying key risks set out in Chapter 19 (see also Box CC-KR). This combines consideration of biophysical impacts, their likelihood, timing and persistence, with vulnerability of the affected system, based on exposure, magnitude of harm, significance of the system and its ability to cope with or adapt to projected biophysical changes. These key risks differ in the extent to which they can be managed through adaptation and mitigation and their evolution over time, and some are more likely than others, but all warrant attention from a risk-management perspective.

[INSERT TABLE 25-8 HERE
Table 25-8: Key regional risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized on a scale from very low to very high and presented in three timeframes: the present, near-term (2030-2040), and long-term (2080-2100). For the near-term era of committed climate change (here, for 2030-2040), projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. For the longer-term era of climate options (here, for 2080-2100), risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.]

One set of key risks comprises damages to natural ecosystems (significant change in community structure of coral reefs and loss of some montane ecosystems) that can be moderated by globally effective mitigation but to which some damage now seems inevitable. For some species and ecosystems, climatically constrained ecological niches, fragmented habitats and limited adaptive movement collectively present hard limits to adaptation to further climate change (*high confidence*). A second set of key risks (increase in flood risk, water scarcity, heat waves and wild fire) comprises damages that could be severe but can be reduced substantially by globally effective mitigation combined with adaptation, with the need for transformational adaptation increasing with the rate and amount of climate change. A third set of key risks (coastal damages from sea level rise, and loss of agriculture production from severe drying) comprises potential impacts whose scale remains highly uncertain within the 21st century, even for a given global temperature change, and where alternative scenarios materially affect levels of concern, adaptation needs and strategies. Even though scenarios of severe drying (see 25.5.2) or rapid sea level rise approaching 1 m or more by 2100 (see Box 25-2 and WGI 13.5) have low or currently unknown probabilities, the associated impacts would so severely challenge adaptive capacity, including transformational changes, that they constitute important risks.

A first comparative assessment for Australia of exposure and damages from different hazards up to 2100 indicates that river flooding will continue to be the most costly source of direct damages to infrastructure, even though the largest value of assets is exposed to bush fire. Exposure to and damages from coastal inundation are currently smaller, but would rise most rapidly beyond mid-century if sea level rise exceeds 0.5 m (Baynes *et al.*, 2012).

An *emerging risk* is the compounding of extreme events, none of which would constitute a *key* risk in its own right, but that collectively and cumulatively across space and time could stretch emergency response and recovery capacity and hamper regional economic development, including through impacts on insurance markets or multiple concurrent needs for major infrastructure upgrades (NDIR, 2011; Phelan, 2011; Baynes *et al.*, 2012; Booth and Williams, 2012; Karoly and Boulter, 2013). Efforts are underway to better understand the potential importance of cumulative impacts and responses, including the challenges arising from impacts and responses across different levels of government (CSIRO, 2011; Leonard *et al.*, 2013a), but evidence is as yet too limited to identify this as a *key risk* consistent with the definitions adopted in this report (see Chapter 19).

Climate change is projected to bring benefits to some sectors and parts of Australasia, at least under limited warming scenarios associated with globally effective mitigation (*high confidence*). Examples include an extended growing season for agriculture and forestry in cooler parts of New Zealand and Tasmania, reduced winter mortality (*low confidence*) and reduced winter energy demand in most of New Zealand and southern States of Australia, and increased winter hydropower potential in New Zealand's South Island (25.7.1, 25.7.2, 25.7.4, 25.8.1).

The literature supporting this assessment of key risks is uneven among sectors and between Australia and New Zealand; for the latter, conclusions in many sectors are based on limited studies that often use a narrow set of assumptions, models, and data and which, accordingly, have not explored the full range of potential outcomes.

25.10.3. Challenges to Adaptation in Managing Key Risks, and Limits to Adaptation

Two key and related challenges for regional adaptation are apparent: to identify when and where adaptation may imply transformational rather than incremental changes; and, where specific interventions are needed to overcome adaptation constraints, in particular to support transformational responses that require coordination across different spheres of governance and decision-making (Productivity Commission, 2012; Palutikof *et al.*, 2013). The magnitude of climate change, especially under scenarios of limited mitigation, and constraints to adaptation suggest that incremental and autonomous responses will not deliver the full range of available adaptation options nor ensure the continued function of natural and human systems if some key risks are realized (*high confidence*; see also 25.4).

Most incremental adaptation measures in natural ecosystems focus on reducing other non-climate stresses but, even with scaled-up efforts, conserving the current state and composition of the ecosystems most at risk appears increasingly infeasible (25.6.1, 25.6.2). Maintenance of key ecosystem functions and services requires a radical reassessment of conservation values and practices related to assisted colonisation and the values placed on 'introduced' species (Steffen *et al.*, 2009). Divergent views regarding intrinsic and service values of species and ecosystems imply the need for a proactive discussion to enable effective decision-making and resource allocation.

In human systems, incremental adjustments of current risk management tools, planning approaches and early warning systems for floods, fire, drought, water resources and coastal hazards can increase resilience to climate variability and change especially in the near term (IPCC, 2012; Productivity Commission, 2012; Dovers, 2013). A purely incremental approach, however, which generally aims to preserve current management objectives, governance and institutional arrangements, can make later transformational changes increasingly difficult and costly (*high agreement, medium evidence*; e.g. Howden *et al.*, 2010; Park *et al.*, 2012; McDonald, 2013; Stafford-Smith, 2013). Examples of transformational changes include: shifting emphasis from protection to accommodation or avoidance of flood risk, including managed retreat from eroding coasts; the translocation of industries in response to increasing drought, flood and fire risks or water scarcity; and the associated transformation of the economic and social base and governance of some rural communities (Boxes 25-1, -2, 5-9; Nelson *et al.*, 2010; Linnenluecke *et al.*, 2011; Kiem and Austin, 2012; O'Neill and Handmer, 2012; McDonald, 2013; Palutikof *et al.*, 2013).

Consideration of transformational adaptation becomes critical where long life- or lead-times are involved, and where high up-front costs or multiple interdependent actors create constraints that require coordinated and proactive interventions (Stafford-Smith *et al.*, 2011; Productivity Commission, 2012; Palutikof *et al.*, 2013). Deferring such adaptation decisions due to uncertainty about the future will not necessarily minimize costs or ensure adequate flexibility for future responses, although up-front investment and opportunity costs of adaptation can present powerful arguments for delayed or staged responses (Stewart and Wang, 2011; Gorddard *et al.*, 2012; Productivity Commission, 2012; McDonald, 2013). Whether transformational responses are seen as success or failure of adaptation depends on the extent to which actors accept a change in, or wish to maintain current activities and management objectives, and the degree to which the values and institutions underpinning the transformation are shared or contested across stakeholders (Park *et al.*, 2012; Stafford-Smith, 2013). These views will differ not only between communities and industries but also from person to person depending on their individual value systems, perceptions of and attitude to risk, and ability to capitalize on opportunities (see also 25.4.3).

25.11. Filling Knowledge Gaps to Improve Management of Climate Risks

The wide range of projected rainfall changes (averages and extremes) and their hydrological amplification are key uncertainties affecting the scale and urgency of adaptation in agriculture, forestry, water resources, some ecosystems, and wildfire and flood risks. For ecosystems, agriculture and forestry, these uncertainties are compounded by limited knowledge of responses of vegetation to elevated CO_2, changes in ocean pH, and interactions with changing climatic conditions. The uncertainties in future impacts are most critical for decisions with long lifetimes, such as capital infrastructure investment or large-scale changes in land- and water-use. Uncertainties about the rate of sea level rise, and changes in storm paths and intensity, add to challenges for infrastructure design. The use of multi-model means and a narrow set of emissions scenarios in many past studies implies that the full set of climate-related risks and management options remains incompletely explored.

Understanding of ecological and physiological thresholds that, once exceeded, would result in rapid changes in species, ecosystems and their services, is still very limited. The literature is noticeably sparse in New Zealand and for arid Australia. These knowledge gaps are compounded by limited information about the effect of global climate change on patterns of natural climate variability, such as ENSO. Better understanding the effect of evolving natural climate variability and long-term trends, along with rising CO_2 concentrations, on pests, invasive species and native and managed ecosystems could support more robust ecosystem-based adaptation strategies.

Vulnerability of human and managed systems depends critically on future socio-economic characteristics. Research into psychological, economic, social and cultural dimensions of vulnerability, adaptive capacity and underpinning values remains limited and poorly integrated with bio-physical studies. This limits the level of confidence in conclusions regarding future vulnerabilities and the feasibility and effectiveness of adaptation strategies.

These multiple, persistent and structural uncertainties imply that, in most cases, adaptation requires an iterative risk management process. While decision-support frameworks are being developed, it remains unclear to what extent existing governance and institutional arrangements will be able to support more transformational responses, particularly where competing public and private interests and particularly vulnerable groups are involved. The enabling or constraining influences on adaptation from interactions among market forces, institutions, governance, policy and regulatory environments have only recently begun to attract research attention, mostly in Australia.

Climate change impacts, adaptation and mitigation responses in other world regions will affect Australasia, but our understanding of this remains very limited. Existing studies suggest that transboundary effects, mediated mostly via trade but potentially also migration, can be of similar if not larger scale than direct domestic impacts of climate change for economically important sectors such as agriculture and tourism. However, scenarios used in such studies tend to be highly simplified. Effective management of risks and opportunities in these sectors would benefit from better integration of relevant global scenarios of climatic and socio-economic changes into studies of local vulnerability and adaptation options.

Frequently Asked Questions

FAQ 25-1: How can we adapt to climate change if projected future changes remain uncertain?

[to be inserted at end of Section 25.4.2]

Many existing climate change impact assessments in Australia and New Zealand focus on the distant future (2050 to 2100). When contrasted with more near-term non-climate pressures, the inevitable uncertainty of distant climate impacts can impede effective adaptation. Emerging best practice in Australasia recognises this challenge and instead focuses on those decisions that can and will be made in the near future in any case, along with the 'lifetime' of those decisions, and the risk from climate change during that lifetime. Thus, for example, the choice of next year's annual crop, even though it is greatly affected by climate, only matters for a year or two and can be adjusted relatively quickly. Even land-use change among cropping, grazing and forestry industries has demonstrated significant flexibility in Australasia over the space of a decade. When the adaptation challenge is reframed as *implications for near-term decisions*, uncertainty about the distant future becomes less problematic and adaptation responses can be better integrated into existing decision-making processes and early warning systems.

Some decisions, such as those about long-lived infrastructure and spatial planning and of a public good nature, must take a long-term view and deal with significant uncertainties and trade-offs between short- and long-term goals and values. Even then, widely used techniques can help reduce challenges for decision-making – including the 'precautionary principle', 'real options', 'adaptive management', 'no regrets strategies', or 'risk hedging'. These can be matched to the type of uncertainty but depend on a regulatory framework and institutions that can support such approaches, including the capacity of practitioners to implement them robustly.

Adaptation is not a one-off action but will take place along an evolving pathway, in which decisions will be revisited repeatedly as the future unfolds and more information comes to hand (see Figure 25-3). Although this creates learning opportunities, successive short-term decisions need to be monitored to avoid unwittingly creating an adaptation path that is not sustainable as climate change continues, or which would cope only with a limited sub-set of possible climate futures. This is sometimes referred to as maladaptation. Changing pathways – for example, shifting from on-going coastal protection to gradual retreat from the most exposed areas – can be challenging and may require new types of interactions among governments, industry and communities.

[INSERT FIGURE 25-3 HERE
Adaptation as an iterative risk management process. Individual adaptation decisions comprise well known aspects of risk assessment and management (top left panel). Each decision occurs within and exerts its own sphere of influence, determined by the lead- and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single 'correct' adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations and goals.]

FAQ 25-2: What are the key risks from climate change to Australia and New Zealand?

[to be inserted at end of Section 25.10.3]

Our assessment identifies eight key regional risks from climate change. Some impacts, especially on ecosystems, are by now difficult to avoid entirely. Coral reef systems have a limited ability to adapt naturally to further warming and an increasingly acidic ocean. Similarly, the habitat for some mountain or high elevation ecosystems and their associated species is shrinking inexorably with rising temperatures. This implies substantial impacts and some losses even under scenarios of limited warming. Other risks, however, can be reduced substantially by adaptation, combined with globally effective mitigation. These include potential flood damages from more extreme rainfall in most parts of Australia and New Zealand; constraints on water resources from reducing rainfall in southern Australia; increased health risks and infrastructure damages from heat waves in Australia; and, increased economic losses, risks to human life and ecosystem damage from wildfires in southern Australia and many parts of New Zealand. A third set of risks is particularly challenging to manage robustly because the severity of potential impacts varies widely across the range of climate projections, even for a given temperature increase. These concern damages to coastal infrastructure and low-lying ecosystems from continuing sea level rise, where damages would be widespread if sea level turns out to be at the upper end of current scenarios; and, threats to agricultural production in both far south-eastern and far south-western Australia, which would affect ecosystems and rural communities severely at the dry end of projected rainfall changes. Even though some of these key risks are more likely to materialise than others, and they differ in the extent that they can be managed by adaptation and mitigation, they all warrant attention from a risk management perspective, given their potential major consequences for the region.

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Table 25-1: Observed and projected changes in key climate variables, and (where assessed) the contribution of human activities to observed changes. For further relevant information see WGI Chapters 3, 6 (ocean changes, including acidification), 11, 12 (projections), 13 (sea level), and 14 (regional climate phenomena). (*) *medium confidence*, (**) *high confidence*, (***) *very high confidence*, (****) *virtually certain*

Climate variable	*Observed change*	*Direction of projected change*	*Examples of projected magnitude of change (relative to ~1990, unless otherwise stated)*	*Additional comments*
Mean air temperature	***Aus:*** Increased by 0.09 ± 0.03°C per decade since 1911[1] (***) ***NZ:*** Increased by 0.09 ± 0.03°C per decade since 1909[2] (***)	***Aus and NZ:*** Increase[3-8] (****); greatest over inland Aus and least in coastal areas and NZ[5-8] (***)	***Aus:*** 0.6-1.5°C (2030 A1B), 1.0-2.5°C (2070 B1), 2.2-5.0°C (2070 A1FI)[3] ***NZ:*** 0.3-1.4°C (2040 A1B), 0.7-2.3°C (2090 B1), 1.6-5.1°C (2090 A1FI)[5] *CMIP5 RCP4.5, rel. to ~1995[9]:* ***N Aus:*** 0.3-1.6°C (2016-2035), 0.7-2.6°C (2046-2065) ***S Aus & NZ:*** 0.1-1.0°C (2016-2035), 0.6-1.7°C (2046-2065)	***Aus****:* A significant contribution to observed change attributed to anthropogenic climate change[10] (**) with some regional variations attributed to atmospheric circulation variations[11,12] ***NZ:*** Observed change partially attributed to anthropogenic climate change[13] (*)
Sea surface temperature	***Aus:*** Increased by about 0.12°C per decade for NW&NE Aus and by about 0.2°C per decade for SE Aus since 1950[14,15] (***) ***NZ:*** Increased by about 0.07°C per decade over 1909-2009[2] (***)	**Aus and NZ:** Increase[3,7,8] (***) with greater increase in the Tasman sea region (*) [3,7]	***Aus:*** 0.6-1.0°C (2070 B1) and 1.6-2.0°C (2070 A1FI) for southern coastal and 1.2-1.5°C (2070 B1) and 2.2-2.5°C (2070 A1FI) elsewhere[3] ***NZ:*** Similar to projected changes in mean air temperature for coastal waters[5]	
Air temperature extremes	***Aus and NZ:*** Significant trend since 1950: cool extremes have become rarer and hot extremes more frequent and intense[16-19] (**).The Australian heatwave of 2012/13 was exceptional in heat, duration and spatial extent [20].	***Aus and NZ:*** Hot days and nights more frequent and cold days and cold nights less frequent during the 21st century[3,5,21-24] (**)	***Aus:*** Hot days in Melbourne (>35°C max.) increase by 20-40% (2030 A1B), 30-90% (2070 B1) and 70-190% (2070 A1FI)[3] ***NZ:*** Spring and autumn frost-free land to at least triple by 2080s[24]; up to 60 more hot days (>25°C max.) for northern areas by 2090[5]	***Aus****:* Observed trends partly attributable to anthropogenic climate change (**) as they are consistent with mean warming and historical simulations[18,19,21,25], although other factors may have contributed to high extremes during droughts[26-28]
Precipitation	***Aus:*** Late autumn/winter decreases in SW Aus since the 1970s and in SE Aus since the mid 1990s, and annual increases in NW Aus since the 1950s[29-31] (***) ***NZ:*** Mean annual rainfall increased over 1950-2004 in the south and west of the South Island and west of the North Island, and decreased in the north-east of the South Island and east and north of the North Island[32] (***)	***Aus:*** Annual decline in SW Aus (**), elsewhere on most of the southern (*) and NE (*low confidence*) continental edges, with reductions strongest in the winter half year[3,4,9,33-35] (**). Direction of annual change elsewhere is uncertain[3,35,36] (Figure 25.1) (**) ***NZ:*** In the South Island, annual increase in the west and south and decrease in north-east. In the North Island, increase in the west and decrease in eastern and northern regions [5,34,37] (Figure 25.1) (*)	***Aus:*** For 2030 A1B, annual changes of-10% to +5% (N Aus) and -10% to 0% (S Aus), for 2070 B1, -15% to +7.5% (N&E Aus) and -15% to 0% (S Aus), and for 2070 A1FI, -30% to +20% (N&E Aus) and -30% to +5% (S Aus), with larger changes seasonally[3] ***NZ:*** For 2040 A1B, annual changes of -5% to +15% (S&W) and -15% to +10% (N&E) and for 2090 A1B, -10% to +25% (S&W) and -20% to +15% (N&E) based on downscaled projections with larger changes seasonally[5,37]	***Aus:*** Observed decline in SW is related to atmospheric circulation changes[38-40] (***), other factors[41], and partly attributable to anthropogenic climate change[40-43] (**). The recent SE rainfall decline is also related to circulation changes[31,44-46] (**), with some evidence of an anthropogenic component[47] ***NZ:*** Observed trends related to increased westerly winds[32]. Projected annual trends dominated by winter and spring trends related to increased westerlies[5]
Precipitation extremes	***Aus:*** Indices of annual daily extremes (e.g. 95th and 99th percentile rainfalls) show mixed or insignificant trends[21,48], but significant increase is evident in recent decades for shorter duration (sub-daily) events[49,50] (**) ***NZ:*** Extreme annual 1-day rainfall decrease in north and east and increase in west since 1930[32] (*)	***Aus and NZ:*** Increase in most regions in the intensity of rare daily rainfall extremes (i.e. current 20 year return period events) and in short duration (sub-daily) extremes (*) and an increase in the intensity of 99 percentile daily extremes (*low confidence*)[5,8,21,51-56]	***Aus:*** For 2090 A2, CMIP3 give increases in the intensity of the 20 year daily extreme of around +200% to -25% depending on region and model[52] ***NZ:*** Increases of daily extreme rainfalls of around 8% per degree C are projected but with significant regional variations[5,56]	***Aus and NZ:*** The sign of observed trends mostly reflects trends in mean rainfall (e.g. there is a decrease in mean and daily extremes in SW Aus)[21,32,49]. Similarly, future increases in intensity of extreme daily rainfall are more likely where mean rainfall is projected to increase[3,5]

Drought	***Aus:*** Defined using rainfall only, drought occurrence over the period 1900-2007 has not changed significantly[57] (**) ***NZ:*** Defined using a soil water balance model, there has been no trend in drought occurrence since 1972[58] (*)	***Aus and NZ:*** Drought frequency is projected to increase in southern Australia [8,54,57,59,60] (*) and in many regions of New Zealand[58,61] (*)	***Aus:*** Occurrence under 2070 A1B and A2 ranges from a halving to 3 times more frequent in N. Aus, and 0-5 times more frequent in southern Aus[60] ***NZ:*** Time spent in drought in eastern and northern New Zealand is projected to double or triple by 2040[61]	***Aus:*** Regional warming may have led to an increase in hydrological drought (*low confidence*)[62,63]
Winds	***Aus:*** Significant decline in storminess over SE Aus since 1885[64] (*), but inconsistent trends in wind observations since 1975[65,66] ***NZ:*** Mean westerly flow increased during the late 20th century (1978–1998), associated with the positive phase of the IPO[67,68]	***Aus:*** Increases in winds in 20-30°S band, with little change to decrease elsewhere, except for winter increases over Tasmania. Decrease to little change in extremes (99th percentile) over most of Australia except Tasmania in winter[69] (*) ***NZ:*** Mean westerly winds and extreme winds (based on projected changes in circulation patterns) are projected to increase, especially in winter[5,70] (*)	***Aus:*** Magnitude of simulated mean changes may exceed 10% under A1B for 2081-2100 relative to 1981-2000 [69] ***NZ:*** Mean westerly flow to increase by around 20% in spring and around 70% in winter, and to decrease by around 20% in summer and autumn, by 2090[5]	***Aus and NZ:*** Many of past and projected changes in mean wind speed can be related to changes in atmospheric circulation[43,67,68] ***NZ:*** Extreme westerlies and southerlies have slightly increased while extreme easterlies have decreased since 1960[13,71]
Mean sea level	***Aus:*** From 1900-2011 the average rate of relative sea level rise (SLR) was 1.4±0.6 mm/yr[72] (***) ***NZ:*** The average rate of relative SLR was 1.7±0.1 mm/yr over 1900-2009[73] (***)	***Aus and NZ:*** Regional sea level rise will *very likely* exceed the 1971-2000 historical rate, consistent with global mean trends[74]. Mean sea level will continue to rise for at least several more centuries[74] (***)	***Aus:*** Off shore regional sea level rise may exceed 10% more than global SLR, see AR5 WGI Chap13, Figure 13.21[74] ***NZ***: Off shore regional sea level rise may be up to 10% more than global SLR[75]	***Aus and NZ**:* Satellite estimates of regional SLR for 1993-2009 are significantly higher than those for 1920-2000, partly reflecting climatic variability[72,73,76,77] ***NZ:*** Allowing for glacial isostatic adjustment, absolute observed SLR is around 2.0mm/yr[73,78]
Extreme sea level	***Aus and NZ:*** Extreme sea levels have risen at a similar rate to global SLR[79]	***Aus and NZ:*** Projected mean SLR will lead to large increases in the frequency of extreme sea level events (***), with other changes in storm surges playing a lesser role[80-83]	***Aus:*** An increase of mean sea level by 0.1m increases the frequency of an extreme sea level event by a factor of between 2 and 10 over southeastern Australia depending on location [80-82],	
Fire weather	***Aus:*** Increased since 1973(**) with 24 out of 38 sites showing increases in the 90th percentile of the McArthur Forest Fire Danger index[84]	***Aus:*** Fire weather is expected to increase in most of southern Australia due to hotter and drier conditions (**), based on explicit model studies carried out for SE Australia [85-88], and change little or decrease in NE[88] (*) ***NZ:*** Fire danger index is projected to increase in many areas[89] (*)	***Aus:*** Increase in days with very high and extreme fire danger index by 2-30% (2020), 5-100% (2050) (using B1 and A2 and two climate models, and 1973-2007 base)[85] ***NZ:*** Increase in days with very high and extreme fire danger index from around 0 to 400% (2040) and 0 to 700% (2090) (using A1B,16 CMIP3 GCMs)[89]	***Aus:*** For the example of Canberra, the projected changes represent the current 17 days per year increasing to 18-23 days in 2020 and 20-33 days in 2050[85]
Tropical cyclones and other severe storms	***Aus:*** No regional change in the number of tropical cyclones (TCs) or in the proportion of intense TCs over 1981-2007[90] (*), but frequency of severe landfalling TCs in NE Aus has declined significantly since the late 19th Century[91] and east-west distribution changed since 1980.[92] There has been no trend in environments suitable for severe thunderstorms[93]	***Aus:*** Tropical cyclones are projected to increase in intensity and stay similar or decrease in numbers[9,94], and occur further south[94] (*low confidence*) ***NZ:*** Projected increase in the average intensity of cyclones in the south during winter, but a decrease elsewhere[70] (*)	***Aus:*** Modelling study shows a 50% reduction in TC occurrence for 2051-2090 relative to 1971-2000, increases in intensity of the modelled storms, and occur around 100km further south[94] ***NZ:*** Occurrence of conditions conducive to convective storm development is projected to increase by 3–6% by 2070-2100 (A2), relative to 1970-2000, with the largest increases over the South Island[70]	***Aus:*** Regional research on convective storms is limited but studies have shown a projected decrease in the frequency of cool-season tornadoes[95], and hail[3] in southern Australia, and increases in the frequency and intensity of hail in the Sydney region[3,96]

Snow and ice	***Aus:*** Late season significant snow depth decline at three out of four Snowy mountain sites over 1957-2002[97] (**) ***NZ:*** Ice volume declined by 36-61% from the mid-late 1800s to the late 1900s[98-100], with glacier volume reducing by 15% between 1976 and 2008[101] (**)	***Aus:*** Both snow depth and area are projected to decline[97] (***) ***NZ:*** Snowline elevations are projected to rise, and winter snow volume and days with low elevation snow cover are projected to decrease[5,102,103] (***)	***Aus:*** Area with at least 30 days cover annually projected to decline 14-54% (2020) and 30-93% (2050)[97] ***NZ:*** By 2090, peak snow accumulation is projected to decline by 32-79% at 1000m and by 6-51% at 2000 m[103]	***NZ:*** Atmospheric circulation variations can enhance or outweigh multi-decadal trends in ice volume over time scales of up to two decades[104,105]

References: [1] Fawcett *et al.* (2012); [2] Mullan *et al.* (2010); [3] CSIRO and BoM (2007); [4] Moise and Hudson (2008); [5] MfE (2008b); [6] AR5-WGI-Atlas-AI68-69; [7] AR5-WGI-Ch11; [8] AR5-WGI-Ch12; [9] AR5-WGI-Ch14; [10] Karoly and Braganza (2005); [11] Hendon *et al.* (2007); [12] Nicholls *et al.* (2010); [13] Dean and Stott (2009); [14] Lough (2008); [15] Lough and Hobday (2011); [16] Chambers and Griffiths (2008); [17] Gallant and Karoly (2010); [18] Nicholls and Collins (2006); [19] Trewin and Vermont (2010); [20] BOM (2013); [21] Alexander and Arblaster (2009); [22] Tryhorn and Risbey (2006); [23] Griffiths *et al.* (2005); [24] Tait (2008); [25] Alexander *et al.* (2007); [26] Deo *et al.* (2009); [27] McAlpine *et al.* (2007); [28] Cruz *et al.* (2010); [29] Hope *et al.* (2010); [30] Jones *et al.* (2009); [31] Gallant *et al.* (2012); [32] Griffiths (2007); [33] Timbal and Jones (2008); [34] AR5-WGI-Atlas-AI70-71; [35] Irving *et al.* (2012); [36] Watterson (2012); [37] Reisinger *et al.* (2010); [38] Bates *et al.* (2008); [39] Frederiksen and Frederiksen (2007); [40] Hope *et al.* (2006); [41] Timbal *et al.* (2006); [42] Cai and Cowan (2006); [43] Frederiksen *et al.* (2011); [44] Cai *et al.* (2011); [45] Nicholls (2010); [46] Smith and Timbal (2010); [47] Timbal *et al.* (2010a); [48] Gallant *et al.* (2007); [49] Westra and Sisson (2011); [50] Jakob *et al.* (2011); [51] Abbs and Rafter (2009); [52] Rafter and Abbs (2009); [53] Kharin *et al.* (2013); [54] IPCC-SREX-Chapter-3; [55] Westra *et al.* (2013); [56] Carey-Smith *et al.* (2010); [57] Hennessy *et al.* (2008a); [58] Mullan *et al.* (2005); [59] Kirono and Kent (2010); [60] Kirono *et al.* (2011); [61] Clark *et al.* (2011); [62] Cai and Cowan (2008); [63] Nicholls (2006); [64] Alexander *et al.* (2011); [65] McVicar *et al.* (2008); [66] Troccoli *et al.* (2012); [67] Parker *et al.* (2007); [68] Mullan *et al.* (2001); [69] McInnes *et al.* (2011a); [70] Mullan *et al.* (2011); [71] Salinger *et al.* (2005); [72] Burgette *et al.* (2013); [73] Hannah and Bell (2012); [74] AR5-WGI-Ch13; [75] Ackerley *et al.* (2013); [76] CSIRO and BoM (2012); [77] Meyssignac and Cazenave (2012); [78] Hannah (2004); [79] Menendez and Woodworth (2010); [80] McInnes *et al.* (2009); [81] McInnes *et al.* (2011b); [82] McInnes *et al.* (2012); [83] Harper *et al.* (2009); [84] Clarke *et al.* (2012); [85] Lucas *et al.* (2007); [86] Hasson *et al.* (2009); [87] Cai *et al.* (2009a); [88] Clarke *et al.* (2011); [89] Pearce *et al.* (2011); [90] Kuleshov *et al.* (2010); [91] Callaghan and Power (2011); [92] Hassim and Walsh (2008); [93] Allen and Karoly (2013); [94] Abbs (2012); [95] Timbal *et al.* (2010b); [96] Leslie *et al.* (2008); [97] Hennessy *et al.* (2008b); [98] Hoelzle *et al.* (2007); [99] Ruddell (1995); [100] Chinn (2001); [101] Chinn *et al.* (2012); [102] Fitzharris (2004); [103] Hendrikx *et al.* (2012); [104] Purdie *et al.* (2011); [105] Willsman *et al.* (2010).

Table 25-2: Constraints and enabling factors for institutional adaptation processes in Australasia.*

Constraint	**Enabling factors**
Uncertainty of projections	Improved guidance and tools to manage uncertainty and support adaptive management [1-8] Increased focus on lead and consequence time of decisions and link with current climate variability and related risks [9-13] Increased communication between practitioners and scientists to identify and provide decision-relevant data and context [2,3,11,13-17]
Availability and cost of data and models	Central provision of relevant core climate and non-climate data, including regional scenarios of projected changes [4,5,7,9,18,19] National first-pass risk assessments [4,5,7,8,18,20-24]
Limited financial and human capability and capacity; time lag in developing expertise	Support for pilot projects [4,8,15,18,24,25] Building capacity through institutional commitment and learning [3,5,11,17,23,26-28] Central databases on guidance, tools, methodologies, case studies [4,5,7,18,24] Regional partnerships and collaborations, knowledge networks [3,4,8,13,15,17,26,28-30]
Unclear problem definition and goals; unclear standards for risk assessment methodologies and decision support tools; limited monitoring and evaluation	Explicit but iterative framing and scoping of adaptation challenge, to reflect alternative entry points for stakeholders while meeting expectations of project sponsors to ensure long-term support [3,11,17,31-34] Tailoring decision-making frameworks to specific problems [1,2,6,17,35,36] Criteria and tools to monitor and evaluate adaptation success [7,18,37-39]
Unclear or contradictory legislative frameworks and responsibilities, unclear liabilities	Clear and coordinated legislative frameworks [5,8,9,15,24,40-45] Defined responsibilities for public and private actors, including liabilities from acting and failure to act [8,9,11,24,41,44,46] Legally binding guidance on the incorporation of climate change in planning mechanisms [5,7,8,15,38,40]
Static planning mechanisms and practice; competing mandates and fragmentation of policies; disciplinary voids or single approaches	Whole-of-council approach to climate adaptation to break up institutional and professional silos [15,33,47] Long-term policy commitments and implementation support [5,18,26,33,48] Increased policy coherence across sectors, regulations and levels of government [9,26,28,40,42,43,47] Enabling risk-based flexible land-use decisions [4,5,9,49] Strengthening multi-disciplinarity across professional fields [14,29,48]
Lack of political leadership; short election cycles; limited community support, participation and awareness for adaptation	Legally binding guidance and clarification of liabilities and duty of care to reduce dependence on individual leadership [5,7-9,15,24,38,40,46,49] Consistent but audience-specific communication of current and potential future vulnerability and implications for community values [4,5,7,26,42,43,50] Comprehensible communication of and access to response options, and their consistency with wider development plans [7,26,28,33,39,42,43] Clearly identified entry points for public participation [17,34,38,39,42,48,51-53]

* Note: The relevance of each constraint varies among organisations, sectors and location. Some enabling factors are only beginning to be implemented or have only been suggested in the literature, hence their effectiveness cannot yet be evaluated. Entries for enabling factors exclude generic mechanisms, such as insurance (see Box 25-7), emergency management and early warning systems, and funding for pilot studies, capital infrastructure upgrades or retreat schemes.

References: [1] Randall *et al.* (2012); [2] Verdon-Kidd *et al.* (2012); [3] Webb *et al.* (2013); [4] Mukheibir *et al.* (2013); [5] Lawrence *et al.* (2013b); [6] Nelson *et al.* (2008); [7] Britton (2010); [8] Gurran *et al.* (2008); [9] Productivity Commission (2012); [10] Stafford-Smith *et al.* (2011); [11] Johnston *et al.* (2013); [12] Park *et al.* (2012); [13] Power *et al.* (2005); [14] Reisinger *et al.* (2011); [15] Smith *et al.* (2008); [16] Stafford-Smith (2013); [17] Yuen *et al.* (2012); [18] Webb and Beh (2013); [19] Roiko *et al.* (2012); [20] DCCEE (2011); [21] DCC (2009); [22] Baynes *et al.* (2012); [23] Smith *et al.* (2010); [24] SCCCWEA (2009); [25] DSEWPC (2011); [26] Low Choy *et al.* (2012); [27] Gardner *et al.* (2010); [28] Fidelman *et al.* (2013); [29] Mustelin *et al.* (2013); [30] Serrao-Neumann *et al.* (2013); [31] Fünfgeld *et al.* (2012); [32] Kuruppu *et al.* (2013); [33] Britton *et al.* (2011); [34] Alexander *et al.* (2012); [35] Maru *et al.* (2011); [36] Preston *et al.* (2008); [37] Norman *et al.* (2012); [38] Rouse and Norton (2010); [39] Preston *et al.* (2011); [40] Rive and Weeks (2011); [41] Abel *et al.* (2011); [42] Norman (2009); [43] Gurran *et al.* (2006); [44] McDonald (2013); [45] Minister of Conservation (2010); [46] McDonald (2010); [47] Measham *et al.* (2011); [48] Rouse and Blackett (2011); [49] McDonald (2011); [50] Hine *et al.* (2013); [51] Burton and Mustelin (2013); [52] Hobson and Niemeyer (2011); [53] Gardner *et al.* (2009a).

Table 25-3: Examples of detected changes in species, natural and managed ecosystems, consistent with a climate change[1] signal, published since the AR4. Confidence in detection of change is based on the length of study, and the type, amount and quality of data in relation to the natural variability in the particular species or system. Confidence in the role of climate being a major driver of the change is based on the extent to which the detected change is consistent with that expected under climate change, and to which other confounding or interacting non-climate factors have been considered and been found insufficient to explain the observed change.

Type of change and nature of evidence	**Examples**	**Time scale of observations**	**Confidence in the detection of biological change**	**Potential climate change driver(s) [1]**	**Confidence in the role of climate vs other drivers**
Morphology *Limited evidence* (1 study)	Declining body size of southeast Australian passerine birds, equivalent to ~7° latitudinal shift (Gardner *et al.*, 2009)	~100 years	***medium*** trend significant for 4 out of 8 species, two other species show same trend but not statistically significant	Warming air temperatures ~1.0ºC over same period	***medium*** Nutritional cause discounted
Geographic distribution *High agreement, robust evidence* for many marine species & mobile terrestrial species	Southerly range extension of the barrens-forming sea urchin *Centrostephanus rodgersii* from the New South Wales coast to Tasmania; flow on impacts to marine communities including lobster fishery; shift of 160 km per decade over 30 years (Ling, 2008; Ling *et al.*, 2008; Ling *et al.*, 2009; Banks *et al.*, 2010)	~30-50 years (first recorded in Tasmania late 1970s)	***high***	Increased sea surface temperature (SST), Ocean warming in SE Australia, increased southerly penetration of the East Australian Current (EAC), 350 km over 60 years	***high***
	Forty-five fish species, representing 27 families (about 30% of the inshore fish families occurring in the region), exhibited major distributional shifts in Tasmania (Last *et al.*, 2011)	distributions from late 1880s, 1980s and present (1995-now)	***high***	Increased SST SE Australia, increased southerly penetration of EAC	***medium*** Changed fishing practices have potentially contributed to trends
	Southward range shift of intertidal species (average minimum distance 116 km) off west coast of Tasmania; 55% species recorded at more southerly sites, only 3% species expanded to more northerly sites (Pitt *et al.*, 2010)	~50 years Sites resampled 2007-2008, compared with 1950s	***medium***	Increased SST in SE Australia (average 0.22ºC per decade), increased southerly penetration of the EAC, 350 km over 60 years	***medium***

Life cycles *Robust evidence, medium agreement*; increasing documentation of advances in phenology in some species (mainly migration and reproduction in birds, emergence in butterflies, flowering in plants) but also significant trends towards later life cycle events in some taxa (see meta-analysis for Southern Hemisphere phenology (Chambers *et al.*, 2013a)	Significant advance in mean emergence date of 1.5 days per decade (1941-2005) in the Common Brown butterfly *Heteronympha merope* in Australia (Kearney *et al.*, 2010)	65 years	***high***	Increase in local air temperatures of 0.16°C per decade (1945-2007)	***high*** Advance consistent with physiologically based model of temperature influence on development
	Advances in spring phenology of migratory birds, and both advances and delays in phenology in other seasons at multiple Australian sites: meta-analysis of 52 species and 145 datasets (Chambers *et al.*, 2013b)	Multiple time periods from 1960s, all included 1990s and 2000s	***high***	Local climate trends (increasing air temperature, decreased raindays) were more important than broad-scale drivers such as the Southern Oscillation Index. Strongest associations were with decreased raindays.	***high*** *No other potential confounding facotrs identified*
	Earlier wine-grape ripening at 9 of 10 sites in Australia (Webb *et al.*, 2012)	Multiple time periods up to 64 years (average 41 years)	***high***	Increased length of growing season, increased average temperature and reduced soil moisture	***medium*** Changed husbandry techniques, resulting in lower crop yields, may have contributed to trend
	Timing of migration of glass eels, *Anguilla* spp. advanced by several weeks in Waikato River, North island, New Zealand (Jellyman *et al.*, 2009)	30 years (2004-2005 compared to 1970s)	***medium***	Warming water temperatures in spawning grounds	***low*** Changes in discharge discounted as contributing factor
Marine productivity *Limited evidence, medium agreement*	Otolith (“ear stone”) analyses in long-lived Pacific fish indicates significantly increased growth rates for shallow-water species (<250 m) (3 of 3 species), reduced growth rates of deep-water (>1000 m) species (3 of 3 species); no change observed in the 2 intermediate-depth species (Thresher *et al.*, 2007)	Birth years ranged 1861-1993 (fish 2-128 years old)	***high***	Increasing growth rates in species in top 250m associated with warming SST, declining growth rates in species >1000m associated with long-term cooling (as indicated by Mg/Ca ratios and delta^{18}O in deep water corals)	***medium*** Changed fishing pressure may have contributed to trend
	~50% decline in growth rate and biomass of spring phytoplankton bloom in western Tasman Sea (Thompson *et al.*, 2009)	60 year dataset; decline recorded over period 1997-2007	***high***	Increased SST and extension EAC associated with reduced nutrient availability	***medium***

Vegetation change *Limited agreement & evidence*; interacting impacts of changed land practices, altered fire regimes, increasing atmospheric CO_2 concentration and climate trends difficult to disentangle	Expansion of monsoon rainforest at expense of eucalypt savanna and grassland in Northern Territory, Australia (Banfai and Bowman, 2007; Bowman *et al.*, 2010)	~40 years	***medium***	Increases in rainfall and atmospheric CO_2	***medium*** Changes in fire regimes and land management practices may have contributed to trend
	Net increase in mire wetland extent (10.2%) and corresponding contraction of adjacent eucalypt woodland in seven sub-catchments in south east Australia (Keith *et al.*, 2010)	Weather data covers >40 years (depending on parameter); vegetation mapping from 1961-1998	***medium***	Decline in evapo-transpiration	***low*** Resource exploitation, fire history and autogenic mire development discounted
Freshwater communities *Limited evidence* (1 study)	Decline in families of macroinvertebrates that favour cooler, faster-flowing habitats in New South Wales streams and increase in families favouring warmer and more lentic conditions (Chessman, 2009)	13 years (1994-2007)	***medium***	Increasing water temperatures and declining flows	***low*** Variation in sampling, changes in water quality, impacts of impoundment and water extraction may have contributed to trends
Disease *Limited evidence, robust agreement*	Emergence and increased incidence of coral diseases including white syndrome (since 1998), and black band disease (since 1993-4) (Bruno *et al.*, 2007; Sato *et al.*, 2009; Dalton *et al.*, 2010)	1998 onwards	***medium***	Increasing SST	***high***
Coral reefs *Robust evidence & high agreement*	Multiple mass bleaching events since 1979 (see 25.6.2, 30.5)	1979 onwards	***high***	Increasing SST	***high***
	Calcification of *Porites* on GBR declined 21% (1971-2003, 4 reefs; Cooper *et al.*, 2008); about 11% (1990-2005, 69 reefs; De'ath *et al.*, 2009)	1971-2003; 1990-2005	***high***	Increasing SST	***high*** Changes in water quality discounted

Table 25-4: Examples of potential consequences of climate change for invasive and pathogenic species relevant to Australia and New Zealand, with consequence categories based on Hellman et al. (2008).

Consequence	Projected change	Organism/Ecosystem affected
altered mechanisms of transport and introduction	Increased risk of introduction of Asiatic Citrus Psyllid, (*Diaphorina citri*), vector of the disease huanglongbing [1]	Australian citrus industry and native citrus and other rutaceaous species and endemic psyllid fauna
altered distribution of existing invasive & pathogenic species	*Nassella neesiana* (Chilean needle grass): increased droughts favour establishment [2]	Managed pasture in New Zealand
	Warming and drying may encourage the spread of existing invasives such as *Pheidole megacephala* in New Zealand and provide suitable conditions for other exotic ant species if they invade [3]	Human health and potentially agricultural and natural ecosystems
	Reduced climatic suitability for exotic invasive grasses in Australia (11 species including *Nassella* sp.) [4]	Australian rangeland
	Range of the invasive weed *Lantana camara* (lantana) projected to extend from Northern Australia to Victoria, South Australia and Tasmania [5]	Multiple
	Projected increases in the range of three recently naturalised sub-tropical plants (*Archontophoenix cunninghamiana*, *Psidium guajava*, *Schefflera actinophylla*) [6]	Native ecosystems in New Zealand
altered climatic constraints on invasive & pathogenic species	Queensland fruit fly (*Bactrocera tryoni*) moving southwards [7]	Australian horticulture
	Significant association between amphibian declines in upland rainforests of north Queensland and three consecutive years of warm weather suggests future warming could increase the vulnerability of frogs to chytridiomycosis caused by the chytrid fungus *Batrachochytrium dendrobatadis* [8]	Native frogs
altered impact of existing invasive & pathogenic species	*Fusarium pseudograminearum* causing crown rot increases under elevated CO_2 [9]	Australian wheat
	Increased abundance of the root-feeding nematode *Longidorus elongatus* under elevated CO_2 [10]	New Zealand pasture
	Increased severity of Swiss needle cast disease caused by *Phaeocryptopus gaeumannii* [11]	Douglas fir plantations in New Zealand, impact more severe in North Island
altered effectiveness of management strategies	Light brown apple moth, *Epiphyas postvittana* (Walker) (*Lepidoptera:Tortricidae*) reduction in natural enemies due to asynchrony and loss of host species [12]	Australian horticulture
	Projected changes in the efficacy of five biological control systems demonstrating a range of potential disruption mechanisms [13]	Pastoral and horticultural systems in New Zealand

References: [1] Finlay *et al.* (2009); [2] Bourdôt *et al.* (2012); [3] Harris and Barker (2007); [4] Gallagher *et al.* (2012a); [5] Taylor *et al.* (2012b); [6] Sheppard (2012); [7] Sutherst *et al.* (2000); [8] Laurance (2008); [9] Melloy *et al.* (2010); [10] Yeates and Newton (2009); [11] Watt *et al.* (2011b); [12] Thomson *et al.* (2010); [13] Gerard *et al.* (2012).

Table 25-5: Examples of co-beneficial climate change adaptation options for urban areas and barriers to their adoption. Options in italics are already widely implemented in Australia and New Zealand urban areas.

Climate impact	**Adaptation options**	**Co-benefits**	**Barriers to adoption**
Hot days and heatwaves [1-8]	Greening cities/roofs; *more green spaces*; *well-designed energy efficient buildings*; occupant behavioral change; standards for new and retrofitting of existing infrastructure and assets; new methods and material for transport infrastructure to withstand higher extreme temperature	Energy efficiency; reduced risk of blackouts; fewer health impacts; resilient infrastructure and assets; resilient community	Lack of standards; high installation costs; limited understanding of benefits; high individual discount rate; split of private costs and public benefits
Decreased water supply and drought [See Box 25-2 for more]	Supply augmentation (*water recycling*, *rainwater harvesting*, *increased storage*, desalinisation); *demand management*; *infrastructure upgrades*; *integrated urban sensitive design*	Water self-sufficiency for current and future demand/population; less pipe/storage leakage; reduced environmental impacts from abstraction	Potential health impacts of recycled water; lower than expected uptake of demand options and relaxation after crises; trade-offs between supply and demand management; cost and environmental impacts of some augmentation options
River and local flooding, coastal erosion and inundation [See Boxes 25-1 and 25-8 for more]	New standards and improvements to *building, water infrastructure (e.g. drainage and sewerage)* and transport infrastructure; *upgrades of protection systems*; *retaining floodplains/floodways*; restoring wetlands; buffers from hazard-prone areas; *raising minimum floor levels*; rezoning/ relocation	Reduced damages to homes and infrastructure and loss of life; decreased insurance premiums; habitat protection	High implementation cost especially if retrospective on existing stock; rezoning/ relocation can affect property prices and are highly contested
Severe storms and tropical cyclones [9-12]	New building design to withstand higher wind pressures; rezoning/relocation	Reduced damages to homes and infrastructure and loss of life; decreased insurance premiums	High implementation cost; rezoning/ relocation can affect property prices and are highly contested
Corrosion from increased atmospheric CO_2 levels [13,14]	Improved standards for construction using concrete; application of coatings for existing building stock	Reduced rates of carbonation-induced corrosion of concrete	Effectiveness of coatings varies with age and condition of concrete

References: [1] BRANZ (2007); [2] Coutts *et al.* (2010); [3] Moon and Han (2011); [4] Stephenson *et al.* (2010); [5] Williams *et al.* (2010); [6] CSIRO *et al.* (2007); [7] Taylor and Philp (2010); [8] QUT (2010); [9] Mason and Haynes (2010); [10] Wang *et al.* (2010b); [11] Stewart and Wang (2011); [12] Mason *et al.* (2013); [13] Stewart *et al.* (2012); [14] Wang *et al.* (2012).

Table 25-6: Examples of interactions between impacts and adaptation measures in different sectors. In each case, impacts or responses in one sector have the potential to conflict (cause negative impacts) or be synergistic (have co-benefits) with impacts or responses in another sector, or with another type of response in the same sector.

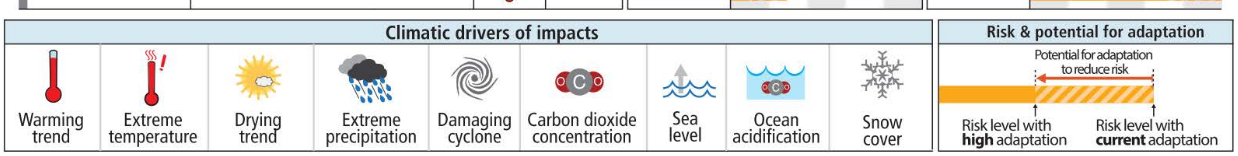
Primary goal	Sector(s) affected	Examples of interactions between impacts and adaptation responses
Reduction of bushfire risk in natural landscapes	Biodiversity, tourism	Potential for greater conflict between conservation managers and other park users in Kosciuszko National Park if increasing fire incidence causes park closures, either to reduce risk, or to rehabilitate vegetation after fires (Wyborn, 2009), e.g. Objectives of the Wildfire Management Overlay (WMO) in Victoria conflicts with vegetation conservation (Hughes and Mercer, 2009).
Reduction of risk to energy transmission from bushfires	Biodiversity, energy	Underground cabling would reduce both the susceptibility of transmission networks to fire and ignition sources for wild fires, thus reducing risks to ecosystems and settlements; constraints include significant investment cost, diverse ownership of assets and lack of an overarching national strategy (ATSE, 2008; Parsons Brinkerhoff, 2009; Linnenluecke *et al.*, 2011).
Protection of coastal infrastructure	Biodiversity, tourism	Seawalls may provide habitat but these communities have different diversity and structure to those developing on natural substrates (Jackson *et al.*, 2008); groynes potentially alter beach fauna diversity and community structure (Walker *et al.*, 2008); continuing hard protection against sea level rise results in long-term loss of coastal amenities (Gorddard *et al.*, 2012).
Avoidance of risks from sea level rise via relocation	Indigenous communities	Relocation can avoid increasing local pressures on communities from sea level rise but raises complex cultural, land rights, legal and economic issues, e.g. potential relocation of Torres Strait islander communities (Green *et al.*, 2010b; McNamara *et al.*, 2011).
Allocating scarce water resources via market instruments	Rural areas, agriculture, mining	Market based instruments such as water trading help allocation of scarce water resources to the highest value uses. The negative implications of this include potential loss of access to lower value users, which in some areas includes agriculture and drinking water supplies, with potentially significant social, environmental and wider economic consequences (Kiem and Austin, 2012).
Increased water security via augmentation of supply for urban and agricultural systems	Biodiversity, water demand management	Water storage can buffer urban settlements and agricultural systems against high variability in river flows, but altered flow regimes can have significant negative impacts on freshwater ecosystems (Bond *et al.*, 2008; Pittock *et al.*, 2008; Kingsford, 2011). Discharge from desalination plants (e.g. in Perth and Sydney) can lead to substantial local increases in salinity and temperature, and the accumulation of metals, hydrocarbons and toxic anti-fouling compounds in receiving waters (Roberts *et al.*, 2010); increasing supply can reduce the effectiveness of demand-side measures (Barnett and O'Neill, 2010; Taptiklis, 2011; Box 25-2).

Table 25-7: Examples of interactions between adaptation and mitigation measures (green rows denote synergies where multiple benefits may be realized, orange rows denote potential tradeoffs and conflicts; grey row gives an example of complex, mixed interactions). The primary goal may be adaptation or mitigation.

Primary goal	Sector(s) affected	Examples of interactions between adaptation and mitigation responses
Adaptation to decreasing snowfall	Biodiversity, energy use, water use	Snowmaking in the Australian Alps would require large additional energy and water resources by 2020 of 2500-3300 ML of water per month, more than half the average monthly water consumption by Canberra in 2004-05. Increased snowmaking negatively affects vegetation, soils and hydrology of subalpine-alpine areas (Pickering and Buckley, 2010; Morrison and Pickering, 2011; ABS, 2012a).
Air conditioning for heat stress	Health, energy use	Rising temperatures degrade building energy efficiency (Wang *et al.*, 2010a) and increase energy demand and associated CO_2 emissions if summer cooling needs are met by increased air conditioning (Stroombergen *et al.*, 2006; Thatcher, 2007; Wang *et al.*, 2010a).
Renewable wind energy production	Biodiversity	Wind-farms can have localised negative effects on bats and birds. However, risk assessment of the potential negative impacts of wind turbines on threatened bird species in Australia indicated low to negligible impacts on all species modelled (Smales, 2006).
Urban densification	Biodiversity, water, health	Higher urban density to reduce energy consumption from transport and infrastructure can result in loss of permeable surfaces and tree cover, intensify flood risks, and exacerbate discomfort and health impacts of hotter summers (Hamin and Gurran, 2009).
Water supply from desalination	Energy demand	Meeting increasing urban water demand via desalination plants increases energy demand and CO_2 emissions if this demand is met by increased fossil fuel energy generation (Barnett and O'Neill, 2010; Stamatov and Stamatov, 2010).
Secure food production in a warming climate	Nitrous oxide and methane emissions	Net greenhouse gas emissions intensity from dairy systems in southern Australia have been estimated to increase in future in several locations due to a changing climate and management responses (Cullen and Eckard, 2011; Eckard and Cullen, 2011). A shift towards perennial C4 grasses would increase methane emissions from grazing ruminants due to lower feed quality, but studies in south-west Australia suggest this could be more than offset by increased soil carbon storage (Thomas *et al.*, 2012; Bradshaw *et al.*, 2013).
Housing design to reduce peak energy demand	Energy use, infrastructure, health	Reducing peak energy demand through building design and demand management reduces vulnerability of electricity networks and transmission losses during heat waves (Parsons Brinkerhoff, 2009; Nguyen *et al.*, 2010), reduces heat stress during summer and provides health benefits during winter (Strengers, 2008; Howden-Chapman, 2010; Strengers and Maller, 2011; Ren *et al.*, 2012).
Energy from second-generation biofuels	Biodiversity, rural areas, agriculture	New crops such as oil mallees or other eucalypts may provide multiple benefits, especially in marginal areas, displacing fossil fuels or sequestering carbon, generating income for landholders (essential oils, charcoal, bio-char, biofuels), and providing ecosystem services including reducing erosion (Cocklin and Dibden, 2009; Giltrap *et al.*, 2009; McHenry, 2009).
Reduced emissions from fires	Biodiversity, livelihoods	Improved management of savanna fires to reduce the extent of high intensity late season fires could substantially reduce emissions as well as having significant benefits for biodiversity and indigenous employment (Russell-Smith *et al.*, 2009; Bradshaw *et al.*, 2013).
Reduce methane emissions from feral camels	Biodiversity, agriculture	Feral camels in Australia are projected to double from 1 to 2 million by 2020. Controlling their numbers to reduce methane emissions could have significant biodiversity benefits (NRMMC, 2010; Bradshaw *et al.*, 2013). Economic benefits of reduced grazing competition, infrastructure damage and greenhouse gases could outweigh costs of camel reductions (Drucker *et al.*, 2010).

Table 25-8: Key regional risks from climate change and the potential for reducing risk through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments by chapter authors, with evaluation of evidence and agreement in the supporting chapter sections. Each key risk is characterized on a scale from very low to very high and presented in three timeframes: the present, near-term (2030-2040), and long-term (2080-2100). For the near-term era of committed climate change (here, for 2030-2040), projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. For the longer-term era of climate options (here, for 2080-2100), risk levels are presented for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for a continuation of current adaptation and for a hypothetical highly adapted state. Relevant climate variables are indicated by icons. For a given key risk, change in risk level through time and across magnitudes of climate change is illustrated, but because the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks, sectors, or regions.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Impacts can be delayed but now appear very difficult to avoid entirely, even with combined globally effective mitigation and planned adaptation					
Significant change in community composition and structure of coral reef systems in Australia (*high confidence*)	Ability of corals to adapt naturally appears limited and insufficient to offset the detrimental effects of rising temperatures and acidification. Other options are mostly limited to reducing other stresses (water quality, tourism, fishing) and early warning systems; direct interventions such as assisted colonisation and shading have been proposed but remain untested at scale.		25.6.2, 30.5, Box CC-CR Box CC-OA	Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Loss of montane ecosystems and some native species in Australia (*high confidence*)	Direct adaptation options are limited, but reducing other stresses such as pests and diseases, predator control and enhancing connectivity of habitats provides immediate co-benefits; need to consider facilitating migration and assisted colonisation.		25.6.1	Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Impacts have the potential to be severe but can be reduced substantially by globally effective mitigation combined with adaptation					
Increased frequency and intensity of flood damage to infrastructure and settlements in Australia and New Zealand (*high confidence*)	Significant adaptation deficit in some regions to current flood risk; effective adaptation includes land-use controls and relocation as well as protection and accommodation of increased risk to ensure flexibility.		25.2, Table 25-1, Box 25-8, 25-9	Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Constraints on water resources in southern Australia (*high confidence*)	Water resources already struggling to meet unrestrained demand in many locations and exacerbated by projected population growth; effective adaptation relies on combination of demand and supply mechanisms.		25.5.1, Box 25-2, 25-9	Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Increased morbidity, mortality and infrastructure damages during heat waves in Australia (*high confidence*)	Vulnerability is exacerbated by population growth and ageing; transport and power infrastructure already severely stressed during heat waves in many regions, with significant financial costs from future upgrades.		25.7.4, 25.8.1	Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Wild fire damages to ecosystems and settlements and risks to human life in southern Australia and many parts of New Zealand (*high confidence*)	Part of integrated landscape management; trade-offs between different management objectives and settlement patterns and goals (biodiversity versus protection of human life and property).		Table 25-1, Box 25-6	Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Impacts whose severity depends on changes in climate variables that span a particularly large range; the most severe end would present major challenges					
Widespread damages to coastal infrastructure and low-lying ecosystems in Australia and New Zealand (*high confidence*)	Adaptation deficit in some locations to current coastal erosion and flood risk; successive building and protection cycles constrain flexible responses; effective adaptation includes land-use controls and ultimately relocation as well as protection and accommodation.		Table 25-1, 25.6.1, 25.6.2, Box 25-2, 25-9	Moderate sea level rise (AR5 WGI 13.5; Box 25-2) High sea level rise (>1m by 2100): Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Significant reduction in agriculture production in the Murray-Darling Basin and far south-eastern and south-western Australia (*high confidence*)	Immediate co-benefits from improved management of over-allocated water resources and balancing competing demands, but the extreme dry end would threaten agricultural production as well as ecosystems and some rural communities.		25.2, 25.6.1, 25.7.2, Table 25-1, Box 25-2, 25-5	Wet end of scenario (25.2, 25.5.2, Figure 25-4) Dry end of scenario: Present Near-term (2030-2040) 1.5°C Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high



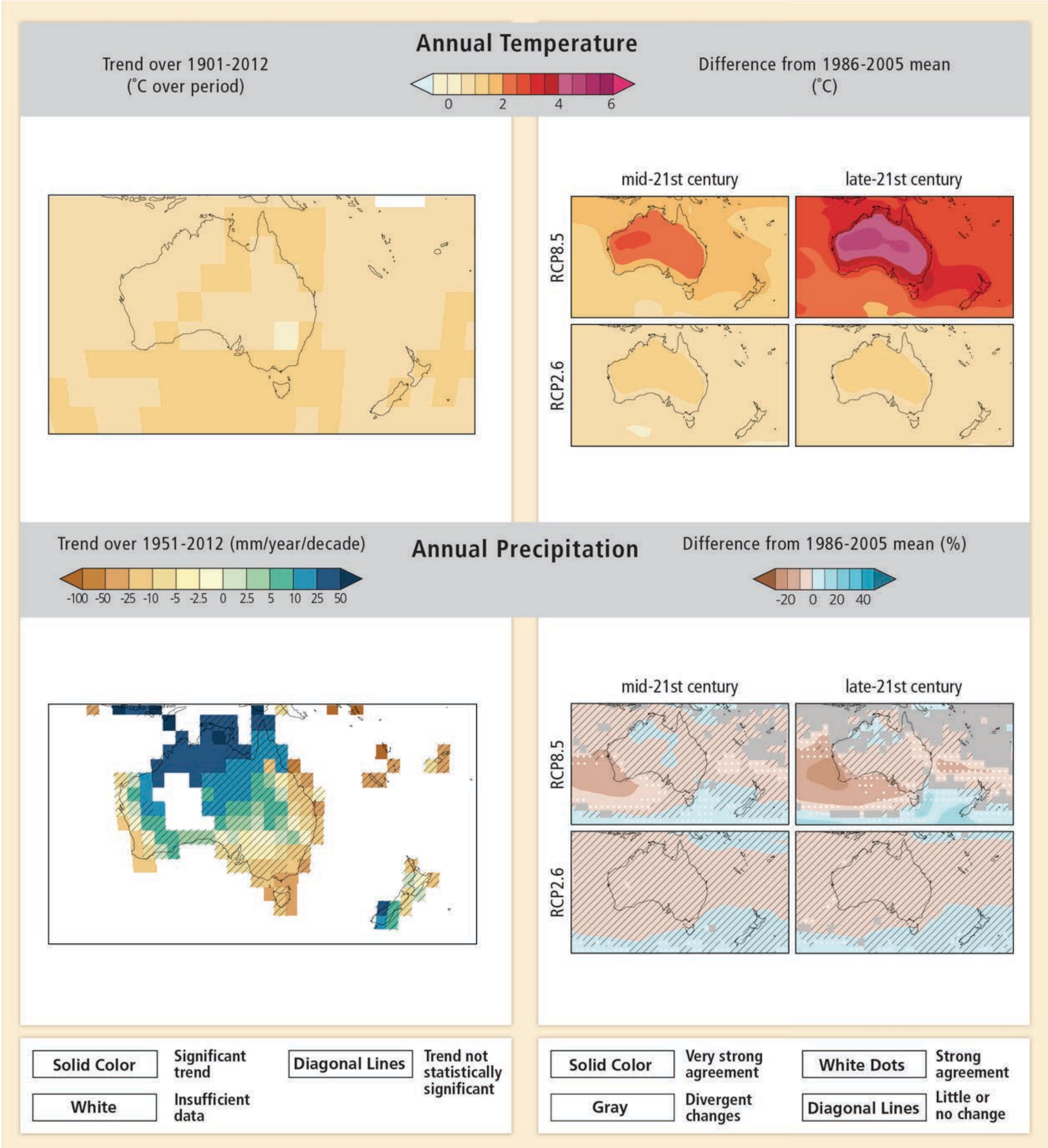


Figure 25-1: Observed and projected changes in annual average temperature and precipitation. (Top panel, left) Observed temperature trends from 1901-2012 determined by linear regression [WGI AR5 Figures SPM.1 and 2.21]. (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression [WGI AR5 Figure SPM.2]. For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant. (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5 [Boxes 21-3 and CC-RC].

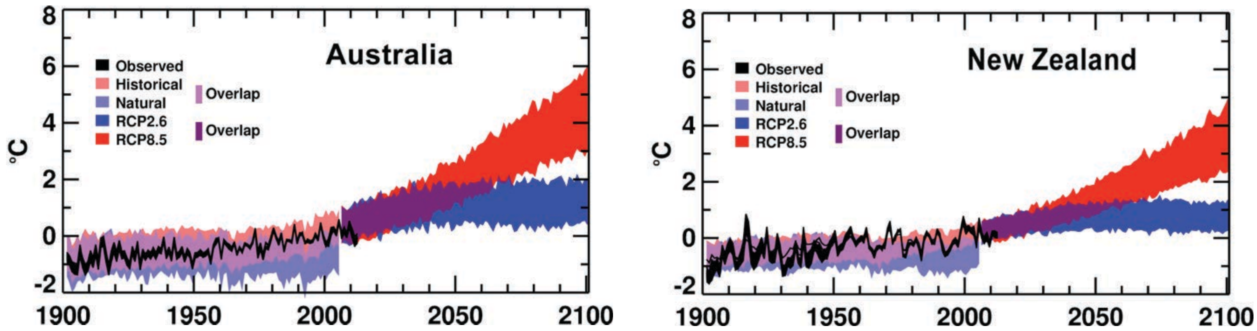


Figure 25-2: Observed and simulated variations in past and projected future annual average near-surface air temperature over land areas of Australia (left) and New Zealand (right). Black lines show various estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with 'historical' changes in anthropogenic and natural drivers (63 simulations), historical changes in 'natural' drivers only (34), the 'RCP2.6' emissions scenario (63), and the 'RCP8.5' (63). Data are anomalies from the 1986-2005 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.

[Illustration to be redrawn to conform to IPCC publication specifications.]

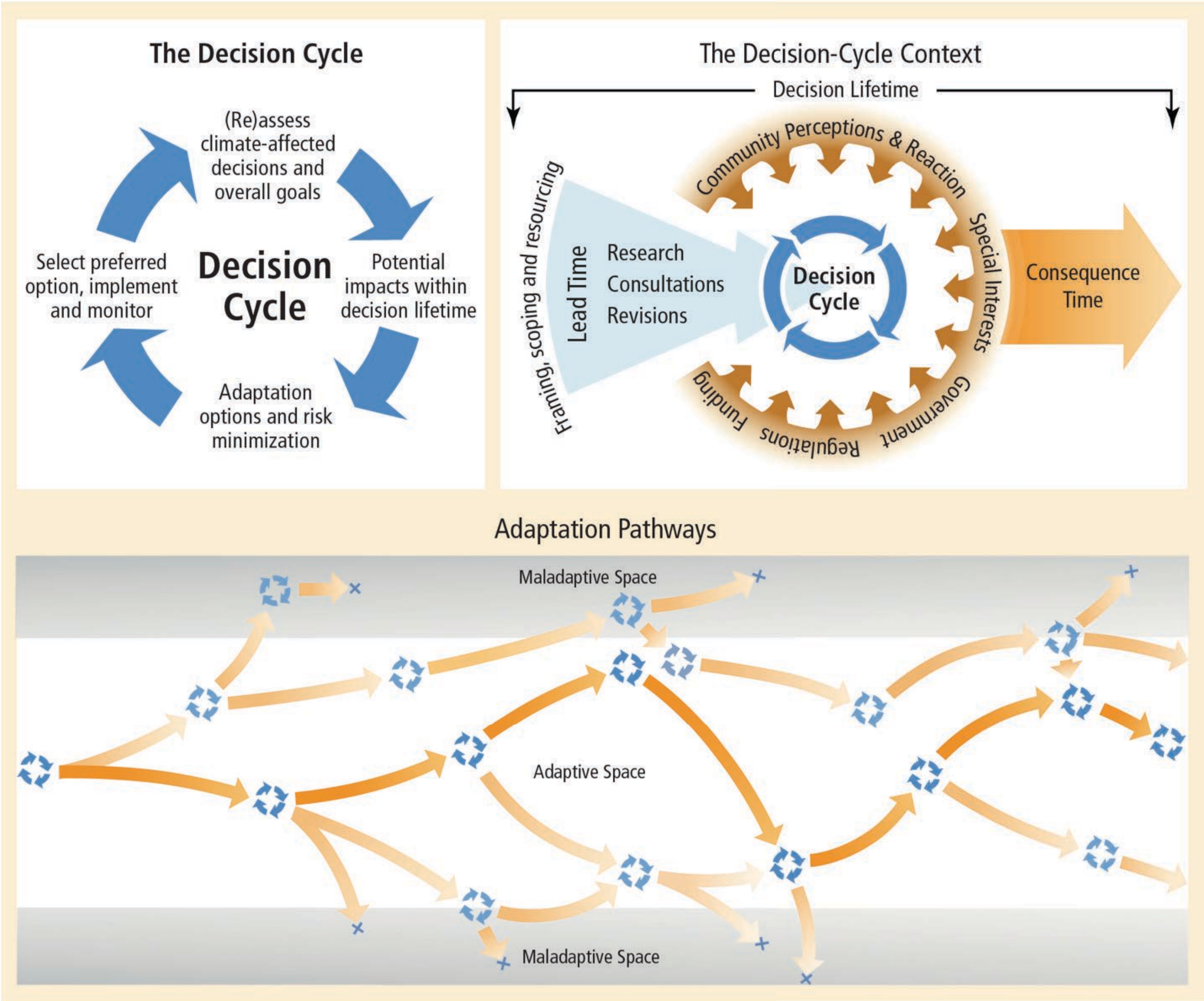


Figure 25-3: Adaptation as an iterative risk management process. Individual adaptation decisions comprise well known aspects of risk assessment and management (top left panel). Each decision occurs within and exerts its own sphere of influence, determined by the lead- and consequence time of the decision, and the broader regulatory and societal influences on the decision (top right panel). A sequence of adaptation decisions creates an adaptation pathway (bottom panel). There is no single ‘correct’ adaptation pathway, although some decisions, and sequences of decisions, are more likely to result in long-term maladaptive outcomes than others, but the judgment of outcomes depends strongly on societal values, expectations and goals.

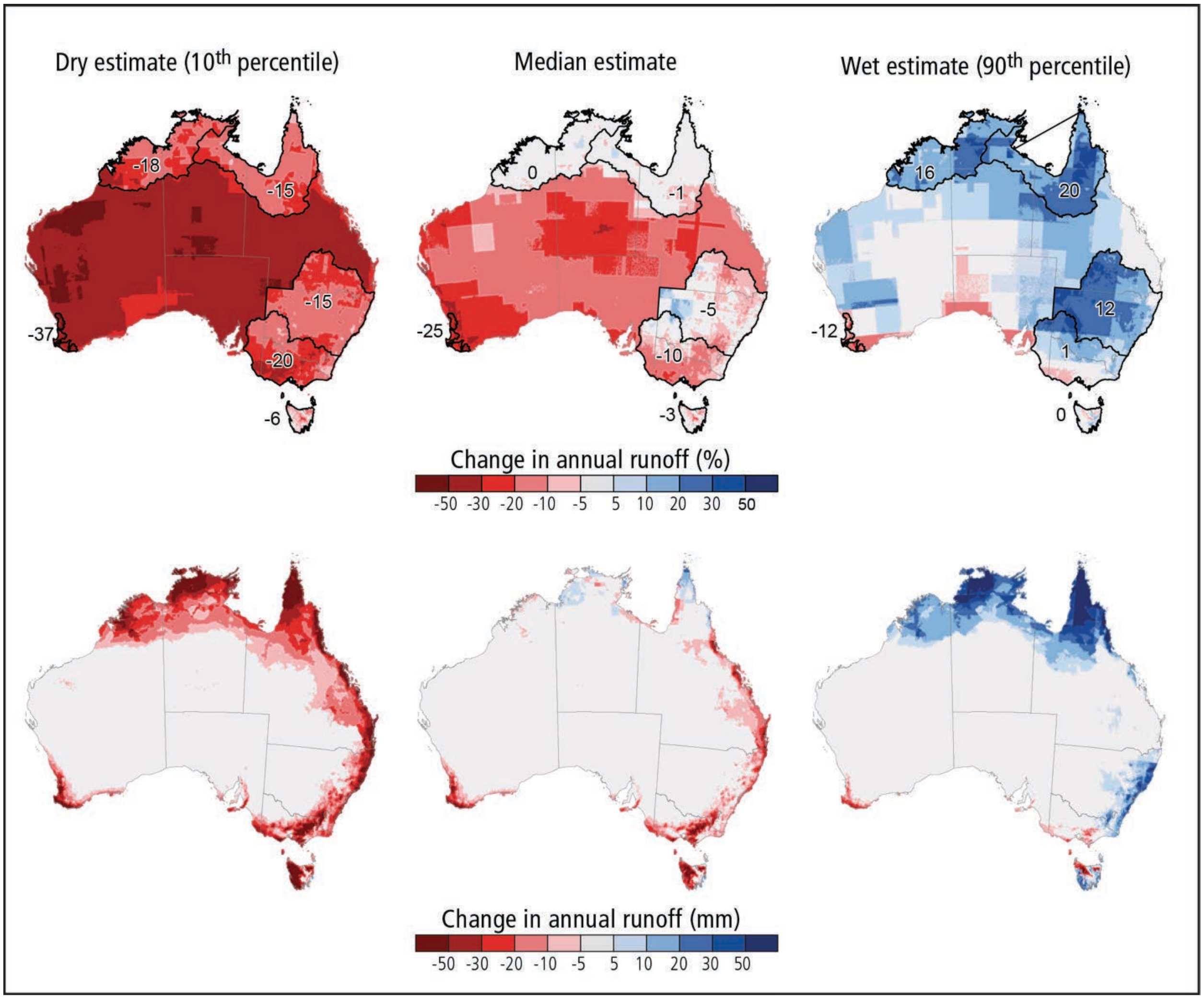


Figure 25-4: Estimated changes in mean annual runoff for 1°C global average warming above current levels. Maps show changes in annual runoff (percentage change; top row) and runoff depth (millimetres; bottom row), for dry, median and wet (10^{th} to 90^{th} percentile) range of estimates, based on hydrological modelling using 15 CMIP3 climate projections (Chiew *et al.*, 2009; CSIRO, 2009; Petheram *et al.*, 2012; Post *et al.*, 2012). Projections for 2°C global average warming are about twice that shown in the maps (Post *et al.*, 2011). (Figure adapted from Chiew and Prosser, 2011; Teng *et al.*, 2012).

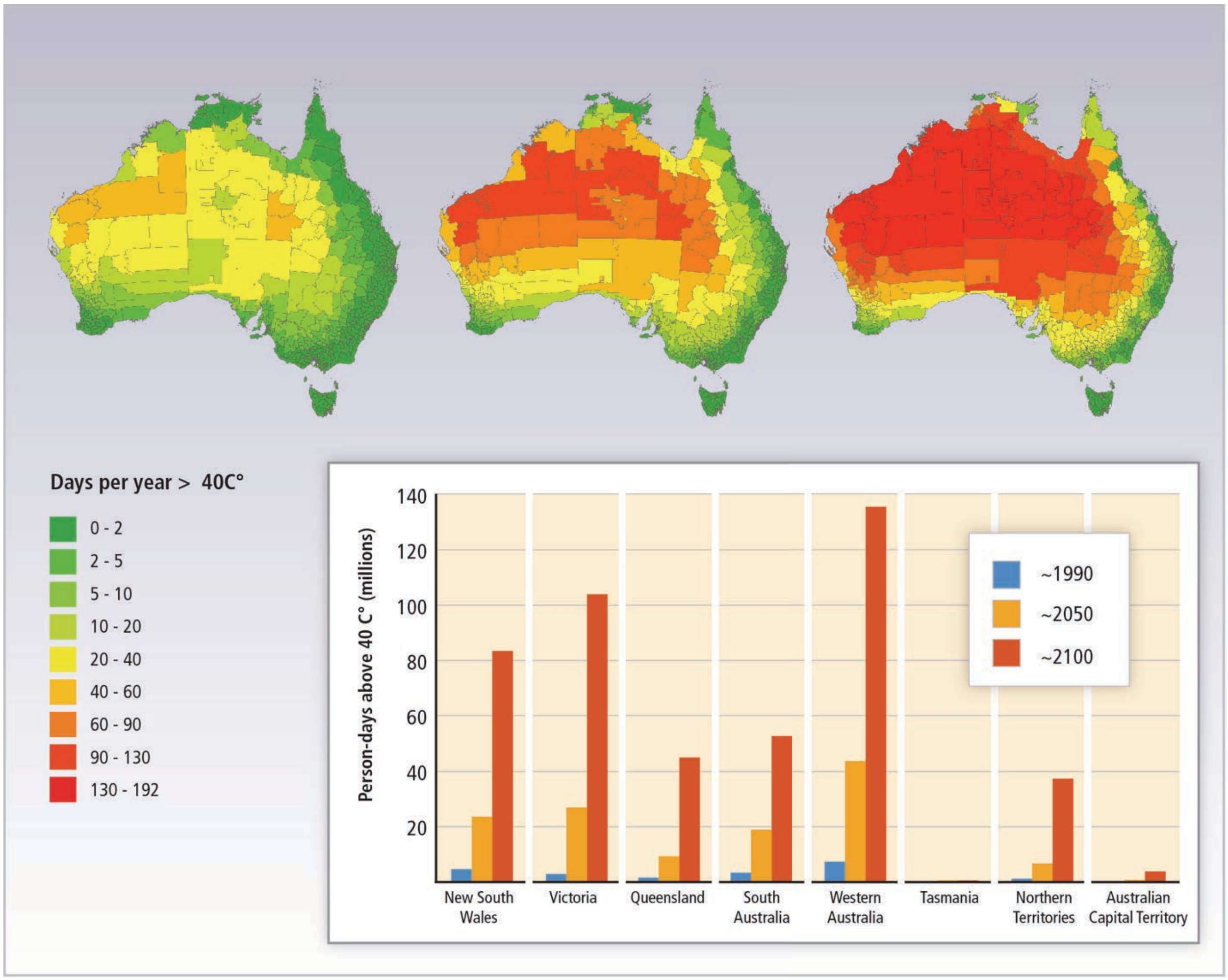


Figure 25-5: Projected changes in exposure to heat under a high emissions scenario (A1FI). Maps show the average number of days with peak temperatures >40°C, for ~1990 (based on available meteorological station data for the period 1975-2004), ~2050 and ~2100. Bar charts show the change in population heat exposure, expressed as person-days exposed to peak temperatures >40°C, aggregated by State/Territory and including projected population growth for a default scenario. Future temperatures are based on simulations by the GFDL-CM2 global climate model (Meehl *et al.*, 2007), re-scaled to the A1FI scenario; simulations based on other climate models could give higher or lower results. Data from Baynes *et al*. (2012).

Chapter 26. North America

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Contents

Executive Summary

Overview

North America's climate has changed and some societally-relevant changes have been attributed to anthropogenic causes (*very high confidence*) [Figure 26-1]. Recent climate changes and individual extreme events demonstrate both impacts of climate-related stresses and vulnerabilities of exposed systems (*very high confidence*) [Figure 26-2]. Observed climate trends in North America include an increased occurrence of severe hot weather events over much of the US, decreases in frost days, and increases in heavy precipitation over much of North America (*high confidence*). [26.2.2.1] The attribution of observed changes to anthropogenic causes has been established for some climate and physical systems (e.g., earlier peak flow of snowmelt run-off and declines in the amount of water stored in spring snowpack in snow-dominated streams and areas of western United States and Canada (*very high confidence*) [Figure 26-1]. Evidence of anthropogenic climatic influence on ecosystems, agriculture, water resources, infrastructure, and urban and rural settlements is less clearly established, though, in many areas, these sectors exhibit substantial sensitivity to climate variability (*high confidence*) (26.3.1; 26.3.2; 26.4.2.1; 26.4.2.2; 26.4.3.1; Box 26-3; 26.5.1; 26.7.1.1; 26.7.2; 26.8.1; Figure 26-2).

Many climate stresses that carry risk – particularly related to severe heat, heavy precipitation and declining snowpack – will increase in frequency and/or severity in North America in the next decades (*very high confidence*). Global warming of approximately 2°C (above the pre-industrial baseline) is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low snow years, and shifts towards earlier snowmelt runoff over much of the western US and Canada [26.2.2.2]. Together with climate hazards such as higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability, these changes are projected to lead to increased stresses to water, agriculture, economic activities and urban and rural settlements (high confidence) [26.3.2.1-26.3.2.4; 26.5.2; 26.7.1.2; 26.8.3]. Global warming of approximately 4°C is *very likely* to cause larger changes in extreme heat events, daily-scale precipitation extremes and snow accumulation and runoff, as well as emergence of a locally-novel temperature regime throughout North America [26.2.2.2]. This higher level of global temperature change is *likely* to cause decreases in annual precipitation over much of the southern half of the continent and increases in annual precipitation over much of the northern half of the continent [26.2.2.2]. The higher level of warming would present additional and substantial risks and adaptation challenges across a range of sectors (*high confidence*). [26.3.3, 26.5.2, 26.6.2, 26.7.2.2, 26.8.3]

We highlight below key findings on impacts, vulnerabilities, projections, and adaptation responses relevant to specific North American sectors: ecosystems, water, agriculture, human health, urban and rural settlements, infrastructure and the economy. We then highlight challenges and opportunities for adaptation, and future risks and adaptive capacity for three key climate-related risks.

Sector-Specific Climate Risks and Adaptation Opportunities

North American ecosystems are under increasing stress from rising temperatures, CO_2 concentrations, and sea-levels, and are particularly vulnerable to climate extremes (*very high confidence*). Climate stresses occur alongside other anthropogenic influences on ecosystems, including land-use changes, non-native species, and pollution, and in many cases will exacerbate these pressures (*very high confidence*). [26.4.1; 26.4.3]. Evidence since the Fourth Assessment Report highlights increased ecosystem vulnerability to multiple and interacting climate stresses in forest ecosystems, through wildfire activity, regional drought, high temperatures, and infestations (*medium confidence*) [26.4.2.1; Box 26-2]; and in coastal zones due to increasing temperatures, ocean acidification, coral reef bleaching, increased sediment load in run-off, sea level rise, storms, and storm surges (*high confidence*) [26.4.3.1]. In the near term, conservation and adaptation practices can buffer against climate stresses to some degree in these ecosystems, both through increasing system resilience, such as forest management to reduce vulnerability to infestation, and in reducing co-occurring non-climate stresses, such as careful oversight of fishing pressure (*medium confidence*) [26.4.4].

Water resources are already stressed in many parts of North America due to non-climate change anthropogenic forces, and are expected to become further stressed due to climate change (*high confidence*) [26.3, 26.3.1]. Decreases in snowpacks are already influencing seasonal streamflows (*high confidence*) [26.3.1]. While indicative of future conditions, recent floods, droughts, and changes in mean flow conditions cannot yet be attributed to climate change (*medium to high confidence)* [26.3.1, 26.3.2]. The 21st century is projected to witness decreases in water quality and increases in urban drainage flooding throughout most of North America under climate change as well as a decrease in instream uses such as hydropower in some regions (*high confidence)* [26.3.2.2, 26.3.2.3, 26.3.2.4]. Additionally, there will be decreases in water supplies for urban areas and irrigation in North America except in general for southern tropical Mexico, northwest coastal US, and west coastal Canada (*high to medium confidence*, 26.3.2.1). Many adaptation options currently available can address water supply deficits; adaptation responses to flooding and water quality concerns are more limited (*medium confidence*) [26.3.3].

Effects of temperature and climate variability on yields of major crops have been observed (*high confidence*) [25.5.1]. Projected increases in temperature, reductions in precipitation in some regions, and increased frequency of extreme events would result in net productivity declines in major North American crops by the end of the 21st Century without adaptation, although the rate of decline varies by model and scenario, and some regions, particularly in the north, may benefit (*very high confidence*) [26.5.2]. Given that North America is a significant source of global food supplies, projected productivity declines here may affect global food security (*medium confidence*)**.** At 2°C, adaptation has high potential to off-set projected declines in yields for many crops, and many strategies offer mitigation co-benefits; but effectiveness of adaptation would be reduced at 4°C *(high confidence)*. [26.5.3] Adaptation capacity varies widely among producers, and institutional support—currently lacking in some regions—greatly enhances adaptive potential (*medium confidence*) [26.5.4].

Human health impacts from extreme climate events have been observed, although climate change-related trends and attribution have not been confirmed to-date. Extreme heat events currently result in increases in mortality and morbidity in North America (*very high confidence*), with impacts that vary by age, location and socioeconomic factors (*high confidence*) [26.6.1.2]. Extreme coastal storm events can cause excess mortality and morbidity, particularly along the east coast of the United States, and the gulf coast of both Mexico and the United States (*high confidence*) [26.6.1.1]. A range of water-, food-, and vector-borne infectious diseases, air pollutants, and airborne pollens are influenced by climate variability and change (medium confidence) [26.6.1.3, 26.6.1.4, 26.6.1.5, 26.6.1.6]. Further climate warming in NA will impose stresses on the health sector through more severe extreme events such as heat waves and coastal storms, as well as more gradual changes in climate and CO_2 levels. [26.6.2] Human health impacts in NA from future climate extremes can be reduced by adaptation measures such as targeted and sustainable air conditioning, more effective warning and response systems, enhanced pollution controls, urban planning strategies, and resilient health infrastructure (*high confidence*) [26.6.3].

Observed impacts on livelihoods, economic activities, infrastructure and access to services in North American urban and rural settlements have been attributed to sea level rise, changes in temperature and precipitation, and occurrences of such extreme events as heat waves, droughts and storms (high confidence) [26.8.2.1]. Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific social and environmental factors and processes that contribute to risk, vulnerability and adaptive capacity such as hazard magnitude, populations access to assets, built environment features and governance (high confidence) [26.8.2.1 and 26.8.2.2]. Some of these processes (e.g., the legacy of previous and current stresses) are common to urban and rural settlements, while others are more pertinent to some types of settlements than others. For example, human and capital risks are highly concentrated in some highly exposed urban locations, while in rural areas, geographic isolation and institutional deficits are key sources of vulnerability. Among the most vulnerable are indigenous peoples due to their complex relationship with their ancestral lands and higher reliance on subsistence economies, and those urban centers where high concentrations of populations and economic activities in risk-prone areas combine with several socio-economic and environmental sources of vulnerability (high confidence) [26.8.2.1 and 26.8.2.2]. Although larger urban centers would have higher adaptation capacities, future climate risks from heat waves, droughts, storms and sea level rise in cities would be enhanced by high population density, inadequate infrastructures, lack of institutional capacity and degraded natural environments (high agreement, medium evidence) [26.8.3].

Much of North American infrastructure is currently vulnerable to extreme weather events and, unless investments are made to strengthen them, would be more vulnerable to climate change (*medium confidence*). Water resources and transportation infrastructure are in many cases deteriorating, thus more vulnerable to extremes than strengthened ones (*high confidence*). Extreme events have caused significant damage to infrastructure in many parts of North America; risks to infrastructure are particularly acute in Mexico but are a big concern in all three countries (*high confidence*) [26.7].

Most sectors of the North American economy have been affected by and have responded to extreme weather, including hurricanes, flooding, and intense rainfall (*high confidence*) (Figure 26-2). Despite a growing experience with reactive adaptation, there are few examples of proactive adaptation anticipating future climate change impacts, and these are largely found in sectors with longer-term decision-making, including energy and public infrastructure. Knowledge about lessons learned and best adaptive practices by industry sector are not well-documented in the published literature [26.7]. There is an emerging concern that dislocation in one sector of the economy may have an adverse impact on other sectors due to supply chain interdependency (*medium confidence*) [26.7]. Slow onset perils – like sea level rise, drought, and permafrost thaw – are an emerging concern for some sectors, with large regional variation in awareness and adaptive capacity (*medium confidence*).

Adaptation Responses

Adaptation – including through technological innovation, institutional strengthening, economic diversification, and infrastructure design – can help to reduce risks in the current climate, and to manage future risks in the face of climate change (medium confidence) [26.8.4; 26.9.2]. There is increasing attention to adaptation among planners at all levels of government but particularly at the municipal level, with many jurisdictions engaging in assessment and planning processes. These efforts have revealed the significant challenges and sources of resistance facing planners at both the planning and implementation stages, particularly the adequacy of informational, institutional, financial and human resources, and lack of political will (*medium confidence*) [26.8.4.2; 26.9.3]. Specific strategies introduced into policy to date tend to be incremental rather than transformational. Fiscal constraints are higher for Mexican jurisdictions and sectors than for Canada or the US. The literature on sectoral-level adaptation is stronger in the areas of technological and engineering adaptation strategies than in social, behavioral and institutional strategies. Adaptation actions have the potential to result in synergies or tradeoffs with mitigation and other development actions and goals (*high confidence*) [26.8.4.2; 26.9.3].

26.1. Introduction

This chapter assesses literature on observed and projected impacts, vulnerabilities and risks as well as on adaptation practices and options in three North American countries: Canada, Mexico and United States (US). The North American Arctic region is assessed in Chapter 28: Polar Regions. North America ranges from the tropics to frozen tundra, and contains a diversity of topography, ecosystems, economies, governance structures and cultures. As a result, risk and vulnerability to climate variability and change differ considerably across the continent depending on geography, scale, hazard, socio-ecological systems, ecosystems, demographic sectors, cultural values and institutional settings. This chapter seeks to take account of this diversity and complexity as it affects and is projected to affect vulnerabilities, impacts, risks and adaptation across North America.

No single chapter would be adequate to cover the range and scope of the literature about climate change vulnerabilities, impacts and adaptations in our three focus countries. (Interested readers are encouraged to review the following reports: (Instituto Nacional de Ecología y Cambio Climático, 2012a; National Climate Assessment Development Advisory Committee, 2013). We therefore attempt to take a more integrative and innovative approach. In addition to describing current and future climatic and socioeconomic trends of relevance to understanding risk and vulnerability in North America (section 26.2), we contrast climate impacts, vulnerabilities and adaptations across and within the three countries in the following key sectors: water resources and management (section 26.3); ecosystems and biodiversity (section 26.4); agriculture and food security (section 26.5); human health (section 26.6); and key economic sectors and services (section 26.7). We use a comparative and place-based approach to explore the factors and processes associated with differences and commonalities in vulnerability, risk and adaptation between urban and rural settlements (section 26.8); and to illustrate and contrast the nuanced challenges and opportunities adaption entails at the city, the subnational and the national level (sections 26.8.4 and 26.9; Box 26-3). We highlight two case studies that cut across sectors, systems or national boundaries. The first, on wildfires (Box 26-2), explores some of the connections between climatic, physical and socioeconomic process (e.g., decadal climatic oscillation, droughts, wildfires land-use, and forest management) and across systems and sectors (e.g., fires direct and indirect impacts on local economies, livelihoods, built environments and human health). The second takes a look at one of the world's longest border between a high-income (US) and middle income country (Mexico) and briefly reflects on the challenges and opportunities of responding to climate change in a transboundary context (Box 26-1). We close with a section (26.10) summarizing key multi-sectoral risks and uncertainties and discussing some of the knowledge gaps that will need to be filled by future research.

Findings from the Fourth Assessment Report

This section summarizes *key findings on North America,* as identified in Chapter 13 of the Fourth IPCC assessment focused on Mexico (Magrin *et al.,* 2007), and Chapter 14 on Canada and the US (Field *et al.*, 2007). It focuses on observed and projected impacts, vulnerabilities and risks as well as on adaptation practices and options and highlights areas of agreement and difference between the AR4's two chapters and our consolidated North American chapter.

Observed impacts and processes associated with vulnerability. Both chapter 14 [14.2] and our chapter (Figure 26-2) find that over the past decades, economic damage from severe weather has increased dramatically. Our chapter confirms that although Canada and the US have considerably more adaptive capacity than Mexico, their vulnerability depends on the effectiveness and timing of adaptation and the distribution of capacity, which vary geographically and between sectors. [14.2.6; 14.4; 14.5] [26.2.2; 26.8.2]

Chapters 13 and 14 did not assess impacts, vulnerabilities and risks in urban and rural settlements, but rather assessed literature on *future risks* in the following sectors:

- *Ecosystems*: Both AR4 and our chapter find that ecosystems are under increased stress from increased temperatures, climate variability and other climate stresses (e.g., sea level rise and storm-surge flooding), and that these stresses interact with developmental and environmental stresses (e.g., as salt intrusion, pollution, population growth and the rising value of infrastructure in coastal areas) [13.4.4; 14.2.3; 14.4.3]. Differential capacities for range shifts and constraints from development, habitat fragmentation, invasive species, and broken ecological connections would alter ecosystem structure, function and services in terrestrial ecosystems [14.2; 14.4]. Both reports show that dry soils and warm temperatures are associated with increased wildfire activity and insect outbreaks in Canada and the US [14.2; 14.4; 26.4.2.1].
- *Water resources:* AR4 projects millions in Mexico to be at risk from the lack of adequate water supplies due to climate change[13.4.3]; our chapter, however, finds that water resources are already stressed by non-climatic factors, such as population pressure that will be compounded by climate change [26.3.1]. Both reports find that in the US and Canada rising temperatures would diminish snowpack and increase evaporation [26.2.2.1], thus affecting seasonal availability of water [14.2.1; 26.3.1]. The reports also agree that these effects will be amplified by water demand from economic development, agriculture and population growth, thus imposing further constraints to over-allocated water resources and increasing competition among agricultural, municipal, industrial and ecological uses [14.4.1; 14.4.6; 26.3.3]. Both agree water quality will be further stressed [14.4.1; 26.3.2.2; 13.4.3]. There is more information available now on water adaptation than in AR4 [14.5.1; 26.3.3; 13.5.1.3], and is possible to attribute changes in extreme precipitation, snowmelt and snowpack to climate change [26.3.1; 14.2.1; 13.2.4]
- *Agriculture*: The AR4 noted that while increases in grain yields in the US and Canada are projected by most scenarios [14.4.4], in Mexico the picture is mixed for wheat and maize, with different projected impacts depending on scenario used [13.4.2]. Research since the AR4 has offered more cautious projections of yield change in North America due to shifts in temperature and precipitation, particularly by 2100; and significant harvest losses due to recent extreme weather events have been observed [26.5.1]. Furthermore, our chapter reports on recent research that underscores the context specific nature of adaptation capacity and of institutional support and shows that these factors, which greatly enhance adaptive potential, are currently lacking in some regions [26.5.3].
- *Health*: AR4 focused primarily on a set of future health risks. These include changes in the geographical distribution and transmission of diseases such as dengue [13.4.5]; increases in respiratory illness, including exposure to pollen and ozone [14.4] and in mortality from hot temperatures and extreme weather in Canada and the US. AR4 also projects that climate change impacts on infrastructure and human health in cities of Canada and the US would be compounded by aging infrastructure, maladapted urban form and building stock, urban heat islands, air pollution, population growth and an aging population [14.4; 14.5]. Without increased investments in measures such as early warning and surveillance systems, air conditioning, and access to health care, hot temperatures and extreme weather in Canada and the US are predicted to result in increased adverse health impacts [14.4; 14.5]. Our chapter provides a more detailed assessment of these future risks [26.6], besides assessing a richer literature on observed health impacts [26.6.1].
- *Adaptation*: AR4 found that Mexico has early warning and risk management systems, yet it faces planning and management barriers. In Canada and the US, a decentralized response framework has resulted in adaptation that tends to be reactive, unevenly distributed, and focused on coping with rather than preventing problems [14.5]. Both chapters see ‘mainstreaming’ climate issues into decision making as key to successful adaptation [14.5; 13.5]. The current chapter provides a summary of the growing empirical literature on emerging opportunities and constraints associated with recent institutional adaptation planning activities since the AR4 [26.3.3; 26.4.3; 236.5.3; 26.6.3; 26.8.4;26.9].

In summary, scholarship on climate change impacts, adaptation and vulnerability has grown considerably since the AR4 in North America, particularly in Canada and the US. It is possible now not only to detect and attribute to anthropogenic climate change some impacts such as changes in extreme precipitation, snowmelt and snowpack, but also to examine trends showing increased insect outbreaks, wildfire events and coastal flooding. These latter trends have been shown to be sensitive to climate, but, like the local climate patterns that cause them, have not yet been positively attributed to anthropogenic climate change (see Figure 26-1).

[INSERT FIGURE 26-1 HERE
Figure 26-1 Detection and attribution of climate change impacts. Comparisons of the adequacy of currently available data to detect trends and the degree of understanding of causes of those changes in climatic extreme events in the United States (left; Peterson *et al.*, 2013) and degree of understanding of the climate influence in key impacts in North America (right). Note that “climate influence” means that the impact has been documented to be sensitive to climate, not that it has been attributed to climate change. Filled boxes indicate that formal detection and attribution to climate change has been performed for the given impact; shaded boxes indicate that a trend has been detected from background variability in the given impact, but formal attribution to climate change has not occurred and the trend could be due to other drivers; and open boxes indicate that a trend has not currently been detected. Key impacts are: 1) earlier peak flow of snowmelt run-off in snow-dominated streams and rivers in western North America [26.3.1], 2) declines in the amount of water stored in spring snowpack in snow-dominated areas of western North America [26.3.1], 3) northward and upward shifts in species’ distributions in multiple taxa of terrestrial species, although not all taxa and regions [26.4.1], 4) increases in coastal flooding [26.8.1], 5) increases in wildfire activity, including fire season length and area burned by wildfires in the western United States and boreal Canada [Box 26-2], 6) storm-related disaster losses in the United States (most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk) [26.7.6.1, 26.8.1], 7) increases in bark beetle infestation levels in pine tree species in western North America [26.4.2.1], 8) yield increases due in part to increasing temperatures in Canada and higher precipitation in the US; yield variances attributed to climate variability in Ontario and Quebec; yield losses attributed to climate-related extremes across North America [26.5.1], 9) changes in storm-related mortality in the United States [26.6.1.2], 10) changes in heat-related mortality in the United States [26.6.1.2], 11) increases in tree mortality rates in old-growth forests in the western United States and western Canada from 1960-2007 [26.4.2.1], 12) changes in flooding in some urban areas due to extreme rainfall [26.3.1, 26.8.2.1], 13) increase in water supply shortages due to drought [26.8.1, 26.3], and 14) changes in cold-related heat mortality [26.6.1.2].]

26.2. Key Trends Influencing Risk, Vulnerability, and Capacities for Adaptation

26.2.1. Demographic and Socioeconomic Trends

26.2.1.1. Current Trends

Canada, Mexico and US share commonalities but also differ in key dimensions shaping risk, vulnerability and adaptation such as population dynamics, economic development, and institutional capacity. During the last years, the three countries, particularly the US, have suffered economic losses from extreme weather events (Figure 26-2). Hurricanes, droughts, floods and other climate-related hazards produce risk as they interact with increases in exposed populations, infrastructure and other assets and with the dynamics of such factors shaping vulnerability as wealth, population size and structure, and poverty (Figure 26-2 and Figure SPM.1). Population growth has been slower in Canada and US than in Mexico (Population Division, Department of Economic and Social Affairs, 2011). Yet population growth in Mexico also decreased from 3.4 percent between 1970-1980 to 1.5 percent yearly during 2000-2010. Populations in the three countries are aging at different rates (Figure 26-2). In 2010, 14.1% of the population in Canada was 60 years and older, compared to 12.7% in the US, and 6.1% in Mexico (Population Division, Department of Economic and Social Affairs, 2011). Urban populations have grown faster than rural populations, resulting in a North America that is highly urbanized (Canada 84.8%, Mexico 82.8% and US 85.8%). Urban populations are also expanding into peri-urban spaces, producing rapid changes in population and land use dynamics that can exacerbate risks from such hazards as floods and wildfires (Eakin *et al.*, 2010; Romero-Lankao *et al.*, 2012a). Mexico has a markedly higher poverty rate (34.8%) than Canada (9.1%) and the US (12.5%) (Figure 26-2), with weather events and climate affecting poor people’s livelihood assets, including crop yields, homes, food security, and sense of place (Chapter 13, section 26.8.2). Between 1970 and 2012, a 10 percent increase in single person households – who can be vulnerable because of isolation and low income and housing quality (Roorda *et al.*, 2010), has been detected in the US (Vespa *et al.*, 2013).

[INSERT FIGURE 26-2 HERE
Figure 26-2: Extreme events illustrating vulnerabilities for Mexico, the United States, and Canada. This figure offers a graphic illustration of location of extreme events and relevant vulnerability trends. The observed extreme events have not been attributed to anthropogenic climate change, yet they are climate-sensitive sources of impact illustrating vulnerability of exposed systems, particularly if projected future increases in the frequency and/or intensity of such events should materialize. The figure includes:

a) A map (bottom) with population density at 1km resolution highlighting exposure and represented using 2011 Landscan data (Bright *et al.*, 2012).
b) A map (top) with significant weather events taking place during 1993-2012. The map only includes disasters with overall losses of more than $1 billion US dollars in US, or more than $500 million US dollars in Mexico and Canada, adjusted to 2012 values (Source: (NatCatSERVICE, 2010). Hence, it does not include the occurrence of disasters of small and medium impact, and it does not capture the impacts of disasters on populations' livelihoods and wellbeing. Disasters represented by points that are located at the approximate geographic center of affected regions, frequently span more than one subnational jurisdiction (e.g., the 2012 drought affected 12 Mexican states, Annex Table).
c) Four panels (right) with trends in socio-demographic indicators used in the literature to measure vulnerability to hazards (Romero-Lankao *et al.*, 2012): poverty rates, percentage of elderly, GDP per capita and total population (Sources: Comisión Económica para América Latina y el Caribe; U.S. Census Bureau, 2011; Statistics Canada, 2012).]

While concentrations of growing populations, water, sanitation, transportation and energy infrastructure and industrial and service sectors in urban areas can be a source of risk, geographic isolation and high dispersion of rural populations also introduce risk because of long distances to essential services (section 26.8.2). Rural populations are more vulnerable to climate events due to smaller labor markets, lower income levels and reduced access to public services. Rural poverty could also be aggravated by changes in agricultural productivity, particularly in Mexico where 65% of the rural population is poor, agricultural income is seasonal, and most households lack insurance (Scott, 2007). Food price increases, which may also result from climate events, would contribute to food insecurity (World Bank, 2011; Lobell *et al.*, 2011).

Migration is a key trend affecting North America, recently with movements between urban centers and from rural Mexico into Mexico's cities, and in the US. Rates of migration from rural Mexico are positively associated with natural disaster occurrence and increased poverty trends (Saldaña-Zorilla and Sandberg, 2009), and with decreasing precipitation (Nawrotski *et al.*, 2013). Studies of migration induced by past climate variability and change indicate a preference for short-range domestic movement, a complex relationship to assets with indications that the poorest are less able to migrate, and the role of pre-existing immigrant networks in facilitating international migration (Oppenheimer, 2013).

North America has become more economically integrated following the 1994 North American Free Trade Agreement. Prior to a 2007-2008 reduction in trade, the three countries registered dynamic growth in industry, employment and global trade of agricultural and manufactured goods (World Bank, 2009). Notwithstanding North America's economic dynamism, increased socioeconomic disparities (Autor *et al.*, 2008) have affected such determinants of vulnerability as differentiated human development and institutional capacity within and across countries.

_____ START BOX 26-1 HERE _____

Box 26-1. Adapting in a Transboundary Context: the Mexico-U.S. Border Region

Extending over 3111 km (1933 miles; (U.S. Census Bureau, 2011), the border between the United States and Mexico, which can be defined in different ways (Varady and Ward, 2009), illustrates the challenges and opportunities of responding to climate change in a transboundary context. Changing regional climate conditions and socioeconomic processes combined shape differentiated vulnerabilities of exposed populations, infrastructure and economic activities.

Since at least 1999, the region has experienced high temperatures and aridity anomalies leading to drought conditions (Woodhouse *et al.*, 2010; Wilder *et al.*, 2013) affecting large areas on both sides of the border, and considered the most extreme in over a century of recorded precipitation patterns for the area (Seager and Vecchi, 2010; Cayan *et al.*, 2010; Nielsen-Gammon, 2011). Streamflow in already oversubscribed rivers such as the Colorado and Rio Grande (Nakaegawa *et al.*, 2013) has decreased. Climatological conditions for the area have been unprecedented, with sustained high temperatures that may have exceeded any experienced for 1,200 years. While these changes cannot conclusively be attributed to anthropogenic climate change, they are consistent with climate change projections (Woodhouse *et al.*, 2010).

The population of the Mexico-US Border is rapidly growing and urbanizing, doubling from just under 7 million in 1983 to over 15 million in 2012 (Peach and Williams, 2007). Since 1994, rapid growth in the area has been fueled by rapid economic development subsequent to passage of the North American Free Trade Agreement (NAFTA). Between 1990 and 2001 the number of *assembly factories* or *maquiladoras* in Mexico grew from 1700 to nearly 3,800, *with* 2,700 in the border area. By 2004, it was estimated that more than one million Mexicans were employed in more than 3,000 *maquiladoras* located along the border (U.S. Environmental Protection Agency and Secretaría de Medio Ambiente y Recursos Naturales, 2011; U.S. Environmental Protection Agency, 2012).

Notwithstanding this growth, challenges to adaptive capacity include high rates of poverty in a landscape of uneven economic development (Wilder *et al.*, 2013). Large sections of the urban population, particularly in Mexico, live in informal housing lacking the health and safety standards needed to respond to hazards, and with no insurance (Collins *et al.*, 2011). Any effort to increase regional capacity to respond to climate needs to take existing gaps into account. Additionally, there is a prevalence of incipient or actual conflict (Mumme, 1999), given by currently or historically contested allocation of land and water resources (e.g., an over-allocated Colorado river ending in Mexico above the Sea de Cortes (Getches, 2003). Climate change, therefore, would bring additional significant consequences for the region’s water resources, ecosystems, and rural and urban settlements.

The impacts of regional climatic and non-climatic stresses compound existing urban vulnerabilities that are different across countries. For instance, besides degrading highly diverse ecosystems (Wilder *et al.*, 2013), residential growth in flood-prone areas in Ciudad Juarez has not been complemented with the provision of determinants of adaptive capacity to residents, such as housing, health care and drainage infrastructure. As a result, while differences in mean hazard scores are not significantly different between Ciudad Juarez (Mexico) and El Paso (US), social vulnerability and average risk are three times and two times higher in Ciudad Juárez than in El Paso respectively (Collins, 2008).

Projected warming and drying would impose additional burdens on already stressed water resources and ecosystems and compound existing vulnerabilities for populations, infrastructure and economic activities (Wilder *et al.*, 2013). The recent drought in the region illustrated the multiple dimensions of climate-related events, including notable negative impacts on the agricultural sector, water supplies, food security, and risk of wildfire (discussed in Box 26.2) (Wehner *et al.*, 2011; Schwalm *et al.*, 2012; Hoerling *et al.*, 2012).

Adaptation opportunities and constraints are shared across international borders, creating the need for cooperation among local, national and international actors. Although there are examples of efforts to manage trans-border environmental issues, such as the US-Mexico International Boundary and Water Commission agreement (International Boundary and Water Commission, 2012), constraints to effective cooperation and collaboration include different governance structures (centralized in Mexico, decentralized in the US); institutional fragmentation; asymmetries in the use and dissemination of information, and language (Wilder *et al.*, 2010; Megdal and Scott, 2011; Wilder *et al.*, 2013).

_____ END BOX 26-1 HERE _____

26.2.1.2. Future Trends

The North American population is projected to continue growing, reaching between 531.8 (B2) and 660.1 (A2) million by 2050 (International Institute for Applied System Analysis, 2007). The percentage of elderly people (over

64 years) is also projected to continue to increase, by 23.4%-26.9% in Canada, 12.4%-18.4 % in Mexico, and 17.3%-20.9% in the US by 2050 (B2 and A2 respectively) (International Institute for Applied System Analysis, 2007). The elderly are highly vulnerable to extreme weather events (heat waves in particular, Figure 26-2) (Martiello and Giacchi, 2010; Diffenbaugh and Scherer, 2011; Romero-Lankao, 2012; White-Newsome *et al.*, 2012). Numbers of single-person households and female-headed households — both of which are vulnerable because of low income and housing quality – are anticipated to increase (Roorda *et al.*, 2010). Institutional capacity to address the demands posed by increasing numbers of vulnerable populations may also be limited, with resulting stress on health and the economy.

Three other shifts are projected to influence impacts, vulnerabilities and adaptation to climate change in North America: urbanization, migration, and socioeconomic disparity. With small differences between countries, both the concentration of growing populations in some urban areas and the dispersion of rural populations are projected to continue to define North America by 2050. Assuming no change in climate, between 2005 and 2030 the population of Mexico-City-Metro-Area will increase by 17.5%, while between 2007 and 2030 available water will diminish by 11.2% (Romero-Lankao, 2010). Conversely, education, a key determinant of adaptive capacity (Chapter 13), is expected to expand to low-income households, minorities, and women, which could increase the coping capacity of households and have a positive impact on economic growth (Goujon *et al.*, 2004). However, the continuation of current patterns of economic disparity and poverty would hinder future adaptive capacity. Inequality in Mexico is larger (Figure 26-2), having a Gini coefficient (according to which the higher the number the higher economic disparity) of 0.56, in contrast to 0.317 for Canada and 0.389 for the US (Organisation for Economic Co-operation and Development, 2010). Mexico is one of five countries in the world that is projected to experience the highest increases in poverty due to climate-induced extreme events (52% increase in rural households; 95.4% in urban wage-labor households) (CMIP3, A2) (Ahmed *et al.*, 2009).

Some studies project increased North American migration in response to climate change. Feng, Krueger and Oppenheimer (2010) estimated the emigration of an additional 1.4 to 6.7 million Mexicans by 2080 based on projected maize yield declines, range depending on model (B1, UKMO and GDFL). Oppenheimer speculates that the indirect impacts of migration "could be as substantial as the direct effects of climate change in the receiving area," because the arrival migrants can increase pressure on climate sensitive urban regions (Oppenheimer, 2013, 442).

26.2.2. Physical Climate Trends

Some processes important for climate change in North America are assessed in other Chapters of AR5, including WGI Chapter 2 (*Observations: Atmosphere and Surface*), WGI Chapter 4 (*Observations: Cryosphere*), WGI Chapter 12 (*Long-term Climate Change: Projections, Commitments and Irreversibility*), WGI Chapter 14 (*Climate Phenomena and their Relevance for Future Regional Climate Change*), WGI Annex I (*Atlas of Global and Regional Climate Projections*), and WGII Chapter 21 (*Regional Context*). In addition, comparisons of emissions, concentrations, and radiative forcing in the RCPs and SRES scenarios can be found in WGI Annex II (*Climate System Scenario Tables*).

26.2.2.1. Current Trends

It is *very likely* that mean annual temperature has increased over the past century over most of North America (WGI SPM.1) (Figure 26-3). Observations also show increases in the occurrence of severe hot events over the US over the late 20th century (Kunkel *et al.*, 2008), a result in agreement with observed late-20th-century increases in extremely hot seasons over a region encompassing northern Mexico, the US and parts of eastern Canada (Diffenbaugh and Scherer, 2011). These increases in hot extremes have been accompanied by observed decreases in frost days over much of North America (Alexander et al., 2006; Brown *et al.*, 2010) WGI 2.6.1, decreases in cold spells over the US (Kunkel *et al.*, 2008) WGI 2.6.1, and increasing ratio of record high to low daily temperatures over the US (Meehl *et al.*, 2009). However, warming has been less pronounced and less robust over areas of the central and southeastern US (e.g., (Alexander et al., 2006; Peterson *et al.*, 2008); WGI 2.6.1; WGI SPM.1) (Figure 26-3). It is possible that this pattern of muted temperature change has been influenced by changes in the hydrologic cycle (e.g., (Pan *et al.*, 2004; Portmann *et al.*, 2009), as well as by decadal-scale variability in the ocean (e.g., (Meehl *et al.*, 2012; Kumar *et al.*, 2013b).

[INSERT FIGURE 26-3 HERE
Figure 26-3: Observed and projected Changes in annual temperature and precipitation. (Top panel, left) observed temperature trends from 1901-2012 determined by linear regression [WGI AR5 Figures SPM.1 and 2.21]. (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression. [WGI AR5 Figure SPM.2] For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-3 and CC-RC]**]**

It is *very likely* that annual precipitation has increased over the past century over areas of the eastern US and Pacific Northwest (WGI Fig. 2.29) (Figure 26-3). Observations also show increases in heavy precipitation over Mexico, the US and Canada between the mid-20th century and the early 21st century (Peterson and Baringer, 2009; DeGaetano, 2009; Pryor *et al.*, 2009); WGI 2.6.2. Observational analyses of changes in drought are more equivocal over North America, with mixed sign of trend in dryness over Mexico, the US and Canada (WGI 2.6.2 and Fig 2.42) (Dai, 2011; Sheffield *et al.*, 2012). There is also evidence for earlier occurrence of peak flow in snow-dominated rivers globally (Rosenzweig, 2007); WGI 2.6.2). Observed snowpack and snow-dominated runoff have been extensively studied in the western US and western Canada, with observations showing primarily decreasing trends in the amount of water stored in spring snowpack from 1960-2002 (with the most prominent exception being the central and southern Sierra Nevada) (Mote, 2006) and primarily earlier trends in the timing of peak runoff over the 1948-2000 period (Stewart *et al.*, 2006) (WGI 4.5 and Fig. 4.21). Observations also show decreasing mass and length of glaciers in North America (WGI 4.3 and Fig. 4.9, 4.10, 4.11). Further, in assessing changes in the hydrology of the western US, it has been concluded that “up to 60% of the climate-related trends of river flow, winter air temperature, and snow pack between 1950 and 1999 are human-induced”(Barnett *et al.*, 2008).

Observational limitations prohibit conclusions about trends in severe thunderstorms (WGI 2.6.2) and tropical cyclones (WGI 2.6.3) over North America. The most robust trends in extratropical cyclones over North America are determined to be towards more frequent and intense storms over the northern Canadian Arctic and towards less frequent and weaker storms over the southeastern and southwestern coasts of Canada over the 1953-2002 period (WGI 2.7.4)(Wang *et al.*, 2006).

WGI concludes that “Global mean sea level (GMSL) has risen by 0.19 [0.17–0.21] m over the period 1901–2010” and that “it is *very likely* that the mean rate was 1.7 [1.5 to 1.9] mm yr^{-1} between 1901 and 2010 and increased to 3.2 [2.8 to 3.6] mm yr^{-1} between 1993 and 2010” (WGI 3 Executive Summary). In addition, observed changes in extreme sea level have been caused primarily by increases in mean sea level (WGI 3.7.5). Regional variations in the observed rate of sea level rise can result from processes related to atmosphere and ocean variability (such as lower rates along the west coast of the US) or vertical land motion (such as high rates along the US Gulf Coast), but the persistence of the observed regional patterns is unknown (WGI 3.7.3).

26.2.2.2. Climate Change Projections

Chapters 11 and 12 of the WGI contribution to the AR5 assess near-term and long-term future climate change, respectively. Chapter 14 of the WGI contribution assesses processes that are important for regional climate change, with section 14.8.3 focused on North America. Many of the WGI conclusions are drawn from Annex I of the WGI contribution to the AR5.

The CMIP5 ensemble projects *very likely* increases in mean annual temperature over North America, with *very likely* increases in temperature over all land areas in the mid- and late-21st-century periods in RCP2.6 and RCP8.5 (Figure 26-3). Ensemble-mean changes in mean annual temperature exceed 2˚C over most land areas of all three countries in the mid-21st-century period in RCP8.5 and the late-21st-century period in RCP8.5, and exceed 4˚C over most land areas of all three countries in the late-21st-century period in RCP8.5. However, ensemble-mean changes in mean annual temperature remain within 2˚C above the late 20th century baseline over most North American land areas in both the mid- and late-21st-century periods in RCP2.6. The largest changes in mean annual temperature occur over the high latitudes of the United States and Canada, as well as much of eastern Canada, including greater than 6˚C in the late-21st-century period in RCP8.5. The smallest changes in mean annual temperature occur over areas of southern Mexico, the Pacific Coast of the United States, and the southeastern United States.

The CMIP5 ensemble projects warming in all seasons over North America beginning as early as the 2016-2035 period in RCP2.6, with the greatest warming occurring in winter over the high latitudes (WGI Annex I and Figure 26-3)(Diffenbaugh and Giorgi, 2012). The CMIP5 and CMIP3 ensembles suggest that the response of warm-season temperatures to elevated radiative forcing is larger as a fraction of the baseline variability than the response of cold-season temperatures (Diffenbaugh and Scherer, 2011; Kumar *et al.*, 2013b), and the CMIP3 ensemble suggests that the response of temperature in low-latitude areas of North America is larger as a fraction of the baseline variability than the response of temperature in high-latitude areas (Diffenbaugh and Scherer, 2011). In addition, CMIP3 and a high-resolution climate model ensemble suggest that the signal-to-noise ratio of 21st century warming is far greater over the western US, northern Mexico and the northeastern US than over the central and southeastern US (Diffenbaugh *et al.*, 2011), a result that is similar to the observed pattern of temperature trend significance in the US (Figure 26-3).

Most land areas north of 45˚N exhibit *likely* or *very likely* increases in mean annual precipitation in the late-21st-century period in RCP8.5 (Figure 26-3). The high latitude areas of North America exhibit *very likely* changes in mean annual precipitation throughout the illustrative RCP periods, with *very likely* increases occurring in the mid-21st-century period in RCP2.6 and becoming generally more widespread at higher levels of forcing. In contrast, much of Mexico exhibits *likely* decreases in mean annual precipitation beginning in the mid-21st-century period in RCP8.5, with the area of *likely* decreases expanding to cover most of Mexico and parts of the southcentral and southwestern US in the late-21st-century period in RCP8.5. *Likely* changes in mean annual precipitation are much less common at lower levels of forcing. For example, *likely* changes in mean annual precipitation in the mid- and late-21st-century periods in RCP2.6 are primarily confined to increases over areas of Canada and Alaska, with no areas of Mexico and very few areas of the contiguous US exhibiting differences that exceed the baseline variability in more than 66% of the models.

CMIP5 projects increases in winter precipitation over Canada and Alaska, consistent with projections of a poleward shift in the dominant cold-season stormtracks (WGI 14.8.3) (Yin, 2005), extratropical cyclones (Trapp *et al.*, 2009) and areas of moisture convergence (WG1 14.8.3), as well as with projections of a shift towards positive North Atlantic Oscillation (NAO) trends (Hori *et al.*, 2007) WGI 14.8.3). CMIP5 also projects decreases in winter precipitation over the southwestern US and much of Mexico associated with the poleward shift in the dominant stormtracks and the expansion of subtropical arid regions (Seager and Vecchi, 2010); WGI 14.8.3). However, there are uncertainties in hydroclimatic change in western North America associated with the response of the tropical Pacific sea surface temperatures (SSTs) to elevated radiative forcing (particularly given the influence of tropical SSTs on the Pacific North American pattern (PNA) and north Pacific storm tracks) (Cayan *et al.*, 1999; Findell and Delworth, 2010; Seager and Vecchi, 2010); WGI 14.8.3), and not all CMIP5 models simulate the observed recent hydrologic trends in the region (Kumar *et al.*, 2013a)

For seasonal-scale extremes, CMIP5 projects substantial increases in the occurrence of extremely hot seasons over North America in early, middle and late 21st century periods in RCP8.5 (Diffenbaugh and Giorgi, 2012) (Figure 26-4). For example, during the 2046-2065 period in RCP8.5, more than 50% of summers exceed the respective late-20th-century maximum seasonal temperature value over most of the continent. CMIP3 projects similar increases in extremely hot seasons, including greater than 50% of summers exceeding a mid-20th-century baseline throughout much of North America by the mid-21st-century in the A2 scenario (Duffy and Tebaldi, 2012), and greater than 70% of summers exceeding the highest summer temperature observed on record over much of the western US, southeastern US and southern Mexico by the mid-21st-century in the A2 scenario (Battisti and Naylor, 2009). CMIP5 also projects substantial decreases in snow accumulation over the US and Canada (Diffenbaugh *et al.*, 2012) (Figure 26-4), suggesting that the increases in cold-season precipitation over these regions reflect a shift towards increasing fraction of precipitation falling as rain rather than snow (Diffenbaugh *et al.*, 2012). Over much of the western US and western Canada, greater than 80% of years exhibit March snow amount that that is less than the late-20th-century median value beginning in the mid-21st-century period in RCP8.5, with the ensemble-mean change exceeding 2 standard deviations of the ensemble spread. Likewise, greater than 60% of years exhibit March snow amount that is less than the late-20th-century minimum value in the late-21st-century period in RCP8.5, with the ensemble-mean change exceeding 2 standard deviations of the ensemble spread (Diffenbaugh and Giorgi, 2012) (Figure 26-4). CMIP5 also projects increases in the occurrence of extremely dry summer seasons over much of Mexico, the US and southern Canada (Figure 26-4). The largest increases occur over southern Mexico, where greater than 30% of summers in the late-21st-century period in RCP8.5 exhibit seasonal precipitation that is less than the late 20th century minimum summer precipitation.

[INSERT FIGURE 26-4 HERE
Figure 26-4: Projected changes in extremes in North America. (a) The percentage of years in the 2046–2065 period of RCP8.5 in which the summer temperature is greater than the respective maximum summer temperature of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 2012). (b) The percentage of years in the 2080-2099 period of RCP8.5 in which the summer precipitation is less than the respective minimum summer precipitation of the 1986-2005 baseline period (Diffenbaugh and Giorgi, 2012) (c) The percentage difference in the 20-year return value of annual precipitation extremes between the 2046-2065 period of RCP4.5 and the 1986-2005 baseline period (from (Kharin *et al.*, 2013). The hatching indicates areas where the differences are not significant at the 5% level. (d) The percentage of years in the 2070-2099 period of RCP8.5 in which the March snow water equivalent is less than the respective minimum March snow water equivalent of the 1976–2005 period (Diffenbaugh *et al.*, 2012). The black (white) stippling indicate areas where the multimodel mean exceeds 1.0 (2.0) standard deviations of the multi-model spread. (a-d) The RCPs and time periods are those used in the peer-reviewed studies in which the panels appear. The 2046-2065 period of RCP8.5 and the 2046-2065 period of RCP4.5 exhibit global warming in the range of 2-3˚C above the pre-industrial baseline (WGI Fig. 12.40). The 2080-2099 and 2070-2099 periods of RCP8.5 exhibit global warming in the range of 4-5˚C above the pre-industrial baseline (WGI Fig. 12.40).]

For daily-scale extremes, almost all areas of North America exhibit *very likely* increases of at least 5˚C in the warmest daily maximum temperature by the late-21st-century period in RCP8.5. Likewise, most areas of Canada exhibit *very likely* increases of at least 10˚C in the coldest daily minimum temperature by the late-21st-century period in RCP8.5, while most areas of the US exhibit *very likely* increases of at least 5˚C and most areas of Mexico exhibit *very likely* increases of at least 3˚C (Sillmann *et al.*, 2013) (WGI Fig. 12.13). In addition, almost all areas of North America exhibit *very likely* increases of 5% to 20% in the 20-year return value of extreme precipitation by the mid-21st-century period in RCP4.5 (Figure 26-4), while most areas of the US and Canada exhibit *very likely* increases of at least 5% in the maximum 5-day precipitation by the late-21st-century period in RCP8.5 (Sillmann *et al.*, 2013)(WGI Fig. 12.13). Further, almost all areas of Mexico exhibit *very likely* increases in the annual maximum number of consecutive dry days by the late-21st-century period in RCP8.5 (Sillmann *et al.*, 2013) (WGI Fig. 12.13).

26.3. Water Resources and Management

Water withdrawals are exceeding stressful levels in many regions of North America such as the southwest US, northern and central Mexico (particularly Mexico City), southern Ontario and the southern Canadian Prairies (Romero-Lankao, 2010; National Water Commission of Mexico, 2010; Sosa-Rodriguez, 2010; Averyt *et al.*, 2011;

Environment Canada, 2013a). Water quality is also a concern with 10% to 30% of the surface monitoring sites in Mexico having polluted water (National Water Commission of Mexico, 2010), and about 44% of assessed stream miles, and 64% of assessed lake areas in the US not clean enough to support their uses (U.S. Environmental Protection Agency, 2004). Stations in Canada's 16 most populated drainage basins reported at least fair quality, with many reporting good or excellent quality (Environment Canada, 2013b). In basins outside of the populated areas there are some cases of declining water quality where impacts are related to resource extraction, agriculture, and forestry (Hebben, 2009).

Water management infrastructure in most areas of North America is in need of repair, replacement or expansion (Section 26.7). Climate change, land use changes and population growth, and demand increases will add to these stresses(U.S. Global Change Research Program, 2009).

26.3.1. Observed Impacts of Climate Change on Water Resources

Droughts and Floods: As reported in WG1, Chapter 10 and 26.2.2.1, it is not possible to attribute changes in drought frequency in North America to anthropogenic climate change (Prieto-González *et al.*, 2011; Axelson *et al.*, 2012; Orlowsky and Senevirantne, 2013) (Figure 26-1). Few discernible trends in flooding have been observed in the US (Chapter 3). Changes in the magnitude or frequency of flood events have not been attributed to climate change. Floods are generated by multiple mechanisms (e.g., land use, seasonal changes and urbanization); trend detection is confounded by flow regulation, teleconnections and long-term persistence (section 26.2.2.1; (Kumar *et al.*, 2009; Collins, 2009; Smith *et al.*, 2010; Villarini and Smith, 2010; Villarini *et al.*, 2011; Hirsch and Ryberg, 2012; Prokoph *et al.*, 2012; Instituto Nacional de Ecología y Cambio Climático, 2012a; Peterson *et al.*, 2013).

Mean Annual Streamflow: While annual precipitation and runoff increases have been found in the Midwestern and Northwestern United States, decreases have been observed in southern states (Georgakakos *et al.*, 2013) . Chapter 3, WG2 notes the correlation between changes in streamflow and observed regional changes in temperature and precipitation. Kumar et al. (2009) suggest that human activities that have influenced observed trends in streamflow making attribution of changes to climate difficult in many watersheds. Nonetheless, earlier peak flow of snowmelt run-off in snow-dominated streams and rivers in western North America has been formally detected and attributed to anthropogenic climate change (Barnett *et al.*, 2008; Das *et al.*, 2011) (Figure 26-1).

Snow Melt: Warm winters produced earlier runoff and discharge but less snow water equivalent and shortened snowmelt seasons in many snow-dominated areas of North America (Barnett *et al.*, 2005; Rood *et al.*, 2008; Reba *et al.*, 2011) (Section 26.2.2., Chapter 3).

26.3.2. Projected Climate Change Impacts and Risks

26.3.2.1. Water Supply

Most of this assessment focuses on surface water as there are few groundwater studies (Tremblay *et al.*, 2011; Georgakakos *et al.*, 2013). Impacts and risks vary by region and model used.

In arid and semi-arid western US and Canada and in most of Mexico, except the southern tropical area, water supplies are projected to be further stressed by climate change, resulting in less water availability and increased drought conditions (Seager *et al.*, 2007; Instituto Mexicano de Tecnología del Agua, 2010; Cayan *et al.*, 2010; Montero Martinez *et al.*, 2010; MacDonald, 2010; Comisión Nacional del Agua, 2011; Prieto-González *et al.*, 2011; Bonsal *et al.*, 2012; Sosa-Rodriguez, 2013; Orlowsky and Senevirantne, 2013; Diffenbaugh and Field, 2013). Compounding factors include salt water intrusion, and increased groundwater and surface water pollution (Leal Asencio *et al.*, 2008).

In the US southwest and southeast, ecosystems and irrigation are projected to be particularly stressed by decreases in water availability due to the combination of climate change, growing water demand, and water transfers to urban and industrial users (Seager *et al.*, 2009; Georgakakos *et al.*, 2013). In the Colorado River Basin crop irrigation requirements for pasture grass are projected to increase by 20% by 2040 and by 31% by 2070 (Dwyer *et al.*, 2012). In the Rio Grande basin, New Mexico, runoff is projected decrease by 8%-30% by 2080 due to climate change. Water transfers may entail significant transaction costs associated with adjudication and potential litigation; and might have economic, environmental, social, and cultural impacts that vary by water user (Hurd and Coonrod, 2012). In Mexico, water shortages combined with increased water demands are projected to increase surface and groundwater over exploitation (Comisión Nacional del Agua, 2011).

Other parts of North American are projected to have different climate risks. The vulnerability of water resources over the tropical southern region of Mexico is projected to be low for 2050: precipitation decreases from 10%-5% in the summer and no precipitation changes in the winter. After 2050, greater winter precipitation is projected, increasing the possibility of damaging hydropower and water storage damns by floods, while precipitation is projected to decrease by 40%-35% in the summer (Instituto Mexicano de Tecnología del Agua, 2010).

Throughout the 21st century, cities in NW Washington are projected to have drawdown of average seasonal reservoir storage in the absence of demand reduction because of less snow pack even though annual stream flows increase. Without accounting for demanding increases, projected reliability of all systems remains above 98% through mid and late century (Vano *et al.*, 2010a; Comisión Nacional del Agua, 2011). Throughout the eastern US, water supply systems will be negatively impacted by lost snowpack storage; rising sea levels contributing to increased storm intensities and salt water intrusion; possibly lower stream-flows; land use and population changes; and other stresses (Sun *et al.*, 2008; Obeysekera *et al.*, 2011).

In Canada’s Pacific Northwest Region, cool season flows are expected to increase, while warm seasons flows would decrease (Hamlet, 2011). Southern Alberta, where approximately two-thirds of Canadian irrigated land is located, is projected to experience declines in mean annual stream flow, especially during the summer (Shepherd *et al.*, 2010; Poirier and de Loë, 2012; Tanzeeba and Gan, 2012). In the Athabasca River Basin in northern Alberta, modeling results consistently indicate large projected declines in mean annual flows (Kerkhoven and Gan, 2011). In contrast, modeling results for basins in Manitoba indicate an increase in mean annual runoff (Choi *et al.*, 2009). Some model results for the Fraser River Basin in British Columbia indicate increases in mean annual runoff by the end of the 21st Century, while others indicate decreases (Kerkhoven and Gan, 2011). In central Quebec, (Chen *et al.*, 2011b) project a general increase in discharge during November-April, and a general decrease in summer discharge under most climate change conditions.

26.3.2.2. Water Quality

Many recent studies project water quality declines due to the combined impacts of climate change and development (Daley *et al.*, 2009; Tu, 2009; Praskievicz and Chang, 2011; Wilson and Weng, 2011; Tong *et al.*, 2012). Increased wildfires linked to a warming climate are expected to affect water quality downstream of forested headwater regions (Emelko *et al.*, 2011). Model simulation of lakes under a range of plausible higher air temperatures (Tahoe, Great Lakes, Lake Onondaga and shallow polymictic lakes), depending on the system, predict a range of impacts such as increased phytoplankton, fish and cyanobacteria biomass, lengthened stratification periods with risks of significant hypolimnetic oxygen deficits in late summer with solubilization of accumulated phosphorous and heavy metals with accelerated reaction rates, and decreased lake clarity (Dupuis and Hann, 2009; Trumpickas *et al.*, 2009; Sahoo *et al.*, 2011; Taner *et al.*, 2011). Model simulations have found seasonal climate change impacts on nonpoint source pollution loads, while others have found no impact (Marshall and Randhir, 2008; Tu, 2009; Taner *et al.*, 2011; Praskievicz and Chang, 2011).

Changes in physical-chemical-biological parameters and micropollutants are predicted to negatively affect drinking water treatment and distribution systems (Delpla *et al.*, 2009; Carriere *et al.*, 2010; Emelko *et al.*, 2011). Wastewater treatment plants would be more vulnerable as increases in rainfall and wet weather lead to higher rates of inflow and infiltration (New York City Department of Environmental Protection, 2008; King County Department of Natural Resources and Parks, 2008; Flood and Cahoon, 2011). They would also face reduced hydraulic capacities due to higher sea levels and increased river and coastal flooding (Flood and Cahoon, 2011), with higher sea levels also threatening sewage collection systems (Rosenzweig *et al.*, 2007; King County Department of Natural Resources and Parks, 2008)

26.3.2.3. Flooding

Projected increases in flooding (Georgakakos *et al.*, 2013) may affect sectors ranging from agriculture and livestock in southern tropical Mexico (National Water Commission of Mexico, 2010) to urban and water infrastructure in areas such as Dayton, Ohio, metro Boston and the Californian Bay-Delta region (Committee on Flood Control Alternatives in the American River Basin *et al.*, 1995; Kirshen *et al.*, 2006; California Department of Water Resources, 2009; Wu, 2010). Floods could begin earlier, have earlier peaks and longer durations (e.g., southern Quebec basin). Urbanization can compound the impacts of increased flooding due to climate change, particularly in the absence of flood management infrastructure that takes climate change into account (Hejazi and Markus, 2009; Mailhot and Duchesne, 2010; Sosa-Rodriguez, 2010). (Ntelekos *et al.*, 2010) estimate that annual riverine flood losses in the USA could increase from approximately $2 billion now to $7-$19 billion annually by 2100 depending upon emission scenario and economic growth rate.

26.3.2.4 Instream Uses

Projections of climate impacts on instream uses vary by region and time-frame. Hydropower generation, affected by reduced lake levels, is projected to decrease in arid and semi-arid areas of Mexico (Comisión Intersecretarial de Cambio Climatico, 2009; Sosa-Rodriguez, 2013) and in the Great Lakes (Buttle *et al.*, 2004; Mortsch *et al.*, 2006; Georgakakos *et al.*, 2013). In the US Pacific Northwest under several emission scenarios. it is projected to increase in 2040 by approximately 5% in the winter and decrease by approximately 13% in the summer, with annual reductions of approximately 2.5%. Larger increases and decreases are projected by 2080 (Hamlet *et al.*, 2010). On the Peribonka River system in Quebec, annual mean hydropower production will similarly decrease in the short-term increase by as much as 18 % in late 21st century (Minville *et al.*, 2009). Navigation on the Great Lakes, Mississippi River and other inland waterways may benefit from less ice cover but will be hindered by increased floods and low river levels during droughts (Georgakakos *et al.*, 2013).

26.3.3. Adaptation

There are a range of structural and non-structural adaptation measures being implemented with many being no-regret policies. For instance, in preparation for more intense storms, New York City is using green infrastructure to capture rainwater before it can flood the combined sewer system and is elevating boilers and other equipment above ground (Bloomberg, 2012). The Mexican cities of Monterrey, Guadalajara, Mexico City and Tlaxcala are reducing leaks from water systems (Comisión Intersecretarial de Cambio Climatico, 2009; National Water Commission of Mexico, 2010; Sosa-Rodriguez, 2010; Romero-Lankao, 2010). Regina, SK has increased urban water conservation efforts (Natural Resources Canada, 2008).

The 540-foot high, 1300-foot long concrete Ross Dam in the state of Washington, US was built on a special foundation so it could later be raised in height (Simmons, 1974). Dock owners in the Trent-Severn Waterway in the Great Lakes have moved their docks into deeper water to better manage impacts on shorelines (Coleman *et al.*, 2013). The South Florida Water Management District is assessing the vulnerability to sea level rise of its aging coastal flood control system and exploring adaptation strategies, including a strategy known as forward pumping (Obeysekera *et al.*, 2011). In Cambridge, Ontario, extra capacity culverts are being installed in anticipation of larger runoff (Scheckenberger *et al.*, 2009).

Water meters have been installed to reduce consumption by different users such as Mexican and Canadian farmers and in households of several Canadian cities (Instituto Nacional de Ecología y Cambio Climático, 2006; Natural Resources Canada, 2008). Agreements and regulations are underway such as the 2009 SECURE Water Act which establishes a federal climate change adaptation program with required studies to assess future water supply risks in the western U.S (42 USC § 10363). One such large, multi-year study was recently completed in the US for the Colorado River (Bureau of Reclamation, 2013) and others are planned. Agreements and regulations are underway, such as the 2007 Shortage Sharing Agreement for the management of the Colorado River, driven by concerns about water conservation, planning, better reservoir coordination, and preserving flexibility to respond to climate change(Bureau of Reclamation, 2007). Quebec Province is requiring dam safety inspections every 10 years to account for new knowledge on climate change impacts (Centre d'expertise hydrique du Québec, 2003). Expanded beyond flood and hydropower management to now include climate change, the Columbia River Treaty is a good example of an international treaty to manage a range of water resources challenges(U.S. Army Corps of Engineers and Bonneville Power Administration, 2013).

26.4. Ecosystems and Biodiversity

26.4.1. Overview

Recent research has documented gradual changes in physiology, phenology and distributions in North American ecosystems consistent with warming trends (Dumais and Prévost, 2007). Changes in phenology and species' distributions, particularly in the United States and Canada, have been attributed to rising temperatures, which have in turn been attributed to anthropogenic climate change via joint attribution (Root *et al.*, 2005; Vose *et al.*, 2012). Concomitant with 20th century temperature increases, northward and upward shifts in plant, mammal, bird, lizard, and insect species' distributions have been documented extensively in the western United States and eastern Mexico (Parmesan, 2006; Kelly and Goulden, 2008; Moritz *et al.*, 2009; Tingley *et al.*, 2009; Sinervo *et al.*, 2010). These distribution shifts consistent with climate-change interact with other environmental changes such as land-use change, hindering the ability of species to respond (Ponce-Reyes *et al.*, 2013).

A range of techniques have been applied to assess the vulnerability of North American ecosystems and species to changes in climate (Loarie *et al.*, 2009; Anderson *et al.*, 2009; Glick and Stein, 2011). A global risk analysis based on dynamic global vegetation models identified boreal forest in Canada as notably vulnerable to ecosystem shift (Scholze *et al.*, 2006). Since the AR4, the role of extreme events, including droughts, flood, hurricanes, storm surges, and heat waves, is a more prominent theme in studies of climate change impacts on North American ecosystems (Chambers *et al.*, 2007; IPCC, 2012).

A number of ecosystems in North America are vulnerable to climate change. For example, species in alpine ecosystems are at high risk due to limited geographic space into which to expand (Villers-Ruiz and Castañeda-Aguado, In press). Many forest ecosystems are susceptible to wildfire and large-scale mortality and infestations events (section 26.4.1). Across the continent, potentially rapid rates of climate change may require location shifts at velocities well outside the range in historical reconstructions (Sandel *et al.*, 2011; Schloss *et al.*, 2012). Changes in temperature, precipitation amount, and carbon dioxide concentrations can have different effects across species and ecological communities (Parmesan, 2006; Matthews *et al.*, 2011), leading to ecosystem disruption and reorganization (Smith *et al.*, 2011; Dukes *et al.*, 2011), as well as movement or loss.

The following section focuses in more depth on climate vulnerabilities in forests and coastal ecosystems. These ecosystems span all three North American countries, are illustrative cases of where understanding the opportunities for conservation and adaptation practices is important, and recent research advances and new evidence of increased vulnerabilities since AR4 motivate further exploration. Further treatment of grasslands and shrublands can be found in AR5 WGII 4.3.3.2.2, wetlands and peatlands 4.3.3.3, and tundra, alpine, and permafrost systems in 4.3.3.4. Additional synthesis of climate change impacts on terrestrial, coastal and ocean ecosystems can be found in Chapter 8 of the US National Climate Assessment (Groffman *et al.*, 2013).

26.4.2. Tree Mortality and Forest Infestation

26.4.2.1. Observed Impacts

Droughts of unusual severity, extent, and duration have affected large parts of western and southwestern North America and resulted in regional-scale forest dieback in Canada, US and Mexico. Extensive tree mortality has been related to drought exacerbated by high summertime temperatures in trembling aspen (*Populus tremuloides*), pinyon pine (*Pinus edulis*) and lodgepole pine (*Pinus contorta*) since the early 2000s (Breshears *et al.*, 2005; Hogg *et al.*, 2008; Raffa *et al.*, 2008; Michaelian *et al.*, 2011; Anderegg *et al.*, 2012). In 2011 and 2012 forest dieback in Northern and central Mexico was associated with extreme temperatures and severe droughts (Comisión Nacional Forestal, 2012a).Widespread forest-mortality events triggered by extreme climate events can alter ecosystem structure and function (Phillips *et al.*, 2009; Allen *et al.*, 2010; Anderegg *et al.*, 2013). Similarly, multi-decadal changes in demographic rates, particularly mortality, indicate climate-mediated changes in forest communities over longer periods (Hogg and Bernier, 2005; Williamson *et al.*, 2009). Average annual mortality rates increased from less than 0.5% of trees per year in the 1960s in forests of western Canada and the US to, respectively, 1.5-2.5% (Peng *et al.*, 2011), and 1.0-1.5% in the 2000s in the US (van Mantgem *et al.*, 2009).

The influences of climate change on ecosystem disturbance, such as insect outbreaks have become increasingly salient and suggest that these disturbances could have a major influence on North American ecosystems and economy in a changing climate. In terms of carbon stores these outbreaks have the potential to turn forests into carbon sources (Kurz *et al.*, 2008a; Kurz *et al.*, 2008b; Hicke *et al.*, 2012). Warm winters in western Canada and US have increased winter survival of the larvae of bark beetles, helping drive large-scale forest infestations and forest die-off in western North America since the early 2000s (Bentz *et al.*, 2010). Beginning in 1994, mountain pine beetle outbreaks have severely affected over 18 million hectares of pine forests in British Columbia, and outbreaks are expanding northwards (Energy, Mines and Resources: Forest Management Branch, 2012).

26.4.2.2. Projected Impacts and Risks

Projected increases in drought severity in southwestern forests and woodlands in United States and northwestern Mexico suggest that these ecosystems may be increasingly vulnerable, with impacts including vegetation mortality (Seager and Vecchi, 2010; Williams *et al.*, 2010; Overpeck and Udall, 2010) and an increase of biological agents such as beetles, borers, pathogenic fungi, budworms and other pests (Drake *et al.*, 2005). An index of forest drought stress calibrated from tree rings indicates that projected drought stress by the 2050s in the SRES A2 scenario from the CMIP3 model ensemble, due primarily to warming-induced rises in vapor pressure deficit, exceeds the most severe droughts of the past 1,000 years (Park *et al.*, 2013).

Under a scenario with large changes in global temperature (SRES A2) increases in growing-season temperature in forest soils in southern Quebec are as high as 5.0 C towards the end of the century and decreases of soil water content reach 20-40% due to elevated evapotranspiration rates (Houle *et al.*, 2012). More frequent droughts in tropical forests may change forest structure and regional distribution, favoring a higher prevalence of deciduous species in the forests of Mexico (Drake *et al.*, 2005; Trejo *et al.*, 2011).

Shifts in climate are expected to lead to changes in forest infestation, including shifts of insect and pathogen distributions into higher latitudes and elevations (Bentz *et al.*, 2010). Predicted climate warming is expected to have effects on bark beetle population dynamics in the western United States, western Canada, and northern Mexico that may include increases in developmental rates, generations per year, and changes in habitat suitability (Waring *et al.*, 2009). As a result, the impacts of bark beetles on forest resources are expected to increase (Waring *et al.*, 2009).

Wildfire, a potentially powerful influence on North American forests in the 21st century, is discussed in Box 26-2.

26.4.3. Coastal Ecosystems

Highly productive estuaries, coastal marshes and mangrove ecosystems are present along the Gulf coast and the East and West coasts of North America. These ecosystems are subject to a wide range of non-climate stressors, including urban and tourist developments and the indirect effects of overfishing (Mortsch *et al.*, 2006; Bhatti *et al.*, 2006; Lund *et al.*, 2007; Comisión Nacional para el Conocimiento y Uso de la Biodiversidad *et al.*, 2007). Climate change adds risks from sea-level rise, warming, ocean acidification, extratropical cyclones, altered upwelling, and hurricanes and other storms.

26.4.3.1. Observed Climate Impacts and Vulnerabilities

Sea level rise, which has not been uniform across the coasts of North America (Crawford *et al.*, 2007; Kemp *et al.*, 2008; Leonard *et al.*, 2009; Zavala-Hidalgo *et al.*, 2010; Sallenger *et al.*, 2012), is directly related to flooding and loss of coastal dunes and wetlands, oyster beds, seagrass and mangroves (Feagin *et al.*, 2005; Cooper *et al.*, 2008; Najjar *et al.*, 2010; Ruggiero *et al.*, 2010; McKee, 2011; Martinez Arroyo *et al.*, 2011).

Increases in sea surface temperature in estuaries alter metabolism, threatening species, especially cold water fish (Crawford *et al.*, 2007). Historical warm periods have coincided with low salmon abundance and restriction of fisheries in Alaska (Crozier *et al.*, 2008; U.S. Global Change Research Program, 2009). North Atlantic cetaceans, and tropical coral reefs in the Gulf of California and the Caribbean have been affected by increases in the incidence of diseases associated with warm waters and low water quality (Mumby *et al.*, 2011; International Council for the Exploration of the Sea, 2011).

Increased concentrations of CO_2 in the atmosphere due to human emissions are causing ocean acidification (Executive summary chapters 5 and 6; FAQ 5.1). Along the temperate coasts of North America acidification directly affects calcareous organisms, including colonial mussel beds, with indirect influences on food webs of benthic species (Wootton *et al.*, 2008). Increased acidity in conjunction with high temperatures has been identified as a serious threat to coral reefs and other marine ecosystems in the Bahamas and the Gulf of California(Doney *et al.*, 2009; Hernández *et al.*, 2010; Mumby *et al.*, 2011).

Tropical storms and hurricanes can have a wide range of effects on coastal ecosystems, potentially altering hydrology, geomorphology (erosion), biotic structure in reefs and nutrient cycling. Hurricane impacts on the coastline change dramatically the marine habitat of sea turtles, reducing feeding habitats, such as coral reefs and areas of seaweed, and nesting places. (Márquez, R. and Jiménez, Ma. del C., 2010; Liceaga-Correa *et al.*, 2011)

26.4.3.2. Projected Impacts and Risks

Projected increases in sea levels, particularly along the coastlines of Florida, Louisiana, North Carolina, and Texas (Kemp *et al.*, 2008; Leonard *et al.*, 2009; Weiss *et al.*, 2011), will threaten many plants in coastal ecosystems through increased inundation, erosion, and salinity levels. In settings where landward shifts are not possible, a 1 m rise in sea level will result in loss of wetlands and mangroves along the Gulf of Mexico of 20% (in Tamaulipas) to 94% (in Veracruz) (Flores Verdugo *et al.*, 2010).

Projected impacts of increased water temperatures include contraction of coldwater fish habitat and expansion of warm-water fish habitat (Mantua *et al.*, 2010), which can increase the presence of invasive species that threaten resident populations (Janetos *et al.*, 2008). Depending on scenario, Chinook salmon in the Pacific Northwest may decline by 20 to 50% by 2040-50 (Battin *et al.*, 2007; Crozier *et al.*, 2008), integrating across restrictions in productivity and abundance at the southern end of their range and expansions at the northern end (Azumaya *et al.*, 2007), although habitat restoration and protection particularly at lower elevations may help mitigate declines in abundance.

Continuing ocean acidification will decrease coral growth and interactions with temperature increases will lead to increased risk of coral bleaching, leading to declines in coral ecosystem biodiversity (Veron *et al.*, 2009) (5.4.2.4, Box CC-OA). Oyster larvae in Chesapeake Bay grew more slowly when reared with CO_2 levels between 560 and 480ppm compared to current environmental conditions (Gazeau *et al.*, 2007; Miller *et al.*, 2009; Najjar *et al.*, 2010).

While future trends in thunderstorms and tropical cyclones are uncertain (26.2.2), any changes, particularly an increase in the frequency of category 4 and 5 storms (Bender *et al.*, 2010; Knutson *et al.*, 2010) could have profound impacts on mangrove ecosystems, which require 25 years for recovery from storm damage (Kovacs *et al.*, 2004; Flores Verdugo *et al.*, 2010).

26.4.4. Ecosystems Adaptation, and Mitigation

In North America, a number of adaptation strategies, are being applied in novel and flexible ways to address the impacts of climate change (Mawdsley *et al.*, 2009; National Oceanic and Atmospheric Administration, 2010; Gleeson *et al.*, 2011; Poiani *et al.*, 2011). The best of these are based on detailed knowledge of the vulnerabilities and sensitivities of species and ecosystems, and with a focus on opportunities for building resilience through effective ecosystem management. Government agencies and nonprofit organizations have established initiatives that emphasize the value of collaborative dialogue between scientists and practitioners, indigenous communities, and grass-roots organizations to develop no-regrets and co-benefits adaptation strategies (Ogden and Innes, 2009; Gleeson *et al.*, 2011; Halofsky *et al.*, 2011; Cross *et al.*, 2012; Instituto Nacional de Ecología y Cambio Climático, 2012b; Cross *et al.*, 2013).

Examples of adaptation measures implemented to respond to climate change impacts on ecosystems are diverse. They include programs to reduce the incidence of Canadian forest pest infestations (Johnston *et al.*, 2010); breeding programs for resistance to diseases and insect pests (Yanchuk and Allard, 2009); use of forest programs to reduce the incidence of forest fires and encourage agroforestry in areas of Mexico (Sosa-Rodriguez, 2013); and selection by forest or fisheries managers of activities that are more adapted to new climatic conditions (Vasseur and Catto, 2008). Example programs have addressed commercial fishing, mass tourism (Pratchett *et al.*, 2008), and enforcement mechanisms for using water regulation technologies to maintain quantity and quality in wetlands around the Great Lakes and San Francisco, California (Mortsch *et al.*, 2006; Okey *et al.*, 2012). Assisted migration is increasingly discussed as a potential management option to maintain health and productivity of forests; yet the technique has logistical and feasibility challenges (Keel, 2007; Hoegh-Guldberg *et al.*, 2008; Winder *et al.*, 2011).

Several lines of evidence indicate that effective adaptation requires changes in approach and becomes much more difficult if warming exceeds 2°C above preindustrial levels (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad *et al.*, 2007; Mansourian *et al.*, 2009; U.S. Forest Service, 2010; Glick and Stein, 2011; Barragan *et al.*, 2011; Instituto Nacional de Ecología y Cambio Climático, 2012b). Even though options for effective adaptation are increasingly constrained at warming over 2°C, some opportunities will remain. In particular, efforts to maintain or increase forest carbon stocks can lead to numerous benefits, including not only benefits for atmospheric CO_2 (Anderson and Bell, 2009; Anderson *et al.*, 2011). Even where there are opportunities, managers face challenges in designing management practices that favor carbon stocks, while at the same time maintaining biodiversity, recognizing the rights of indigenous people, and contributing to local economic development (Food and Agriculture Organization, 2012).

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Box 26-2. Wildfires

Wildfire is a natural process, critical to nutrient cycling, controlling populations of pests and pathogens, biodiversity and fire-adapted species (Bond and Van Wilgen, 1996). However, since the mid-1980s large wildfire activity in North America has been marked by increased frequency and duration, and longer wildfire seasons (Westerling *et al.*, 2006; Williamson *et al.*, 2009). Recent wildfires in western Canada, the US and Mexico relate to long and warm spring and summer droughts, particularly when they are accompanied by winds (Holden *et al.*, 2007; Comisión

Nacional Forestal, 2012b). Interacting processes such as land-use changes associated with the expansion of settlements and activities in peri-urban areas or forested areas, combined with the legacies of historic forest management that prescribed fire suppression, also substantially increase wildfire risk (Radeloff *et al.*, 2005; Peter *et al.*, 2006; Theobald and Romme, 2007; Fischlin *et al.*, 2007; Gude *et al.*, 2008; Collins and Bolin, 2009; Hammer *et al.*, 2009; Brenkert-Smith, 2010).

Drought conditions are strongly associated with wildfire occurrence, as dead fuels such as needles and dried stems promote the incidence of firebrands and spot fires (Keeley and Zedler, 2009; Liu *et al.*, 2012). Drought trends vary across regions (Groisman *et al.*, 2007; Girardin *et al.*, 2012): the western US has experienced drier conditions since the 1970s (Peterson *et al.*, 2013); drought periods in Alberta and Idaho have coincided with large burned areas (Pierce and Meyer, 2008; Kulshreshtha, 2011); heterogeneous patterns of drought severity and a reduction of wildfire risk have been detected for the circumboreal region (Girardin *et al.*, 2009). Decadal climatic oscillations also contribute to differences in drought, and thus in wildfire occurrences. The areas burned in the continent boreal forest and in northwest and central Mexico correlate to the dynamics of seasonal land/ocean temperature variability (Macias Fauria and Johnson, 2006; Skinner *et al.*, 2006; Villers-Ruíz and Hernández-Lozano, 2007; Macias Fauria and Johnson, 2008; Girardin and Sauchyn, 2008); which is shifting toward hotter temperatures and longer droughts. Such human practices as slash-and-burn agriculture can have negative impacts on Mexican forests (Bond and Keeley, 2005; Comisión Nacional de Áreas Naturales Protegidas and The Nature Conservancy, Programa México, 2009).

Drought index projections and climate change regional models show increases in wildfire risk during the summer and fall on the southeast Pacific coast, Northern Plains and the Rocky Mountains (Liu *et al.*, 2012). In places like Sierra Nevada, mixed conifer forests, which have a natural cycle of small, non-crown fires, are projected to have massive crown-fires (Bond and Keeley, 2005) (Table 26-1).

While healthy forests (Davis, 2004) and many fire-maintained systems that burn at lower intensities can provide carbon sequestration and thus mitigation co-benefits (e.g., Longleaf pine savanna, Sierra mixed-conifer)(Fried *et al.*, 2008; North *et al.*, 2012), forests affected by pests and fires are less effective carbon sinks, and wildfires themselves are a source of emissions.

Wildfires pose a direct threat to human lives, property and health. Over the last 30 years, 155 people were killed in wildfires across North America, including 103 in the United States, 50 in Mexico and 2 in Canada (Centre for Research on the Epidemeology of Disasters, 2012). Direct effects include injury and respiratory effects from smoke inhalation, with firefighters at increased risk (Naeher *et al.*, 2007; Reisen and Brown, 2009; Reisen *et al.*, 2011). Wildfire activity causes impacts on human health (section 26.6).

Minimizing adverse effects of wildfires involves short-term and long-term strategies such as planned manipulation of vegetation composition and stand structure (Girardin *et al.*, 2012; Terrier *et al.*, 2013), suppression of fires where required, fuel treatments, use of fire-safe materials in construction, community planning, and reduction of arson. Not all negative consequences of fire can be avoided, though a mixture of techniques can be used to minimize adverse effects (Girardin *et al.*, 2012). Prescribed fire may be an important tool for managing fire risk in Canada and the US (Hurteau and North, 2010; Wiedinmyer and Hurteau, 2010; Hurteau *et al.*, 2011). Managers in the US have encouraged reduction of flammable vegetation around structures with different levels of success (Stewart *et al.*, 2006). However, such efforts depend largely on land-use planning, the socio-economic capacity of communities at risk, the extent of resource dependence, community composition, and the risk perceptions, attitudes and beliefs of decision-makers, private property owners, and affected populations (McFarlane, 2006; Repetto, 2008; Collins and Bolin, 2009; Martin *et al.*, 2009; Trainor *et al.*, 2009; Brenkert-Smith, 2010). Indigenous peoples are at higher risk from wildfire and may have unique requirements for adaptation strategies (Carroll *et al.*, 2010; Christianson *et al.*, 2012a; Christianson *et al.*, 2012b).

Effective forest management requires stakeholder involvement and investment. The provision of adequate information on smoke, prescribed fire, pest management, and forest thinning is crucial, as is building trust between stakeholders and land managers (Dombeck *et al.*, 2004; Flint *et al.*, 2008; Chang *et al.*, 2009). Institutional shifts from reliance on historical records toward incorporation of climate forecasting in forest management is also crucial to effective adaptation (McKenzie *et al.*, 2004; Millar *et al.*, 2007; Kolden and Brown, 2010).

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26.5. Agriculture and Food Security

Projected declines in global agricultural productivity (Chapter 7) have implications for food security among North Americans. Because North America is a major exporter (Food and Agriculture Organization, 2009; Schlenker and Roberts, 2009), shifts in agricultural productivity here may have implications for global food security. Canada and the US are relatively food secure, although households living in poverty are vulnerable. 17.6% of Mexicans are food insecure (Monterroso *et al.*, 2012). Indigenous peoples are highly vulnerable due to high reliance on subsistence (Chapter 12). While this section focuses on agricultural production, food security is related to multiple factors (See Chapter 7).

26.5.1. Observed Climate Change Impacts

Historic yield increases are attributed in part to increasing temperatures in Canada and higher precipitation in the US (Pearson *et al.*, 2008; Sakurai *et al.*, 2011; Nadler and Bullock, 2011); (high agreement, medium evidence), although multiple non-climatic factors affect historic production rates. In many North American regions optimum temperatures have been reached for dominant crops, thus continued regional warming would diminish rather than enhance yields (Jones *et al.*, 2005) (high confidence). Regional yield variances over time have been attributed to climate variability –e.g., Ontario (Cabas *et al.*, 2010) and Quebec (Almaraz *et al.*, 2008). Since 1999 a marked increase in crop losses attributed to climate-related events such as drought, extreme heat and storms has been observed across North America (Hatfield *et al.*, 2013), with significant negative economic effects (Swanson *et al.*, 2007; Chen and McCarl, 2009; Costello *et al.*, 2009) (high confidence). In Mexico, agriculture accounted for 80% of weather-related financial losses since 1990 (Saldaña-Zorrilla, 2008) (Figure 26-2).

26.5.2. Projected Climate Change Risks

Studies project productivity gains in northern regions and where water is not projected to be a limiting factor, across models, time frames and scenarios (Hatfield *et al.*, 2008; Pearson *et al.*, 2008; Wheaton *et al.*, 2010; Stöckle *et al.*, 2010); (high confidence). Overall yields of major crops in North America are projected to decline modestly by mid-century and more steeply by 2100 among studies that do not consider adaptation (very high confidence). Certain regions and crops may experience gains in the absence of extreme events, and projected yields vary by climate model (Paudel and Hatch, 2012; Liu *et al.*, 2013).

Among studies projecting yield declines, two factors stand out: exceedance of temperature thresholds, and water availability. Yields of several important North American agriculture sectors—including grains, forage, livestock and dairy—decline significantly above temperature thresholds (Wolfe *et al.*, 2008; Schlenker and Roberts, 2009; Craine *et al.*, 2010) Temperature increases affect product quality as well –e.g., coffee (Lin, 2007), wine grapes (Hayhoe *et al.*, 2004; Jones *et al.*, 2005), wheat (Porter and Semenov, 2005), fruits and nuts (Lobell *et al.*, 2006), and cattle forage (Craine *et al.*, 2010).

Projected temperature increases would reduce corn, soy and cotton yields by 2020, with declines ranging from 30-82% by 2099 depending on crop and scenario (steepest decline for corn, A1) (Schlenker and Roberts, 2009). Studies also project increasing inter-annual yield variability over time (Sakurai *et al.*, 2011; Urban *et al.*, 2012). Several studies focus on California, one of North America's most productive agricultural regions. Modest and variable yield changes among several California crops are projected to 2026, with yield declines from 9-29% by 2097 (A2, DAYCENT model). (Lobell and Field, 2011; Lee *et al.*, 2011) found little negative effect for California perennials by 2050 due to projected climate change, assuming irrigation access (GCM ensemble, A2 and B1). (Hannah *et al.*, 2013), however, project large declines in land suitability for California viticulture by 2050 (with increases further north) with RCPs 4.5 and 8.5 (GCM ensemble); declines greater under RCP 8.5. Heat-induced livestock stress, combined with reduced forage quality, would reduce milk production and weight gain in cattle (Wolfe *et al.*, 2008; Hernandez *et al.*, 2011).

Precipitation increases off-set but do not entirely compensate for temperature-related declines in productivity (Kucharik and Serbin, 2008). In regions projected to experience increasing temperatures combined with declining precipitation, declines in yield and quality are more acute (Craine *et al.*, 2010; Monterroso Rivas *et al.*, 2011).

Projected change in climate will reduce soil moisture and water availability in the US Western/Southwest, the Western Prairies in Canada, and central and northern Mexico (Pearson *et al.*, 2008; U.S. Global Change Research Program, 2009; Cai *et al.*, 2009; Esqueda *et al.*, 2010; Vano *et al.*, 2010b; Kulshreshtha, 2011) (very high confidence). CMIP5 models indicate soil moisture decreases across the continent in Spring and Summer under RCP8.5, with high agreement (Dirmeyer *et al.*, 2013). Based on a combined exposure/consumptive water use model, the US Great Plains is identified as one of four global future vulnerability hotspots for water availability from the 2030s and beyond, where anticipated water withdrawals would exceed 40% of freshwater resources (Liu *et al.*, 2013). In western US and Canada, projected earlier Spring snowmelt and reduced snowpack would affect productivity negatively regardless of precipitation, as water availability in Summer and Fall are reduced (Schlenker *et al.*, 2007; Forbes *et al.*, 2011; Kienzle *et al.*, 2012).

Projected increases in extreme heat, drought and storms affect productivity negatively (Chen and McCarl, 2009; Kulshreshtha, 2011). The northeastern and southeastern US have been identified as "vulnerability hotspots" for corn and wheat production respectively by 2045 with vulnerability worsening thereafter, using a combined drought exposure and adaptive capacity assessment, with only slight differences between A1B and B2 scenarios (Fraser *et al.*, 2013). Central North America is identified as among the globe's regions of highest risk of heat stress by 2070 (NIES GCM; A1B) (Teixeira *et al.*, 2013).

26.5.3. A Closer Look at Mexico

Much of Mexico's landbase is already marginal for two of the country's major crops: corn and beef (Buechler, 2009). Severe desertification in Mexico due to non-climate drivers further compromises productivity (Huber-Sannwald *et al.*, 2006). Land classified suitable for rain-fed corn is projected to decrease from 6.2% currently to between 3% and 4.3% by 2050 (UKHadley B2, ECHAM5/MPI A2) (Monterroso Rivas *et al.*, 2011). The distribution of most races of corn is expected to be reduced and some eliminated by 2030 (A2, three climate models) (Ureta *et al.*, 2012). Precipitation declines of 0-30% are projected over Mexico by 2040; with the most acute declines in Northwestern Mexico, the primary region of irrigated grain farming (declines steeper in A2 than A1B (18 model ensemble).

Although projected increases in precipitation may contribute to increase in rangeland productivity in some regions (Monterroso Rivas *et al.*, 2011), a study in Veracruz indicates that the effects of projected maximum summer temperatures on livestock heat stress are expected to reach the "Danger level" (at which losses can occur) by 2020 and continue to rise (A2, B2, three GCMs) (Hernandez *et al.*, 2011). Coffee, an economically important crop supporting 500,000 primarily indigenous households (González Martínez, 2006), is projected to decline 34% by 2020 in Veracruz if historic temperature and precipitation trends continue (Gay *et al.*, 2006); see also (Schroth *et al.*, 2009), on declines in Chiapas).

Many of Mexico's agricultural communities are also considered highly vulnerable, due to high sensitivity and/or low adaptive capacity (Monterroso *et al.*, 2012). The agriculture sector here consists primarily of small farmers (Claridades Agropecuarias 2006), who face high livelihood risks due to limited access to credit and insurance (Eakin and Tucker, 2006; Wehbe *et al.*, 2008; Saldaña-Zorilla and Sandberg, 2009; Walthall *et al.*, 2012).

26.5.4. Adaptation

The North American agricultural industry has the adaptive capacity to off-set projected yield declines and capitalize on opportunities under 2° warming. (Butler and Huybers, 2012) project a reduction in US corn yield loss from 14% to 6% with 2° warming, with spatial shifts in varietal selection (not accounting for variability in temperature and precipitation). Incremental strategies, such as planting varieties better suited to future climate conditions and changing planting dates, have been observed across the continent (Bootsma *et al.*, 2005; Conde *et al.*, 2006; Eakin and Appendini, 2008; Coles and Scott, 2009; Nadler and Bullock, 2011; Paudel and Hatch, 2012; Campos *et al.*, 2013). In some sectors we are seeing multi-organizational investments in adaptation. International coffee retailers and non-governmental organizations, for example, are engaged in enhancing coffee farmers' adaptive capacity (Schroth *et al.*, 2009; Soto-Pinto and Anzueto, 2010). Other strategies specifically recommended for Mexico include soil remediation; improved use of climate information; rainwater capture and drip irrigation (Sosa-Rodriguez, 2013). New crop varieties better suited to future climates, including GMOs, are under development in the US (e.g. (Chen *et al.*, 2012), although potential risks have been noted (Quist and Chapela, 2001). Current trends in agricultural practices in commercial regions such as the Midwestern US, however, amplify productivity risks posed by climate change (Hatfield *et al.*, 2013). Incremental strategies will have reduced effectiveness under a 2099/4°C warming scenario, which would require more systemic adaptation, including production and livelihood diversification (Howden *et al.*, 2007; Mehta *et al.*, 2013; Smith and Gregory, 2013; Asseng *et al.*, 2013).

Some adaptive strategies impose financial costs and risks onto producers (Craine *et al.*, 2010;Wolfe *et al.*, 2008), which may be beyond the means of smallholders (Mercer *et al.*, 2012) or economically precluded for low-value crops. Technological improvements improve yields under normal conditions but do not protect harvests from extremes (U.S. Global Change Research Program, 2009;Wittrock *et al.*, 2011). Others may have maladaptive effects (e.g. increased groundwater and energy consumption). Crop-specific weather index insurance, for example (widely implemented in Mexico to support small farmers), may impose disincentives to invest in diversification and irrigation (Fuchs and Wolff, 2010).

Many strategies have co-benefits, however, in fact investments in agricultural adaptation represent a cost-effective mitigation strategy (Lobell *et al.*, 2013). Low- and no-till practices reduce soil erosion and runoff, protect crops from extreme precipitation (Zhang and Nearing, 2005), retain soil moisture, reduce biogenic and geogenic greenhouse gas emissions (Nelson *et al.*, 2009; Suddick *et al.*, 2010), and build soil organic carbon (Aguilera *et al.*, 2013). Planting legumes and weed management on pastures enhance both forage productivity and soil carbon sequestration (Follett and Reed, 2010). Shade perennials increase soil moisture retention (Lin, 2010) and contribute to local cooling (Georgescu *et al.*, 2011). Crop diversification mediates the impacts of climate and market shocks (Eakin and Appendini, 2008) and enhances management flexibility (Chhetri *et al.*, 2010).

Barriers and Enablers

Market forces and technical feasibility alone are insufficient to foster sectoral-level adaptation (Kulshreshtha, 2011). Institutional support is key, found to be inadequate in many contexts (Bryant *et al.*, 2008; Klerkx and Leeuwis, 2009; Jacques *et al.*, 2010; Tarnoczi and Berkes, 2010; Brooks and Loevinsohn, 2011; Alam *et al.*, 2012; Anderson and McLachlan, 2012)(high confidence). Even many suggested adaptation strategies with anticipated economic benefits are often not adopted by farmers, suggesting the need for more attention to culture and behavior (Moran *et al.*, 2013). Attitudinal studies among US farmers indicate limited acknowledgement of anthropogenic climate change, associated with lower levels of support for adaptation (Arbuckle Jr *et al.*, 2013; Gramig *et al.*, 2013) (high agreement, medium evidence).

Other key enablers are access to and quality of information (Tarnoczi and Berkes, 2010; Tarnoczi, 2011; Baumgart-Getz *et al.*, 2012; Tambo and Abdoulaye, 2012), particularly regarding optimum crop management, production inputs and optimum crop-specific geographic information. Social networks are important for information dissemination and farmer support (Chiffoleau, 2009; Wittrock *et al.*, 2011; Baumgart-Getz *et al.*, 2012). Networks among producers may be especially important to the level of awareness and concern farmers hold about climate change(Frank *et al.*, 2010; Sánchez-Cortés and Chavero, 2011), while also enabling extensive farmer-to-farmer exchange of adaptation strategies (Eakin *et al.*, 2009).

26.6. Human Health

Large national assessments of climate and health have been carried out in the US and Canada (Belanger *et al.*, 2008a) (see references in 26.1). These have highlighted the potential for changes in impacts of extreme storm and heat events, air pollution, pollen, and infectious diseases, drawing from a growing NA research base analyzing observed and projected relationships among weather, vulnerability and health. The causal pathways leading from climate to health are complex, and can be modified by factors including economic status, pre-existing illness, age, other health risk factors, access to health care, built and natural environments, adaptation actions and others. Human health is an important dimension of adaptation planning at the local level, much of which has so-far focused on warning and response systems to extreme heat events (New York State Climate Action Council, 2012).

26.6.1. Observed Impacts, Vulnerabilities and Trends

26.6.1.1. Storm-Related Impacts

The magnitude of health impacts of extreme storms depends on interactions between exposure and characteristics of the affected communities (Keim, 2008). Coastal and low-lying infrastructure and populations can be vulnerable due to flood-related interruptions in communications, healthcare access, and mobility. Health impacts can arise through direct pathways of traumatic death and injury (e.g., drowning, impacts of blowing and falling objects; contact with power wires) as well as more indirect, longer-term pathways related to damage to health and transportation infrastructure, contamination of water and soil, vector-borne diseases, respiratory diseases and mental health (Gamble *et al.*, 2008). Infectious disease impacts from flooding include creation of breeding sites for vectors (Ivers and Ryan, 2006) and bacterial transmission through contaminated water and food sources causing gastrointestinal disease. Chemical toxins can be mobilized from industrial or contaminated sites (Euripidou and Murray, 2004). Elevated indoor mold levels associated with flooding of buildings and standing water are identified as risk factors for cough, wheeze and childhood asthma (Bornehag *et al.*, 2001; Jaakkola *et al.*, 2005). Mental health impacts can arise due to the stress of evacuation, property damage, economic loss, and household disruption (Weisler *et al.*, 2006; Gamble *et al.*, 2008; Berry *et al.*, 2010; Bethel *et al.*, 2011). Since 1970, there has been no clear trend in US hurricane deaths, once the singular Katrina event is set aside (Blake *et al.*, 2007).

26.6.1.2. Temperature Extremes

Studies throughout North America have shown that high temperatures can increase the mortality and/or morbidity (e.g., Medina-Ramon and Schwartz, 2007; Kovats and Hajat, 2008; O'Neill and Ebi, 2009; Anderson and Bell, 2009; Knowlton *et al.*, 2009; Deschenes *et al.*, 2009; Kenny *et al.*, 2010; Hajat and Kosatsky, 2010; Cueva-Luna *et al.*, 2011; Hurtado-Díaz *et al.*, 2011; Romero-Lankao *et al.*, 2012b). Extremely cold temperatures have also been associated with increased mortality (Medina-Ramon and Schwartz, 2007), an effect separate from the seasonal phenomenon of excess winter mortality, which does not appear to be directly related to cold temperatures (Kinney, 2012). To date, trends over time in cold-related deaths have not been investigated. Most available NA evidence derives from the US and Canada, though one study reported significant heat- and cold-related mortality impacts in Mexico City (McMichael *et al.*, 2008). US EPA has tracked the death rate in the US from 1979 to 2009 for which death certificates list the underlying cause of death as heat related (U.S. Environmental Protection Agency, Office of Atmospheric Programs, 2012). No clear trend upwards or downwards is yet apparent in this indicator. Note that this case definition is thought to significantly underestimate the total impacts of heat on mortality.

26.6.1.3. Air Quality

Ozone and particulate matter (e.g., PM2.5 and PM10) have been associated with adverse health effects in many locations in North America (Romero-Lankao *et al.*, 2013b). Emissions, transport, dilution, chemical transformation, and eventual deposition of air pollutants all can be influenced by meteorological variables such as temperature, humidity, wind speed and direction, and mixing height (Kinney, 2008). Although air pollution emission trends will play a dominant role in future pollution levels, climate change may make it harder to achieve some air quality goals (Jacob and Winner, 2009). Forest fire is a source of particle emissions in NA, and can lead to increased cardiac and respiratory-disease incidence, as well as direct mortality (Rittmaster *et al.*, 2006; Ebi *et al.*, 2008). The indoor environment also can affect health in many ways, e.g., via penetration of outdoor pollution, emissions or pollutants indoors, moisture-related problems, and transmission of respiratory infections. Indoor moisture leads to mold growth, a problem that is exacerbated in colder regions such as northern NA in the winter (Potera, 2011). Climate variability and change will affect indoor air quality, but with direction and magnitude that remains largely unknown (Institute of Medicine, 2011).

26.6.1.4. Pollen

Exposure to pollen has been associated with a range of allergic outcomes, including exacerbations of allergic rhinitis (Cakmak *et al.*, 2002; Villeneuve *et al.*, 2006) and asthma (Delfino, 2002). Temperature and precipitation in the months prior to the pollen season affect production of many types of tree and grass pollen (Reiss and Kostic, 1976; Minero *et al.*, 1998; Lo and Levetin, 2007; U.S. Environmental Protection Agency, 2008). Ragweed pollen production is responsive to temperatures and to CO_2 concentrations (Ziska and Caulfield, 2000; Wayne *et al.*, 2002; Ziska *et al.*, 2003; Singer *et al.*, 2005). Because pollen production and release can be affected by temperature, precipitation, and CO_2 concentrations, pollen exposure and allergic disease morbidity could change in response to climate change. However, to date, the timing of the pollen season is the only evidence for observed climate-related impacts. Many studies have indicated that pollen seasons are beginning earlier (Emberlin *et al.*, 2002; Rasmussen, 2002; Clot, 2003; Teranishi *et al.*, 2006; Frei and Gassner, 2008; Levetin and Van, 2008; Ariano *et al.*, 2010). Ragweed season length has increased at some monitoring stations in the United States (Ziska *et al.*, 2011). Research on trends in NA has been hampered by the lack of long-term, consistently collected pollen records (U.S. Environmental Protection Agency, 2008).

26.6.1.5. Waterborne Diseases

Waterborne infections are an important source of morbidity and mortality in North America. Commonly reported infectious agents in US and Canadian outbreaks include legionella bacterium, the cryptosporidium parasite, campylobacter, and giardia (Belanger *et al.*, 2008b; Center for Disease Control and Prevention, 2011). Cholera remains an important agent in Mexico (Greer *et al.*, 2008). Risk of waterborne illness is greater among the poor, infants, elderly, pregnant women, and immune-compromised individuals (Rose *et al.*, 2001; Gamble *et al.*, 2008) . In Mexico City, declining water quality has led to ineffective disinfection of drinking water supplies (Mazari-Hiriart *et al.*, 2005; Sosa-Rodriguez, 2010).

Changes in temperature and hydrological cycles can influence the risk of waterborne diseases (Curriero *et al.*, 2001; Greer *et al.*, 2008; Harper *et al.*, 2011). Severe storms have been shown to play a role in water-borne disease risks in Canada (Thomas *et al.*, 2006). Floods enhance the potential for runoff to carry sediment and pollutants to water supplies (Karl *et al.*, 2008). Disparities in access to treated water were identified as a key determinant of under age-5 morbidity due to water borne illnesses in the central State of Mexico (Jimenez-Moleon and Gomez-Albores, 2011).

26.6.1.6. Vectorborne Diseases

The extent to which climate change has altered, and will alter, the geographic distribution of vectors of infectious disease remains uncertain because of the inherent complexity of the ecological system. Spatial and temporal distribution of disease vectors depend not only on climate factors, but also on land use/change, socio-economic and socio-cultural factors, prioritization of vector control, access to health care and human behavioral responses to perception of disease risk, among other factors (Lafferty, 2009; Wilson, 2009). Although temperature drives important biological processes in these organisms, climate variability on a daily, seasonal or interannual scale may result in organism adaptation and shifts, though not necessarily expansion, in geographic range (Lafferty, 2009; Tabachnick, 2010; McGregor, 2011). Range shifts may alter the incidence of disease depending on host receptiveness and immunity, as well as the ability of the pathogen to evolve so that strains are more effectively and efficiently acquired (Reiter, 2008; Beebe *et al.*, 2009; Rosenthal, 2009; Russell, 2009; Epstein, 2010).

North Americans are currently at risk from a number of vector-borne diseases, including Lyme disease (Ogden *et al.*, 2008; Diuk-Wasser *et al.*, 2010), dengue fever (Jury, 2008; Ramos *et al.*, 2008; Johansson *et al.*, 2009; Kolivras, 2010; Degallier *et al.*, 2010; Lambrechts *et al.*, 2011; Riojas-Rodriguez *et al.*, 2011; Lozano-Fuentes *et al.*, 2012), West Nile virus (Morin and Comrie, 2010; Gong *et al.*, 2011) and Rocky Mountain spotted fever, to name a few. Risk is increasing from invasive vector-borne pathogens, such as chikungunya (Ruiz-Moreno *et al.*, 2012) and Rift Valley fever viruses (Greer *et al.*, 2008). There is also potential risk from invasive vector-borne pathogens, such as chikungunya (Ruiz-Moreno *et al.*, 2012) and Rift Valley fever viruses (Greer *et al.*, 2008). Mexico is listed as high risk for dengue fever by the WHO. There has been an increasing number of cases of Lyme disease in Canada and Lyme disease vectors are spreading along climate-determined trajectories (Leighton *et al.*, 2012; Koffi *et al.*, 2012).

26.6.2. Projected Climate Change Impacts

Projecting future consequences of climate warming for heat-related mortality and morbidity is challenging, due in large part to uncertainties in the nature and pace of adaptations that populations and societal infrastructure will undergo in response to long-term climate change (Kinney *et al.*, 2008). Additional uncertainties arise from changes over time in population demographics, economic well-being, and underlying disease risk, as well as in the model-based predictions of future climate and our understanding of the exposure-response relationship for heat-related mortality. However, climate warming will lead to continuing health stresses related to extreme high temperatures, particularly for the northern parts of North America. The health implications of warming winters remain uncertain (Kinney, 2012).

Several recent studies have projected future health impacts due to air pollution in a changing climate (Knowlton *et al.*, 2004; Bell *et al.*, 2007; Tagaris *et al.*, 2009; Tagaris *et al.*, 2010; Chang *et al.*, 2010). There is a large literature examining future climate influences on outdoor air quality in North America, particularly for ozone (Murazaki and Hess, 2006; Steiner *et al.*, 2006; Tao *et al.*, 2007; Kunkel *et al.*, 2007; Holloway *et al.*, 2008; Lin *et al.*, 2008; Nolte *et al.*, 2008; Wu *et al.*, 2008; Avise *et al.*, 2009; Chen *et al.*, 2009; Liao *et al.*, 2009; Racherla and Adams, 2009; Lin *et al.*, 2010; Tai *et al.*, 2010). This work suggests with *medium confidence* that ozone concentrations could increase under future climate change scenarios if emissions of precursors were held constant (Jacob and Winner, 2009). However, analyses show that future increases can be offset through measures taken to limit emission of pollutants (Kelly *et al.*, 2012). The literature for PM2.5 is more limited than that for ozone, and shows a more complex pattern of climate sensitivities, with no clear net influence of warming temperatures (Liao *et al.*, 2007; Tagaris *et al.*, 2008; Avise *et al.*, 2009; Pye *et al.*, 2009; Mahmud *et al.*, 2010). On the other hand, $PM_{2.5}$ plays a crucial role. Regarding outdoor pollen, warming will lead to further changes in the seasonal timing of pollen release (high confidence). Another driver of future pollen could be changing spatial patterns of vegetation as a result of climate change.

Regarding clean water supplies, extreme precipitation can overwhelm combined sewer systems and lead to overflow events that can threaten human health (Patz *et al.*, 2008). Conditional on a future increase in such events, we can anticipate increasing risks related to water-borne diseases.

Whether future warmer winters in the United States and Canada will promote transmission of diseases like dengue and malaria is uncertain, in part, because of access to amenities such as screening and air-conditioning that provide barriers to human-vector contact. Socio-economic factors also play important roles in determining risks. Better longitudinal datasets and empirical models are needed to address research gaps on climate-sensitive infectious diseases, as well as to provide a better mechanism for weighting the roles of external drivers such as climate change on a macro/micro scale, human-environmental changes on a regional to local scale, and extrinsic factors in the transmission of vector-borne infectious diseases (Wilson, 2009; McGregor, 2011).

26.6.3. Adaptation Responses

Early warning and response systems can be developed to build resilience to events like heat waves, storms and floods (Ebi, 2011) and protect susceptible populations, which include infants, children, the elderly, individuals with pre-existing diseases, and those living in socially and/or economically disadvantaged conditions (Pinkerton *et al.*, 2012). Adaptation planning at all scales to build resilience for health systems in the face of a changing climate is a growing priority (Kinney *et al.*, 2011).

Adaptation to heat events can occur via physiologic mechanisms, indoor climate control, urban-scale cooling initiatives, and with implementation of warning and response systems (Romero-Lankao *et al.*, 2012b). Additional research is needed on the extent to which warning systems prevent deaths (Harlan and Ruddell, 2011). Efforts to reduce GHG emissions could provide health co-benefits, including reductions in heat-related and respiratory illnesses (Health Chapter, US National Climate Assessment).

26.7. Key Economic Sectors and Services

There is mounting evidence that many economic sectors across North America have experienced climate impacts and are adapting to the risk of loss and damage from weather perils. This section covers the literature for the energy, transportation, mining, manufacturing, construction and housing, and insurance sectors in North America. Recent studies find a range of adaptive practices and adaptation responses to experience with extreme events, and only an emerging consideration of proactive adaptation in anticipation of future global warming.

26.7.1. Energy

26.7.1.1. Observed Impacts

Energy demand for cooling has increased as building stock and air conditioning penetration have increased (Wilbanks *et al.*, 2012). Extreme weather currently poses risk to the energy system (Wilbanks *et al.*, 2012). For example, Hurriacne Sandy results in a loss of power to 8.5 million customers in the Northeast US (National Oceanic and Atmospheric Administration, 2013). Energy consumption is a major user of water resources in North America, with 49% of the water withdrawals in the US for thermoelectric power (Kenny *et al.*, 2009).

26.7.1.2. Projected Impacts

Demand for summer cooling is projected to increase and demand for winter heating is projected to decrease. Total energy demand in North America is projected to increase in coming decades because of non-climate factors (Galindo, 2009; National Energy Board, 2011; Energy Information Administration, 2013). Climate change is projected to have varying geographic impacts. In Canada, a net decrease in residential annual energy demand is projected by 2050 and by 2100 (Isaac and Van Vuuren, 2009; Schaeffer *et al.*, 2012). It is difficult to project changes in net energy demand in the US because of uncertainties in such factors as climate change, and change in technology, population, and energy prices. Peak demand for electricity is projected to increase more than the average demand for electricity, with capacity expansion needed in many areas (Wilbanks *et al.*, 2012). Given the projected increases in energy demand in the southern United States from climate change (Auffhammer and Aroonruengsawat, 2011; Auffhammer and Aroonruengsawat, 2012) it is reasonable to conclude that Mexico will have a net increase in demand.

Major water resource related concerns include effects of increased cooling and other demands for water and water-scarcity in the west; effects of extreme weather events, sea-level rise, hurricanes, and seasonal droughts in the southeast; and effects of increased cooling demands in the northern regions (Wilbanks *et al.*, 2008; Wilbanks *et al.*, 2012; McDonald, 2012; U.S. Department of Energy, 2013) .

The magnitude of projected impacts on hydropower potential will vary significantly between regions and within drainage basins(Desrochers *et al.*, 2009; Shrestha *et al.*, 2012; Kienzle *et al.*, 2012). Annual mean hydropower production in the Peribonka River in Quebec is estimated to increase by approximately 10% by mid-century and 20% late in the century under the A2 scenario (Minville *et al.*, 2009).

Higher temperatures and increased climate variability can have adverse impacts on renewable energy production such as wind and solar (U.S. Department of Energy, 2013). Changing cloud cover affects solar energy resources, changes in winds affect wind power potentials, and temperature change and water availability can affect biomass production (Wilbanks *et al.*, 2008; U.S. Department of Energy, 2013) .

26.7.1.3. Adaptation

Many adaptations are underway to reduce vulnerability of the energy sector to extreme climate events such as heat, drought, and flooding (U.S. Department of Energy, 2013). Adaptation includes many approaches such as increased supply and demand efficiency (e.g., through more use of insulation), more use of urban vegetation and reflective surfaces, improved electric grid, reduced reliance on above ground distribution systems, and distributed power (Wilbanks *et al.*, 2012). Important barriers to adaptation include uncertainty about future climate change, inadequate information on costs of adaptation, lack of climate resilient energy technologies, and limited price signals (U.S. Department of Energy, 2013). Strategies resulting in energy demand reduction would reduce greenhouse gas emissions and reduce the vulnerability of the sector to climate change.

26.7.2. Transportation

26.7.2.1. Observed Impacts

Much of the transportation infrastructure across North America is aging, or inadequate (Mexico) which may make it more vulnerable to damage from extreme events and climate change. Approximately 11% of all US bridges are structurally deficient, 20% of airport runways are in fair or poor condition, and more than half of all locks are more than 50 years old (US Department of Transportation 2013). More than US$2 trillion is needed to bring infrastructure in the US up to “good condition” (American Society of Civil Engineers, 2009) p. 6. Canadian infrastructure had an investment deficit of C$125 billion in the 1980s and 1990s (Mirza and Haider, 2003).

Some transportation systems have been harmed (Figure 26-2). For example, in 2008, Hurricane Ike caused $2.4 billion in damages to ports and waterways in Texas. (McDonald, 2012). The “superflood” in Tennessee and Kentucky in 2010 caused $2.3 billion in damage (National Oceanic and Atmospheric Administration, 2013).

Hurricane Sandy resulted in flooding of portions of New York City’s subway system, overtopping of runways at La Guardia airport, and caused $400 million in damage to the New Jersey transit system (National Oceanic and Atmospheric Administration, 2013).

26.7.2.2. Projected Impacts

Scholarship on projected climate impacts on transportation infrastructure focuses mostly on US and Canada. Increases in high temperatures, intense precipitation, drought, sea level, and storm surge could affect transportation across the United States. The greatest risks would be to coastal transportation infrastructure, but there could be benefits to marine and lake transportation in high latitudes from less ice cover (Transportation Research Board, 2008). A 1-meter sea level rise combined with a 7-meter storm surge could inundate over half of the highways, arterials, and rail lines in the US Gulf coast (Savonis *et al.*, 2008). Declining water levels in the Great Lakes would increase shipping costs by restricting vessel drafts and reducing vessel cargo volume (Millerd, 2011). In southern Canada by the 2050s, cracking of roads from freeze and thaw would decrease under the B2 and A2 scenarios, structures would freeze later and thaw earlier, while higher extreme temperatures could increase rutting (Mills *et al.*, 2009) and related maintenance and rehabilitation costs (Canadian Council of Professional Engineers, 2008).

A 1 to 1.5°C increase in global mean temperature would increase the costs of keeping paved and unpaved roads in the United States in service by, respectively, US$2 to US$3 billion per year by 2050 (Chinowsky *et al.*, 2013). Tens of thousands to more than 100,000 bridges in the US could be vulnerable to increasing peak river flows in the mid- and late-21st Century under the A1B and A2 scenarios. Strengthening vulnerable bridges to be less vulnerable to climate change is estimated to cost approximately US$100 to $250 billion (Wright *et al.*, 2012).

26.7.2.3. Adaptation

Adaptation steps are being taken in North America, particularly to protect transportation infrastructure from sea level rise and storm surge in coastal regions. Almost all of the major river and bay bridges destroyed by Hurricane Katrina surge waters were rebuilt at higher elevations, and the design of the connections between the bridge decks and piers were strengthened (Grenzeback and Luckmann, 2006).

Adaptation actions include protecting coastal transportation from sea level rise and more intense coastal storms or possibly relocating infrastructure. Many Midwestern states are examining channel protection and drainage designs, while transportation agencies in Canada and the United States have been preparing to manage the aftermath of extreme weather events (Meyer *et al.*, 2013). In addition, new materials may be needed so pavement and rail lines can better withstand more extreme temperatures.

26.7.3. Mining

26.7.3.1. Observed Impacts

Climatic sensitivities of mining activities, including exploration, extraction, processing, operations, transportation and site remediation, have been noted in the limited literature (Chiotti and Lavender, 2008; Furgal and Prowse, 2008; Meza-Figueroa *et al.*, 2009; Ford *et al.*, 2010a; Locke *et al.*, 2011; Gómez-álvarez *et al.*, 2011; Kirchner *et al.*, 2011; Pearce *et al.*, 2011; Stratos Inc, 2011). Drought-like conditions have affected the mining sector by limiting water supply for operations (Pearce *et al.*, 2011), enhancing dust emissions from quarries (Pearce *et al.*, 2011) and increasing concentrations of heavy metals in sediments (Gómez-álvarez *et al.*, 2011). Heavy precipitation events have caused untreated mining wastewater to be flushed into river systems (Pearce *et al.*, 2011). High loads of contamination (from metals, sulfate and acid) at three mine sites in the United States were measured during rainstorm events following dry periods (Nordstrom, 2009).

26.7.3.2. Projected Impacts

Climate change is perceived by Canadian mine practitioners as an emerging risk, and in some cases, a potential opportunity (Ford *et al.*, 2010a; Ford *et al.*, 2011; Pearce *et al.*, 2011; National Round Table on the Environment and the Economy, 2012), with potential impacts on transportation (Ford *et al.*, 2011) and limited water availability (Acclimatise, 2009) from projected drier conditions (Sun *et al.*, 2008; Seager and Vecchi, 2010) being identified as key issues.

An increase in heavy precipitation events projected for much of North America (Warren and Egginton, 2008; Nordstrom, 2009) would adversely affect the mining sector. A study on acid rock damage drainage in Canada concluded that an increase in heavy precipitation events presented a risk of both environmental impacts and economic costs (Stratos Inc, 2011) Damage to mining infrastructure from extreme events, for active and post-operation mines, is also a concern (Pearce *et al.*, 2011). Climate change impacts that affect the bottom-line of mining companies (through direct impacts or associated costs of adaptation), would have consequences for employment, for both the mining sectors and local support industries (Backus *et al.*, 2013).

26.7.3.3. Adaptation

Despite increasing awareness, there are presently few documented examples of proactive adaptation planning within the mining sector (Acclimatise, 2009; Ford *et al.*, 2010a; Ford *et al.*, 2011). However, adjustments to management practices to deal with short-term water shortages, including reducing water intake, increasing recycling and establishing infrastructure to move water from tailing ponds, pits and quarries, have worked successfully in the past (Chiotti and Lavender, 2008). Integrating climate change considerations at the mine planning and design phase increases the opportunity for effective and cost-efficient adaptation (Stratos Inc, 2011).

26.7.4. Manufacturing

26.7.4.1. Observed Impacts

There is little literature focused on climate change and manufacturing, although one study suggested that manufacturing is among the most sensitive sectors to weather in the US (Lazo *et al.*, 2011). Weather affects the supply of raw material, production process, transportation of goods, and demand for certain products. In 2011, automobile manufacturers in North America experienced production losses associated with shortages of components due to flooding in Thailand (Newswire, 2011). In 2013, reduced cattle-supply and higher feed prices associated with drought in Texas led to a decision to close a beef processing plant (Beef Today Editors, 2013). Drought also caused delays for barge shipping on the Mississippi River in 2012 (Reuters, 2012). Major storms, like Hurricanes Sandy, Katrina and Andrew, significantly disrupted manufacturing activities, including plant shutdowns due to direct damages and/or loss of electricity and supply disruptions due to unavailability of parts, and difficulties delivering products due to compromised transportation networks (Baade *et al.*, 2007; Dolfman *et al.*, 2007).

26.7.4.2. Projected Impacts

The drier conditions (Sun *et al.*, 2008; Seager and Vecchi, 2010; Wehner *et al.*, 2011) would present challenges, especially for manufacturers located in regions already experiencing water stress. This could lead to increased conflicts over water between sectors and regions, and affect the ability of regions to attract new facilities or retain existing operations. A study of the effect of changes in precipitation (A1B scenario) on 70 industries in the US between 2010 and 2050 found potentially significant losses in production and employment due to declines in water availability and the interconnectedness of different industries (Backus *et al.*, 2013).

Another potential concern for manufacturing relates to impacts of heat on worker safety and productivity. Several studies suggest that higher temperatures and humidity would lead to decreased productivity and increased occupational health risks (e.g., Kjellstrom *et al.*, 2009; Hanna *et al.*, 2011; Kjellstrom and Crowe, 2011).

26.7.4.3. Adaptation

Some companies are beginning to recognize the risks climate change presents to their manufacturing operations, and consider strategies to build resilience (National Round Table on the Environment and the Economy, 2012). Coca Cola has a water stewardship strategy focusing on improving water use efficiency at its manufacturing plants, while Rio Tinto Alcan is assessing climate change risks for their operations and infrastructure, which include vulnerability of transport systems, increased maintenance costs, and disruptions due to extreme events (National Round Table on the Environment and the Economy, 2012). Air conditioning is a viable and effective adaptation option to address some of the impacts of warming, though it does incur greater demands for electricity and additional costs (Scott *et al.*, 2008a). Sourcing raw materials from different regions and relocating manufacturing plants are other adaptation strategies that can be used to increase resiliency and reduce vulnerability.

26.7.5. Construction and Housing

26.7.5.1. Observed Impacts

The risk of damage from climate change is important for construction industries, though little research has systematically explored the topic (Morton *et al.*, 2011). Private data from insurance companies report a significant increase in severe weather damage to buildings and other insured infrastructure over several decades (Munich Re, 2012).

26.7.5.2. Projected Impacts

Most studies project a significant further increase in damage to homes, buildings and infrastructure (Bjarndadottir *et al.*, 2011; IPCC, 2012). Affordable adaptation in design and construction practices could reduce much of the risk of climate damage for new buildings and infrastructure, involving reform in Building Codes and other standards (Feltmate and Thistlethwaite, 2012). However, adaptation best practices in design and construction are often prohibitively expensive to apply to existing buildings and infrastructure, so much of the projected increase in climate damage risk involves existing buildings and infrastructure.

26.7.5.3. Adaptation

Engineering and construction knowledge exists to design and construct new buildings to accommodate the risk of damage from historic extremes and anticipated changes in severe weather (Kelly, 2010; Ministry of Municipal Affairs and Housing, 2011; Insurance Institute for Business and Home Safety, 2012). Older buildings may be retrofit to increase resilience, but these changes are often more expensive to introduce into an existing structure than if they were included during initial construction.

The housing and construction industries have made advances toward climate change mitigation by incorporating energy efficiency in building design (Heap, 2007). Less progress has been made in addressing the risk of damage from extreme weather events (Kenter, 2010). In some markets, like the Gulf Coast of the United States, change is under way in the design and construction of new homes in reaction to recent hurricanes (Levina *et al.*, 2007; Kunreuther and Michel-Kerjan, 2009; Insurance Institute for Business and Home Safety, 2011), but in most markets across North America there has been little change in building practices. The cost of adaptation measures combined with limited long-term liability for future buildings has influenced some builders to take a wait-and-see attitude (Morton *et al.*, 2011). Exploratory work is under way to consider implementation of building codes that would focus on historic weather experience and also introduce expected future weather risks (Auld *et al.*, 2010; Ontario Ministry of Environment, 2011).

26.7.6. Insurance

26.7.6.1. Observed Impacts

Property insurance and reinsurance companies across North America experienced a significant increase in severe weather damage claims paid over the past three or four decades(Cutter and Emrich, 2005; Munich Re, 2011; Bresch and Spiegel, 2011). Most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk (Pielke Jr *et al.*, 2008; Barthel and Neumayer, 2012). A role for climate change has not been excluded, but the increase to date in damage claims is largely due to growth in wealth and population (IPCC, 2012).

Severe weather and climate risks have emerged over the past decade as the leading cost for property insurers across North America, resulting in significant change in industry practices. The price of insurance increased in regions where the risk of loss and damage has increased. Discounts have been introduced where investments in adaptation have reduced the risk of future weather losses (Mills, 2012). Further detailed discussion on the insurance sector and climate change can be found in section 10.7.

26.7.6.2. Projected Impacts

Without adaptation, there is an expectation that severe weather insurance damage claims would increase significantly over the next several decades across North America (World Bank, 2010). The risk of damage is expected to rise due to continuing growth in wealth, the population living at risk, and climate change. There is also an expectation that some weather perils in North America will increase in severity, including Atlantic hurricanes and the area burned by wildfire (Karl *et al.*, 2008; Balshi *et al.*, 2009), and other perils in frequency, including intense rainfall events (IPCC, 2012).

26.7.6.3. Adaptation

The insurance industry is one of the most studied sectors in North America in terms of climate impacts and adaptation. Most adaptation in the insurance industry has been in response to an increase in severe weather damage, with little evidence of proactive adaptation in anticipation of future climate change (Mills and Lecomte, 2006; Mills, 2007; Mills, 2009; Kunreuther and Michel-Kerjan, 2009; Leurig, 2011; Autorite des Marches Financiers, 2011; Gallagher, 2012). In addition to pricing decisions based on an actuarial analysis of historic loss experience, many insurance companies in the United States and Canada now use climate model information to help determine the prices they charge and discounts they offer. Most insurance companies have established specialized claims handling procedures for responding to catastrophic events (Kovacs, 2005; Mills, 2009).

A recent study of more than 2,000 major catastrophes since 1960 found that insurance is a critical adaptive tool available to help society minimize the adverse economic consequences of natural disasters (von Peter *et al.*, 2012). Government insurance programs for coverage of flood in the United States have been affected by recent hurricanes and previously subsidized premiums have been changed to more accurately reflect risk (Federal Emergency Management Agency, 2013). In the United States and Canada, homeowners make extensive use of insurance to manage a broad range of risks, and those with insurance recover quickly following most extreme weather events. However the majority of public infrastructure is not insured and it frequently takes more than a decade before government services fully recover. In contrast, Mexico has a well-developed program for financing the rebuilding of public infrastructure following a disaster (FONDEN) but insurance markets are only beginning to emerge for homeowners and businesses. In 2012, per capita spending on property and casualty insurance was US$2,239.20 in the United States, US$2,040.40 in Canada, and US$113.00 in Mexico (Seiler *et al.*, 2013).

Insurance companies are also working to influence the behavior of their policyholders to reduce the risk of damage from climate extremes (Kovacs, 2005; Anderson *et al.*, 2006; Mills, 2009). For example, the industry supports the work of the Insurance Institute for Business and Home Safety in the United States, and the Institute for Catastrophic Loss Reduction in Canada, in working to champion change in the building code and communicate to property owners, governments and other stakeholders best practices for reducing the risk of damage from hurricanes, tornadoes, winter storms, wildfire, flood and other extremes.

26.8. Urban and Rural Settlements

Recently a growing body of literature and national assessments have focused on climate-related impacts, vulnerabilities and risks in North American settlements (e.g., US-NCA chapters 11 and 14 and AR5 chapters 8 and 9).

26.8.1. Observed Weather and Climate Impacts

Observed impacts on lives, livelihoods, economic activities, infrastructure and access to services in North American human settlements have been attributed to sea level rise (26.2.2.1), changes in temperature and precipitation, and occurrences of extreme events like heat waves, droughts and storms (Figure 26-2).

Only a handful of these impacts have been attributed to anthropogenic climate change, such as shifts in Pacific Northwest marine ecosystems, which have restricted fisheries and thus affected fishing communities (U.S. Global Change Research Program, 2009). As well, (MacKendrick and Parkins, 2005; Parkins and MacKendrick, 2007; Parkins, 2008; Holmes, 2010) identified 30 communities and 25,000 families in British Columbia negatively affected by the mountain pine beetle outbreak (See 26.4.1.1).

While *droughts* are among the more notable extreme events affecting North American urban and rural settlements recently, with severe occurrences in the Canadian Prairies causing economic and employment losses (2001-2), changes in drought frequency in North America have not been attributed to anthropogenic climate change (Figure 26-1). The 2010-2012 drought across much of the US and Northern Mexico was considered the most severe in a century (MacDonald, 2010). It affected 80% of agricultural land in the US, with 2,000 counties designated disaster zones by September (U.S. Department of Agriculture, Economic Research Service, 2012). Impacts include the loss of 3.2 million tons of maize in Mexico, placing 2.5 million at risk of food insecurity (Direccion General de Comunicacion Social, 2012). Among the most severely affected were indigenous peoples, such as the Rarámuri of Chihuahua (ibid.). Closely associated with droughts, the impacts of recent wildfires have been significant (See Box 26.2), and have intensified inequalities in vulnerability between amenity migrants and low-income residents in peri-urban areas of California and Colorado (Collins and Bolin, 2009).

Other extreme-events include *heat-waves*, resulting in excess urban mortality (O'Neill and Ebi, 2009; Romero-Lankao *et al.*, 2012b); and affecting infrastructure and built environments –e.g., road pavement in Chicago buckled under temperatures over 100^{o}F (CBS Chicago, 2012); in Colorado two wildfires burned over 600 homes (National Climate Data Center, 2013).

Extreme storms and extreme precipitation have also impacted several North American regions (Figures 26-1 and 26-2). Flood frequency has increased in some cities, a trend sometimes associated with more intense precipitation (e.g., Mexico City and Charlotte NC, US) (Villarini *et al.*, 2009; Magana, 2010), while in others this trend is associated with a transition from flood events dominated by snowmelt to those caused by warm-season thunderstorms (e.g., Québec, Canada and Milwaukee, US) (Ouellet *et al.*, 2012; Yang *et al.*, 2013). As illustrated by Sandy (Neria and Shultz, 2012; Powell *et al.*, 2012), storms impact human health and healthcare access (section 26.6.1.1), and impacts on infrastructure and the built environment have been costly. Heavy precipitation, storm surges, flash-floods and wind, including flooding on the US East Coast, and Midwest (2011), hurricanes and floods in the city of Villa Hermosa (Comisión Económica para América Latina y el Caribe,) and other urban areas in southern Mexico (2004-5), have compromised homes and businesses (Comfort, 2006; Kirshen *et al.*, 2008; Jonkman *et al.*, 2009; Romero-Lankao, 2010). Hurricane Wilma alone caused $1.8 billion in damage, among the biggest insurance losses in Latin American history (Galindo *et al.*, 2009).

The impacts of interacting hazards compound vulnerabilities (26.8.2). Coastal settlements are at risk from the combined occurrence of coastal erosion, health effects, infrastructure and economic damage from storm surges. Earlier thaw (Friesinger and Bernatchez, 2010), SLR, and coastal flooding have been detected along the mid-Atlantic, Gulf of Mexico, and St. Lawrence (Kirshen *et al.*, 2008; Zavala-Hidalgo *et al.*, 2010; Friesinger and Bernatchez, 2010; Rosenzweig *et al.*, 2011; Tebaldi *et al.*, 2012).

Climate impacts on the ecosystem-function and -services (e.g., water supplies, biodiversity or flood protection) provided to human settlements are another concern. While acknowledged in some places (e.g., Mexico City Climate Action Plan), they have received relatively less scholarship attention (Hunt and Watkiss, 2011).

26.8.2. Observed Factors and Processes Associated with Vulnerability

Differences in the severity of climate impacts on human settlements are strongly influenced by context-specific vulnerability factors and processes (Table 26.1, Cutter *et al.*, 2013), some of which are common to many settlements, while others are more pertinent to some types of settlements than others. Human settlements simultaneously face a multilevel array of non-climate-related hazards (e.g., economic, industrial, technological) that contribute to climate change vulnerability (McGranahan *et al.*, 2007; Satterthwaite *et al.*, 2007; Romero-Lankao and Dodman, 2011). In the following we highlight key sources of vulnerability for urban and rural systems.

26.8.2.1. Urban Settlements

Hazard risks in urban settlements are enhanced by the *concentration* of populations, economic activities, cultural amenities and built environments particularly when they are in highly-exposed locations such as coastal and arid areas. Cities of concern include those in the Canadian prairies and US-Mexico border region; and major urban areas including Boston, New York, Chicago, Washington DC, Los Angeles, Villa Hermosa, Mexico City and Hermosillo (Comisión Económica para América Latina y el Caribe; Bin *et al.*, 2007; Collins, 2008; Kirshen *et al.*, 2008; Collins and Bolin, 2009; Gallivan *et al.*, 2009; Rosenzweig *et al.*, 2010; Hayhoe *et al.*, 2010; Romero-Lankao, 2010; Wittrock *et al.*, 2011).

Risks may also be heightened by *multiple interacting hazards*. Slow-onset events such as urban heat-islands, for instance, interact with poor air-quality in large North American cities to exacerbate climate impacts on human health (Romero-Lankao *et al.*, 2013a). As illustrated by recent weather events (Figure 26.2), however, hazard interactions can also follow individual, high-magnitude extreme events of short duration, with cascading effects across interconnected energy, transportation, water and health infrastructures and services to contribute to and compound urban vulnerability (Gasper *et al.*, 2011). Wildfire vulnerability in the southwest has been compounded by peri-urban growth (Collins and Bolin, 2009; Brenkert-Smith, 2010). Under current financial constraints in many cities, climate-related economic losses can reduce resources available to address social issues, thus threatening institutional capacity and urban livelihoods (Kundzewicz *et al.*, 2008).

The *urbanization process* and *urban built-environments* of North America can amplify climate impacts as they change land-use and land-surface physical characteristics (e.g., surface albedo, Chen *et al.*, 2011a). A 34% increase in US urban land development (Alig *et al.*, 2004) between 1982 and 1997 had implications for water supplies and extreme event impacts. Effects on water are of special concern (section 26.3), as urbanization can enhance or reduce precipitation, depending on climate regime, geographical location and regional patterns of land, energy and water use (Cuo *et al.*, 2009). Urbanization also has significant impacts on flood climatology through atmospheric processes tied to the Urban Heat Island (UHI), the Urban Canopy Layer (UCL), and the aerosol composition of airsheds (Ntelekos *et al.*, 2010). The UHI can also increase health risks differentially, due to socio-spatial inequalities across and within North American cities (Harlan *et al.*, 2008; Miao *et al.*, 2011).

Urbanization imposes path dependencies that can amplify or attenuate vulnerability (Romero-Lankao and Qin, 2011). For example, the overexploitation of Mexico City's aquifer by 19.1 - 22.2 m^3/s has reduced groundwater levels and caused subsidence, undermining building foundations and infrastructure and increasing residents' vulnerability to earthquakes and heavy rains (Romero-Lankao, 2010).

Elements of the *built-environment* such as housing stock, urban form, the condition of water and power infrastructures, and changes in urban and ecological services also affect vulnerability. Large, impermeable surfaces and buildings disrupt drainage channels and accelerate run-off (Walsh *et al.*, 2005). Damage from floods can be much more catastrophic if drainage or waste collection systems are inadequate to accommodate peak flows

(Richardson, 2010; Sosa-Rodriguez, 2010). While many Canadian and US cities are in need of infrastructure adaptation upgrades (Doyle *et al.*, 2008; Conrad, 2010), Mexican cites are faced with existing infrastructure deficits (Niven *et al.*, 2010; Hardoy and Romero Lankao, 2011), and high levels of socio-spatial segregation (Smolka and Larangeira, 2008) (section 26.7).

Recent weather hazards (Figure 26-2) illustrate that economic activities and highly-valued physical capital of cities (real estate, interconnected infrastructure systems) are very sensitive to climate-related disruptions that can result in high impacts; activities in some urban areas are particularly exposed to key resource constraints (e.g., water in the US-Mexico Border; oil industry in Canada, US and Mexico; Levy et al., 2010; Conrad, 2010); others are dependent upon climate-sensitive sectors (e.g., tourism) (Lal *et al.*, 2011). Disruptions to production, services and livelihoods, and changes in the costs of raw materials also impact the economic performance of cities (Hunt and Watkiss, 2011).

Cities are relatively better endowed than rural populations with individual and neighborhood assets such as income, education, quality of housing and access to infrastructure and services that offer protection from climate hazards. However, intra-urban socio-spatial differences in access to these assets shape response capacities (Harlan and Ruddell, 2011; Romero-Lankao *et al.*, 2013a). All this means that class and socio-spatial segregation are key determinants not only of vulnerability but also of inequalities in risk generation and distribution within cities. Economic elites are better positioned to access the best land and enjoy the rewards of environmental amenities such as clean air, safe drinking water, open space, and tree shade (Morello-Frosch *et al.*, 2002; Harlan *et al.*, 2006; Harlan *et al.*, 2008; Ruddell *et al.*, 2011). Although wealthy sectors are moving into risk prone coastal and forested areas (Collins, 2008), and certain hazards (air pollution) affect both rich and poor alike (Romero-Lankao *et al.*, 2013a), climate risks tend to be disproportionally borne by the poor or otherwise marginalized populations (Cutter *et al.*, 2008; Collins and Bolin, 2009; Romero-Lankao, 2010; Wittrock *et al.*, 2011). In some cities, marginalized populations are moving to peri-urban areas with inadequate services, a portfolio of precarious livelihood mechanisms, and inappropriate risk-management institutions (Collins and Bolin, 2009; Eakin *et al.*, 2010; Monkkonen, 2011; Romero-Lankao *et al.*, 2012a).

Although cities have comparatively higher access than rural municipalities to determinants of institutional capacity such as human resources and revenue pools, their governance arrangements are often hampered by jurisdictional conflicts, asymmetries in information and communication access, fiscal constraints on public services including emergency personnel, and top-down decision making. These governance issues exacerbate urban vulnerabilities and constrain urban adaptation planning (Carmin *et al.*, 2012; Romero-Lankao *et al.*, 2013a).

26.8.2.2. Rural Settlements

The legacy of previous and current stresses contributing to rapid population growth or loss in North American rural communities, reduced employment, or degradation of local knowledge systems, can increase vulnerability (Brklacich *et al.*, 2008; Coles and Scott, 2009; McLeman, 2010). North American rural communities have a higher proportion of lower income and unemployed populations and higher poverty than cities (Whitener and Parker, 2007; Lal *et al.*, 2011; Skoufias *et al.*, 2011). 55% of Mexico's rural residents live in poverty, and the livelihood of 72% of these is in farming (Saldaña-Zorrilla, 2008). US and Canadian rural communities have older populations (McLeman, 2010) and lower education levels (Lal *et al.*, 2011). Indigenous communities have lower education levels, and high levels of poverty, but are younger than average populations (Downing and Cuerrier, 2011). The legacy of their colonial history, furthermore, has stripped Indigenous communities of land and many sources of social and human capital (Brklacich *et al.*, 2008; Hardess *et al.*, 2011). Conversely, rural and indigenous community members possess valuable local and experiential knowledge regarding regional ecosystem services (Nakashima *et al.*, 2011).

Rural economies have limited economic diversity and relatively high dependence on climate-sensitive sectors (Johnston *et al.*, 2008; Natural Resources Canada, 2008; Molnar, 2010); they are sensitive to climate-induced reductions in resource supply and productivity, in addition to direct exposure to climate hazards (Daw *et al.*, 2009). Single-sector economic dependence contributes significantly to vulnerability (Cutter *et al.*, 2003). Engagement in export markets presents opportunity but also exposure to economic volatility (Eakin, 2006; Saldaña-Zorilla and Sandberg, 2009), and economic downturns take attention away from climate change adaptation. Farming and fishing provide both economic and food security, the impacts of climate thus posing a double threat to livelihood (Badjek *et al.*, 2010), particularly among women (Bee *et al.*, 2013). Inter-related factors affecting vulnerability in forestry and fishing communities include over-harvesting, and the cumulative environmental effects of multiple land use activities (Brklacich *et al.*, 2008). Many tourism-based communities are dominated by seasonal economies and low-wage, service-based employment (Tufts, 2010), and small businesses that lack resources for emergency planning (Hystad and Keller, 2006; Hystad and Keller, 2008). Non-renewable resource industries are sensitive to power, water, and transportation disruptions associated with hazards.

Geographic isolation can be a key source of vulnerability for rural communities in North America, imposing long commutes to essential services like hospitals, and non-redundant transportation corridors that can be compromised during extreme events (Chouinard *et al.*, 2008). Many Indigenous communities are isolated, raising the costs and limiting the diversity of imported food, fuel and other supplies, rendering the ability to engage in subsistence harvesting especially critical for both cultural and livelihood wellbeing (Andrachuk and Pearce, 2010; Hardess *et al.*, 2011). Many indigenous peoples also maintain strong cultural attachment to ancestral lands, and thus are especially sensitive to declines in the ability of that land to sustain their livelihoods and cultural wellbeing (Downing and Cuerrier, 2011).

Rural physical infrastructure is often inadequate to meet service needs or is in poor condition (McLeman and Gilbert, 2008; Krishnamurthy *et al.*, 2011), especially for Indigenous communities (section 26.9, Brklacich *et al.*, 2008; Hardess *et al.*, 2011; Lal *et al.*, 2011). A lack of redundant power and communication services can compromise hazard response capacity.

26.8.3. Projected Climate Risks on Urban and Rural Settlements

Urbanization, migration, economic disparity, and institutional capacity will influence future impacts and adaptation to climate change in North American human settlements (section 26.2.1). Water related concerns are assessed in 26.3.2.1 and 26.3.2.3). We describe below a variety of future climate risks identified in the literature, many of which focus on cities (Chapters 8 and 9) and, with the exception of larger centers such as New York and Boston, are qualitative in nature (Hunt and Watkiss, 2011). This is due in part to the difficulty in downscaling the prediction of trends in key trends in climate parameters to an appropriate scale

Model-based *sea-level-rise* (SLR) projections of future risks to cities are characterized by large uncertainties due to global factors (e.g., the dynamics of polar ice-sheets WGI) and regional factors (e.g., regional shifts in ocean circulation, high of the adjacent ocean and local land high) (Blake *et al.*, 2011) (WGI chapter 3). The latter will determine differential SLR impacts on regional land development of coastal settlements (U.S. Government Accountability Office, 2007; Yin *et al.*, 2009; Sobel *et al.*, 2010; Conrad, 2010; Millerd, 2011), making some areas particularly vulnerable to inundation (Cooper and Sehlke, 2012). SLR can also exacerbate vulnerability to extreme events such as hurricanes (Frazier *et al.*, 2010).

Temperature increases would lead to additional health hazards. Baseline warmer temperatures in cities are expected to be further elevated by extreme heat events whose intensity and frequency is projected to increase during the 21st century (section 26.2.2), particularly in northern mid-latitude cities (Jacob and Winner, 2009). Participation in some outdoor activities would also increase as a result of projected increases in warm days (Scott and McBoyle, 2007). Projected snowfall declines in Canada and the Northeast US would reduce length of winter sport seasons and thus affect the economic wellbeing of some communities (McBoyle *et al.*, 2007; Scott *et al.*, 2008b).

Any increase in frequency of *extreme events*, such as intense precipitation, flooding and prolonged dry periods would affect particularly the populations, economic activities, infrastructures and services on coasts, flood-prone deltas and arid regions (Nicholls *et al.*, 2008; Kirshen *et al.*, 2008; Richardson, 2010; Weiss *et al.*, 2011). For example, by the end of this century, New York City is projected to experience nearly twice as many extreme precipitation days compared to today (A2, mean ensemble of 17 models). (Ntelekos *et al.*, 2010; Cayan *et al.*, 2010) project an increase in the number and duration of droughts in the southwest US, with most droughts expected to last over five years by 2050 (GDFL CM2.1 and CNRM CM3, A2 and B1). Assuming no adaptation, total loses from river flooding in metropolitan Boston are estimated to exceed $57 billion by 2100, of which $26 billion is attributed to climate change (Nicholls *et al.*, 2008; Kirshen *et al.*, 2008; Richardson, 2010; Weiss *et al.*, 2011).

Future climate risks on *lives and livelihoods* have been relatively less studied. A handful of studies focused on forestry are notable, indicating potentially substantial shifts in livelihood options without adaptation. Sohngen and Sedjo (Sohngen and Sedjo, 2005) estimate losses from climate change in the Canadian/US timber sector of $1.4 – $2.1 billion per year over the next century. Anticipated future supply reductions in British Columbia as a consequence of the pine beetle outbreak vary from 10 to 62% (Patriquin *et al.*, 2007). Substantial declines in suitable habitat for valued tree species in Mexico have been projected (Gómez-Mendoza and Arriaga, 2007; Gomez-Diaz *et al.*, 2011).

Scholars are starting to project future risks from interacting hazards. For instance, by 2070 with a 0.5m rise in sea-level and under scenarios of socioeconomic growth, storm surges and subsidence, populations at risk in New York, Miami and New Orleans might increase three-fold, while asset exposure will increase more than 10-fold (Hanson *et al.*, 2011).

Essential *infrastructure and services* are key concerns (sections 26.3 and 26.7). Increased occurrence of drought affecting water availability is projected for southwestern US/Northern Mexico, the southern Canadian Prairies and central Mexico, combined with projected increases in water demand due to rapid population growth and agriculture (Schindler and Donahue, 2006; MacDonald, 2010; Lal *et al.*, 2011). Using A1B and A2 scenarios, (Escolero-Fuentes *et al.*, 2009) projected that by 2050, Mexico City and its watersheds will experience a more intense hydrological cycle and a reduction of between 10 to 17% in per capita available water. Sea-level rise is predicted to threaten water and electricity infrastructure with inundation and increasing salinity (Sharp, 2010).

26.8.4. Adaptation

26.8.4.1. Evidence of Adaptation

26.8.4.1.1. What are populations doing? Autonomous Adaptation

As illustrated by recent extreme events (Figure 26-2), individuals and households in North America have not only be affected by extremes, but have also been responding to climate impacts mostly through incremental actions, for example by purchasing additional insurance, or reinforcing homes to withstand extreme weather (Simmons and Sutter, 2007; Romero-Lankao *et al.*, 2012a). Some individuals respond by diversifying livelihoods (Newland *et al.*, 2008; Rose and Shaw, 2008) or migrating (See 26.1.1) (Black *et al.*, 2011).

The propensity to respond to climate and weather hazards is strongly influenced not only by access to household assets, but also by community and governmental support. The emergency response to Sandy illustrates this. Although New York and New Jersey witnessed vivid scenes of 'medical humanitarianism,' because of inadequate communication and coordination among agencies, public health support did not always reach those most in need (Abramson and Redlener, 2013).

The perceived risks of climate change among individuals are equally important. Strong attachment to place and occupation may motivate willingness to support incremental adaptation, enhance coping capacity and foster adaptive learning (Collins and Bolin, 2009; Romero-Lankao, 2010; Aguilar and Santos, 2011; Wittrock *et al.*, 2011). They have also been found to serve as barriers to transformational adaptation (Marshall *et al.*, 2012). Residents of the US stand out in international research as holding lower levels of perceived risk of climate change (AXA Ipsos, 2012), which may limit involvement in household-level adaptation, or support for public investments in adaptation.

26.8.4.1.2. What are governments doing? Planned Adaptation

Leadership in adaptation is far more evident locally than at other tiers of government in North America (Richardson, 2010; Vasseur, 2011; Vrolijks *et al.*, 2011; Henstra, 2012; Carmin *et al.*, 2012). Few municipalities have moved into the implementation stage, however; most programs are in the process of problem diagnosis and planning (Perkins *et al.*, 2007; Moser and Satterthwaite, 2008; Romero-Lankao and Dodman, 2011). Systematic assessments of vulnerability are rare, particularly in relation to population groups (Vrolijks *et al.*, 2011). Surveys of municipal leaders showed adaptation is rarely incorporated into planning, due to lack of resources, information and expertise (Horton and Richardson, 2011), and the prevalence of other issues considered higher priority, suggesting the need for subnational and federal-level facilitation in the form of resources and enabling regulations .

Climate change policies have been motivated by concerns for local economic or energy security and the desire to play leadership roles (Rosenzweig *et al.*, 2010; Anguelovski and Carmin, 2011; Romero-Lankao *et al.*, 2013a). Some policies constitute "integrated" strategies (New York) (Perkins *et al.*, 2007; Rosenzweig *et al.*, 2010), and coordinated participation of multiple municipalities (Vancouver) (Richardson, 2010). Sector-specific climate risk management plans have also emerged (e.g., water conservation in Phoenix, US and Regina, Canada; wildfire protection in Kamloops, Canada and Boulder, US). Municipalities affected by the mountain pine beetle have taken many steps toward adaptation (Parkins, 2008), and coastal communities in eastern Canada are investing in saltwater marsh restoration to adapt to rising sea levels (Marlin *et al.*, 2007). Green roofs, forest thinning and urban agriculture have all been expanding (Chicago, New York, Kamloops, Mexico City), as have flood protection (New Orleans, Chicago), private and governmental insurance policies (section 26.10, Browne and Hoyt, 2000; Ntelekos *et al.*, 2010), safe saving schemes (common in Mexico), air pollution controls (Mexico City), and hazard warning systems (Collins and Bolin, 2009; Coffee *et al.*, 2010; Romero-Lankao, 2010; Aguilar and Santos, 2011).

26.8.4.2. Opportunities and Constraints

Adaptation in human settlements is influenced by local access to resources, political will and the capacity for institutional-level attention and multilevel/multisectoral coordination (Burch, 2010; Romero-Lankao *et al.*, 2013a) (discussed further in the next section).

26.8.4.2.1. Adaptation is path-dependent

Adaptation options are constrained by past settlement patterns and decisions. The evolution of cities as economic hubs, for example, affects vulnerability and resilience (Leichenko, 2011). Urban expansion into mountain, agricultural, protected and otherwise risk-prone areas (Boruff *et al.*, 2005; McGranahan *et al.*, 2007; Collins and Bolin, 2009; Conrad, 2010) invariably alters regional environments. Development histories foreclose some resilience pathways. Previous water development, for example, can result in irreversible overexploitation and degradation of water resources.

26.8.4.2.2. Institutional capacity

At all levels of governance, adaptation in North America is affected by numerous determinants of institutional capacity. Three have emerged in the literature as particularly significant challenges for urban and rural settlements:

- *Economic Resources:* Rural communities face limited revenues combined with higher costs of supplying services (Williamson *et al.*, 2008; Posey, 2009). Small municipal revenue pools translate into fiscal constraints necessary to support public services, including emergency personnel and health care (Lal *et al.*, 2011). Although large cities tend to have greater fiscal capacity, most do not receive financial support for adaptation (Carmin *et al.*, 2012), yet face the risk of higher economic losses.
- *Information and social capital:* Differences in access and use of information, and capacity for learning and innovation, affect adaptive capacity (Romero-Lankao *et al.*, 2013a). Levels of knowledge and prioritization can be low among municipal planners. Information access can be limited, even among environmental

planners (Picketts *et al.*, 2012). The relationship between trust and participation in support networks (social capital) and adaptive capacity is generally positive, however strong social bonds may support narratives that under-estimate climate risk (Wolf *et al.*, 2010; Romero-Lankao *et al.*, 2012b).

- *Participation:* Considering the overlap among impacts and sources of vulnerability in North American human settlements, long-term effectiveness of local adaptation hinges upon inclusion of all stakeholders. Stakeholder involvement lengthens planning time frames, may elicit conflicts, and power relationships can constrain access (Few *et al.*, 2007; Colten *et al.*, 2008). However, effective stakeholder engagement has tremendously enhanced adaptation planning, eliciting key sources of information regarding social values, securing legitimacy (Aguilar and Santos, 2011), and fostering adaptive capacity of involved stakeholders.

_____ START BOX 26-3 HERE _____

Box 26-3. Climate Responses in Three North American Cities

With populations of 20.5, 14 and 2.3 million people, respectively, the metropolitan areas of Mexico City, New York, and Vancouver are facing multiple risks that climate change is projected to aggravate. These risks range from sea level rise, coastal flooding and storm surges in New York and Vancouver to heat waves, heavy rains and associated flooding, air pollution, and heat-island effects in all the three cities (Rosenzweig and Solecki, 2010; Leon and Neri, 2010; City of Vancouver, 2012). Many of these risks result not only from long-term global and regional processes of environmental change, but also from local changes in land and water uses and in atmospheric emissions induced by urbanization (Romero-Lankao, 2010; Leon and Neri, 2010; Kinney *et al.*, 2011; Solecki, 2012).

The three cities have been frontrunners in the climate arena. In Mexico City, the Program of Climate Action 2008–2012 (PAC) and the 2011 Law for Mitigation and Adaptation to Climate Change are parts of a larger 15-year "Green Agenda," with most of designated funds committed to reducing 7 million tonnes of CO_2 equivalent by 2012 (Romero-Lankao *et al.*, 2013). New York City's and Vancouver's Plans are similarly mitigation-centred. As of 2007 New-York's long-term sustainability plan included adaptation (Solecki, 2012; Ray *et al.*, 2013), while Vancouver launched its municipal adaptation plan in July 2012. The shifts in focus from mitigation to adaptation have followed as it has become increasingly clear that even if mitigation efforts are wholly successful, some adverse impacts due to climate change are unavoidable.

Urban leaders in all three cities have emerged as global leaders in sustainability. Mayor Bloomberg of New York; Mayor Ebrard of Mexico City, and David Cadman of Vancouver have, respectively, led the C40, World Mayors Council on Climate Change and International Council for Local Environmental Initiatives (ICLEI). Scientists, private sector actors and nongovernmental organizations have been of no lesser importance. To take advantage of a broad-based interaction between various climate change actors, Mexico City has set up a Virtual Climate Change Centre to serve as a repository of knowledge, models and data on climate change impacts, vulnerability and risks (Romero-Lankao *et al.*, 2013). Information sharing by climate change actors has also taken place in New York, where scientists, and insurance and risk management experts have served on the Panel on Climate Change to advise the city on the science of climate change impacts and "protection levels specific to the city's critical infrastructure" (Solecki, 2012): 564).

The climate plans of the three cities are far reaching, including mitigation and adaptation strategies related to their sustainability goals. The three cities emphasize different priorities in their climate action plans. Mexico City seeks to reduce water and transportation emissions through such actions as improvements in infrastructure and changes in the share of public transport. Vancouver has prioritized the separation of sanitary and stormwater systems, yet this adaptation is not expected to be complete until 2050 (City of Vancouver, 2012). It will also take New York much time, money and energy to expand adaptation strategies beyond the protection of water systems to include all essential city infrastructure (Ray *et al.*, 2013). Overall, few proposed actions will result in immediate effects, and instead call for additional planning, highlighting the significant effort necessary for comprehensive responses.

Overall, adaptation planning in the three cities faces many challenges. In all three regions, multi-jurisdictional governance structures with differing approaches to climate change challenge the ability for coordinated responses (Solecki, 2012; Romero-Lankao *et al.*, 2013). Conflicts in priorities and objectives between various actors and sectors are also prevalent (Burch, 2010). For instance, authorities in Mexico City concerned with avoiding growth into risk-prone and conservation areas (Aguilar and Santos, 2011) compete for regulatory space within a policy agenda that is already coping with a wide range of economic and developmental imperatives (Romero-Lankao *et al.*, 2013).

Climate responses require new types of localized scientific information, such as vulnerability analyses and flood risk assessments, which are not always available (Romero-Lankao *et al.*, 2012a; Ray *et al.*, 2013). Little is known, for instance, about how to predict and respond to common and differential levels of risk experienced by different human settlements. Comprehensive planning is still limited as well. For example, although scholarship exists on disparities in household- and population-level vulnerability and adaptive capacity (Villeneuve and Burnett, 2003; Cutter *et al.*, 2003; Douglas *et al.*, 2012; Romero-Lankao *et al.*, 2013b), equity concerns have received relatively less attention by either of the three cities. Even when local needs are identified, such as the need to protect higher risk homeless and low-income populations (Vancouver), they are often not addressed in action plans.

_____ END BOX 26-3 HERE _____

26.9. Federal and Subnational Level Adaptation

Along with many local governments (section 26.8.4), federal, and subnational tiers of government across North America are developing climate change adaptation plans. These initiatives, which began at the subnational levels (e.g., (Nunavut Department of Sustainable Development, 2003), appear to be preliminary and relatively little has been done to implement specific measures.

26.9.1. Federal Level Adaptation

All three national governments are addressing adaptation to some extent, with a national strategy and a policy framework (Mexico), a federal policy framework (Canada), and the United States having delegated all federal agencies to develop adaptation plans.

In 2005, the Mexican government created the *Inter-Secretarial Commission to Climate Change* (CICC – Comisión Inter-Secretarial de Cambio Climático) to coordinate national public policy on climate change (Comisión Inter-Secretarial de Cambio Climático, 2005; Sosa-Rodriguez, 2013).The government's initiatives are being delivered through the *National Strategy for Climate Change 2007-2012* (Intersecretarial Commission on Climate Change, 2007) and, the *Special Programme on Climate Change 2009-2012*, which identify priorities in research, cross-sectoral action such as developing early warning systems, and capacity development to support mitigation and adaptation actions (Comisión Inter-Secretarial de Cambio Climático, 2009). The *Policy Framework for Medium Term Adaptation* (Consejo Intersecretarial de Cambio Climático, 2010) aims at framing a single national public policy approach on adaptation with a time-horizon up to 2030. The General Law of Climate Change requires state governments to implement mitigation and adaptation actions (Diario Oficial de la Federación, 2012).

Canada is creating a Federal Adaptation Policy Framework intended to mainstream climate risks and impacts into programs and activities to help frame government priorities (Environment Canada, 2011a). In 2007, the federal Government made a four-year adaptation commitment to develop six Regional Adaptation Collaboratives (RAC) in provinces across Canada, ranging in size and scope, from flood protection and drought planning, to extreme weather risk management; and assessing the vulnerability of Nunavut's mining sector to climate change (Natural Resources Canada, 2011). In 2011, the federal government renewed financial support for several adaptation programs and provided new funding to create a Climate Adaptation and Resilience Program for Aboriginals and Northerners, and Enhancing Competitiveness in a Changing Climate program (Environment Canada, 2011b). Canada recently launched an Adaptation Platform to advance adaptation priorities across the country (Natural Resources Canada, 2013).

The US government embarked in 2009 on a government-wide effort to have all federal agencies address adaptation; to apply understanding of climate change to agency missions and operations; to develop, prioritize, and implement actions; and to evaluate adaptations and learn from experience. (The White House, 2009; Bierbaum *et al.*, 2012). A 2013 plan issued by the President enhanced the US government effort supporting adaptation (Executive Office of the President, 2013). The US Government provides technical and information support for adaptation by non-federal actors, but does not provide direct financial support for adaptation (Parris *et al.*, 2010).

Some federal agencies took steps to address climate change adaptation prior to this broader interagency effort. In 2010, the US Department of Interior created Climate Science Centers to integrate climate change information and management strategies in eight regions and 21 Landscape Conservation Cooperatives (Secretary of the Interior, 2010), while the US Environmental Protection Agency's Office of Water developed a climate change strategy (U.S. Environmental Protection Agency, National Water Program, 2011).

26.9.2. Subnational Level Adaptation

A number of states and provinces in all three countries have developed adaptation plans. For example, in Canada, Quebec's 2013-2020 adaptation strategy outlines 17 objections covering a number of managed sectors and ecosystems (Government of Quebec, 2012). British Columbia is modernizing its *Water Act* to alter water allocation during drought to reduce agricultural crop and livestock loss and community conflict, while protecting aquatic ecosystems (British Columbia Ministry of the Environment, 2010).

In the US California was the first state to publish an adaptation plan calling for a 20% reduction in per capita water use by 2020 (California Natural Resources Agency, 2009). Maryland first developed a plan on coastal resources and then broadened it to cover human health, agriculture, ecosystems, water resources, and infrastructure (Maryland Commission on Climate Change Adaptation and Response Working Group, 2008; Maryland Department of the Environment on behalf of the Maryland Commission on Climate Change, 2010). The State of Washington is addressing environment, infrastructure, and communities; human health and security; ecosystems, species, and habitat; and natural resources (Washington State Built Environment: Infrastructure & Communities Topic Advisory Group, 2011; Washington State Human Health and Security Topic Advisory Group, 2011; Washington State Species, Habitats and Ecosystems Topic Advisory Group, 2011; Washington State Natural Resources Working Lands and Waters Topic Advisory Group, 2011).

Of the three national governments, only Mexico requires that states develop adaptation plans. In Mexico, seven of 31 states, Veracruz, Mexico City, Nuevo León, Guanajuato, Puebla, Tabasco, and Chiapas, have all developed their *State Programmes for Climate Change Action* (Programas Estatales de Acción ante el Cambio Climático - PEACC), while Baja California Sur, Hidalgo, and Campeche are in the final stage and 17 states are still in the planning and developing stage (Instituto de Ecología del Estado de Guanajuato, 2011). The proposed adaptation actions focus mainly on: 1) reducing physical and social vulnerability of key sectors and populations; 2) conservation and sustainable management of ecosystems, biodiversity, and ecosystem services; 3) developing risk management strategies; 4) strengthening water management; 5) protecting human health, and; 6) improving current urban development strategies, focusing on settlements and services, transport and land use planning.

26.9.3. Barriers to Adaptation

Chapter 16 provides a more in-depth discussion on adaptation barriers and limits. Adaptation plans tend to exist as distinct documents and are often not integrated into other planning activities (Preston *et al.*, 2011). Most adaptation activities have only involved planning for climate change rather than specific actions, and few measures have been implemented (Preston *et al.*, 2011; Bierbaum *et al.*, 2012).

Even though Canada and the US are relatively well-endowed in their capacity to adapt, there are significant constraints on adaptation, with financing being a significant constraint in all three countries (Carmin *et al.*, 2012). Barriers include legal constraints (e.g., (Jantarasami *et al.*, 2010) lack of coordination across different jurisdictions

(Smith *et al*., 2009; National Research Council, 2010; Instituto Nacional de Ecología y Cambio Climático, 2012b), leadership (Smith *et al.*, 2009; Moser and Ekstrom, 2010), and divergent perceptions about climate change (Bierbaum *et al.*, 2012; Moser, 2013). Although obtaining accurate scientific data was ranked less important by municipalities(Carmin *et al.*, 2012), an important constraint is lack of access to scientific information and capacity to manage and use it (Moser and Ekstrom, 2010; Instituto Nacional de Ecología y Cambio Climático, 2012b). Adaptation activities in developed countries such as the US tend to address hazards and propose adaptations that tend to protect current activities rather than facilitate long term change. In addition, the adaptation plans generally do not attempt to increase adaptive capacity (Eakin and Patt, 2011). However, making changes to institutions needed to enable or promote adaptations can be costly (Marshall, 2013).

Although multilevel and multisectoral coordination is a key component of effective adaptation, it is constrained by factors such as mismatch between climate and development goals, political rivalry, and lack of national support to regional and local efforts (Brklacich *et al.*, 2008; Sander-Regier *et al.*, 2009; Brown, 2009; Sydneysmith *et al.*, 2010), (Craft and Howlett, 2013; Romero-Lankao *et al.*, 2013a). Traditionally, environmental or engineering agencies are responsible for climate issues (e.g., Mexico City, Edmonton and London, Canada), but have neither the decision making power nor the resources to address all dimensions involved. Adaptation planning requires long-term investments by government, business, grassroots organizations and individuals (e.g., Romero-Lankao, 2007; Croci *et al.*, 2010; Sarah, 2010; Richardson, 2010).

26.9.4. Maladaptation, Trade-Offs, and Co-Benefits

Adaptation strategies may introduce trade-offs or maladaptive effects for policy goals in mitigation, industrial development, energy security, and health (Hamin and Gurran, 2009; Laukkonen *et al.*, 2009). Snow-making equipment, for example, mediates snowpack reductions, but has high water and energy requirements (Scott *et al.*, 2007). Irrigation and air conditioning have immediate adaptive benefits for North American settlements, but are energy-consumptive. Sea walls protect coastal properties, yet negatively affect coastal processes and ecosystems (Richardson, 2010).

Conventional sectoral approaches to risk management and adaptation planning undertaken at different temporal and spatial scales have exacerbated vulnerability in some cases e.g., peri-urban areas in Mexico (Eakin *et al.*, 2010; Romero-Lankao, 2012). Approaches that delegate response planning to residents in the absence of effective knowledge exchange have resulted in maladaptive effects (Friesinger and Bernatchez, 2010).

Other strategies offer synergies and co-benefits. Policies addressing air pollution (Harlan and Ruddell, 2011) or housing for the poor, particularly in Mexico (Colten *et al.*, 2008), can often be adapted at low or no cost to fulfill adaptation and sustainability goals (Badjek *et al.*, 2010). Efforts to temper declines in production or competitiveness in rural communities could involve mitigation innovations, including carbon sequestration forest plantations (Holmes, 2010). Painting roofs white reduces the effects of heat and lowers energy demand for cooling (Akbari *et al.*, 2009).

Adaptation planning can be greatly enhanced by incorporating regionally or locally-specific vulnerability information (Clark *et al.*, 1998; Barsugli *et al.*, 2012; Romsdahl *et al.*, 2013). Methods for mapping vulnerability have been improved and effectively utilized (Romero-Lankao *et al.*, 2013b). Similarly, strategies supporting cultural preservation and subsistence livelihood needs among Indigenous peoples would enhance adaptation (Ford *et al.*, 2010b), as would integrating traditional culture with other forms of knowledge, technologies, education and economic development (Hardess *et al.*, 2011).

26.10. Key Risks, Uncertainties, Knowledge Gaps, and Research Needs

26.10.1. Key Multi-Sectoral Risks

We close this chapter with our assessment of key current and future regional risks from climate change with an evaluation of the potential for risk reduction through adaptation (Table 26-1). Two of the three examples, wildfires and urban floods, illustrate that multiple climate drivers can result in multiple impacts (e.g., loss of ecosystems integrity, property damage and health impacts due to wildfires and urban floods). The three risks evaluated in Table 26-1 also show that *relative risks* depend on the context specific articulation and dynamics of such factors as

- The magnitude and rate of change of relevant climatic and non-climatic drivers and hazards. For instance, the risk of urban floods depends not only on global climatic conditions (current versus future global mean temperatures of 2˚C and 4˚C), but also on urbanization, a regional source of hazard risk that can enhance or reduce precipitation, as it affects the hydrologic cycle and, hence, has impacts on flood climatology (section 26.8.2.1);
- The internal properties and dynamics of the system being stressed. For example, some ecosystems are more fire-adapted than others. Some populations are more vulnerable to heat-stress because of age, pre-existing medical conditions, working conditions and lifestyles (e.g., outdoor workers, athletes);
- Adaptation potentials and limits. For example, while residential air conditioning (A/C) can effectively reduce health risk, availability and usage of A/C is often limited among the most vulnerable individuals. Furthermore, A/C is sensitive to power failures and its use has mitigation implications.

[INSERT TABLE 26-1 HERE
Table 26-1: Key risks from climate change and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of this chapter, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.]

The judgments about risk conveyed by the Table 26-1 are based on assessment of the literature and expert judgment by chapter authors living under current socio-economic conditions. Therefore, risk levels are estimated for each timeframe, assuming a continuation of current adaptation potentials and constraints. Yet over the course of the 21st century, socioeconomic and physical conditions can change considerably for many sectors, systems and places. The dynamics of wealth generation and distribution, technological innovations, institutions, even culture, can substantially affect North American levels of risk tolerance within the social and ecological systems considered in the Table (see also Box TS.8).

26.10.2. Uncertainties, Knowledge Gaps, and Research Needs

The literature on climate impacts, adaptation and vulnerability in North America has grown considerably, as has the diversity of sectors and topics covered (e.g., urban and rural settlements, food security, and adaptation at local, state and national levels). However, limitations in the topical and geographical scope of this literature are still a challenge (e.g., more studies have focused on insurance than on economic sectors such as industries, construction and transportation). It is also challenging to summarize results across many studies and identify trends in the literature when there are differences in methodology, theoretical frameworks and causation narratives (e.g., between outcome and contextual approaches) making it hard to compare “apples to oranges” (Romero-Lankao *et al.*, 2012b) While the US and Canada have produced large volumes of literature, Mexico lags well behind. It was, therefore, difficult to devote equal space to observed and projected impacts, vulnerabilities and adaptations in Mexico in comparison with its Northern neighbors. With its large land area, population and important, albeit understudied, climate change risks and vulnerabilities, more climate change research focusing on Mexico is direly needed.

The literature on North America tends to be dominated by sector level analyses. Yet, climate change interacts with other physical and social processes to create differential risks and impact levels. These differences are mediated by context-specific physical and social factors shaping the vulnerability of exposed systems and sectors. Furthermore, while studies often focus on isolated sectorial effects, impacts happen in communities, socio-ecologic systems and regions, and shocks and dislocations in one sector or region often affect other sectors and regions due to social and physical interdependencies. This point is illustrated by our border region and wildfire boxes and the human settlements section, which discuss place-based impacts, vulnerabilities and adaptations. Unfortunately, literature using placed-based or integrated approaches to these complexities is limited. Indeed although in early drafts the authors of this chapter attempted to put more emphasis on place-based analysis and comparisons, the literature was inadequate to support such an effort. The IPCC includes chapters on continents and large regions to make it possible to assess how multiple climate change impacts can affect these large areas. However, this macro view gives insufficient detail on context specific local impacts and risks, missing the on-the-ground reality that the effects of climate change are and will be experienced at much smaller scales, and those smaller scales are often where meaningful mitigation and adaptation actions can be generated. In order to give local actors relevant information on which to base these local actions, more research is needed to better understand the local and regional effects of climate change across sectors.

Frequently Asked Questions

FAQ 26.1: What impact is climate having on North America? *[to remain at the end of the chapter]*
Recent climate changes and extreme events demonstrate clear impacts of climate-related stresses in North America (*high confidence*). There has been increased occurrence of severe hot weather events over much of the US and increases in heavy precipitation over much of North America (*high confidence*). Such events as droughts in northern Mexico and south-central US, floods in Canada, and hurricanes such as Sandy, demonstrate exposure and vulnerability to extreme climate (*high confidence).* Many urban and rural settlements, agricultural production, water supplies, and human health have been observed to be vulnerable to these and other extreme weather events (Figure 26-2). Forest ecosystems have been stressed through wildfire activity, regional drought, high temperatures, and infestations, while aquatic ecosystems are being affected by higher temperatures and sea level rise.

Many decision makers, particularly in the United States and Canada, have the financial, human and institutional capacity to invest in resilience, yet a trend of rising losses from extremes has been evident across the continent (Figure 26-2), largely due to socio-economic factors, including a growing population, equity issues and increased property value in areas of high exposure. In addition, climate change is *very likely* to lead to more frequent extreme heat events and daily precipitation extremes over most areas of North America, more frequent low snow years, and shifts towards earlier snowmelt runoff over much of the western US and Canada (*high confidence*). These changes combined with higher sea levels and associated storm surges, more intense droughts, and increased precipitation variability are projected to lead to increased stresses to water, agriculture, economic activities and urban and rural settlements (*high confidence*).

FAQ 26.2: Can adaptation reduce the adverse impacts of climate in North America?
[to remain at the end of the chapter]
Adaptation – including land use planning, investments in infrastructure, emergency management, health programs, and water conservation – has significant capacity to reduce risks from current climate and climate change (Figure 26-3). There is increasing attention to adaptation among planners at all levels of government but particularly at the municipal level, with many jurisdictions engaging in assessment and planning processes. Yet, there are few documented examples of implementation of proactive adaptation and these are largely found in sectors with longer-term decision-making, including energy and public infrastructure *(high confidence*). Adaptation efforts have revealed the significant challenges and sources of resistance facing planners at both the planning and implementation stages, particularly the adequacy of informational, institutional, financial and human resources, and lack of political will (*medium confidence*).

While there is high capacity to adapt to climate change across much of North America, there are regional and sectoral disparities in economic resources, governance capacity, and access to and ability to utilize information on climate change which limit adaptive capacity in many regions and among many populations such as the poor and indigenous communities. For example, there is limited capacity for many species to adapt to climate change, even with human intervention. At lower levels of temperature rise, adaptation has high potential to off-set projected declines in yields for many crops, but this effectiveness is expected to be much lower at higher temperatures. The risk that climate stresses will cause profound impacts on ecosystems and society – including the possibility of species extinction or severe adverse socio-economic shocks – highlights limits to adaptation.

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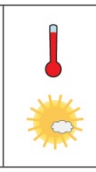
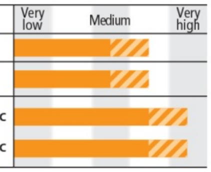
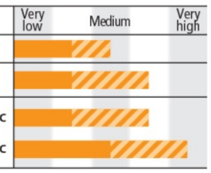
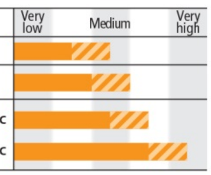
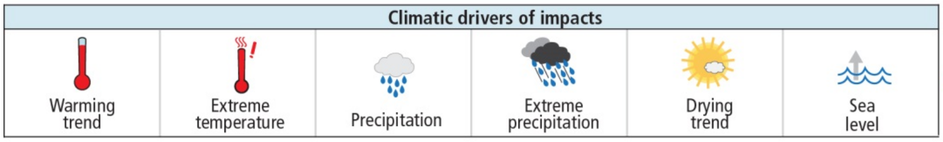
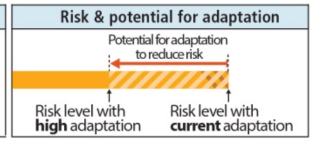
Table 26-1: Key risks from climate change and the potential for risk reduction through adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of this chapter, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030-2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080-2100), for global mean temperature increase of 2°C and 4°C above preindustrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Loss of ecosystem integrity, property loss, human morbidity and mortality due to **wildfires** (*high confidence*)	Some ecosystems are more fire-adapted than others. Forest managers and municipal planners are increasingly incorporating fire protection measures (e.g., prescribed burning, introduction of resilient vegetation). Institutional capacity to support ecosystem adaptation is limited. Adaptation of human settlements is constrained by rapid private property development in high-risk areas and by limited household-level adaptive capacity.		26.4, 26.8.1.2, Box 26-2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	
Heat-related human mortality (*high confidence*)	Residential air conditioning (A/C) can effectively reduce risk. However, availability and usage of A/C is often limited among the most vulnerable individuals, and is subject to complete loss during power failures. In addition, there are vulnerable populations including athletes and outdoor workers for whom air conditioning is not available. Community- and household-scale adaptations have the potential to reduce exposure to heat extremes via: family support; heat warnings; cooling centers; greening; high albedo surfaces, etc.		26.6.1.2, 26.8.1.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	
Property and infrastructure damage; supply chain, ecosystem and social system disruption; public health; and water quality impairement from river and coastal **urban floods** (*high confidence*)	Implementing management of urban drainage is expensive and very disruptive to urban areas. There are many no-regret strategies with co-benefits (e.g., less impervious surfaces leading to more groundwater recharge, green infrastructure, and roof-top gardens). Sea level rise increases water elevations in coastal outfalls, which impedes drainage. In many cases, older rainfall design standards are being used which need to be updated to reflect current climate conditions. Significant challenges are also being faced by urban managers due to increased flooding from coastal storms and river-flooding.		26.2.2.2, 26.3.3.2, 26.3.3.3, 26.3.4, 26.4.2, 26.4.2.2, 26.6.1.1, 26.6.1.5, 26.6.2, 26.7, 26.7.1.1, 26.7.5.2.2, 26.8.1.1,26.8.1.2, 26.8.2.1, 26.8.3, 26.8.4.1.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	

Climatic drivers of impacts



Risk & potential for adaptation



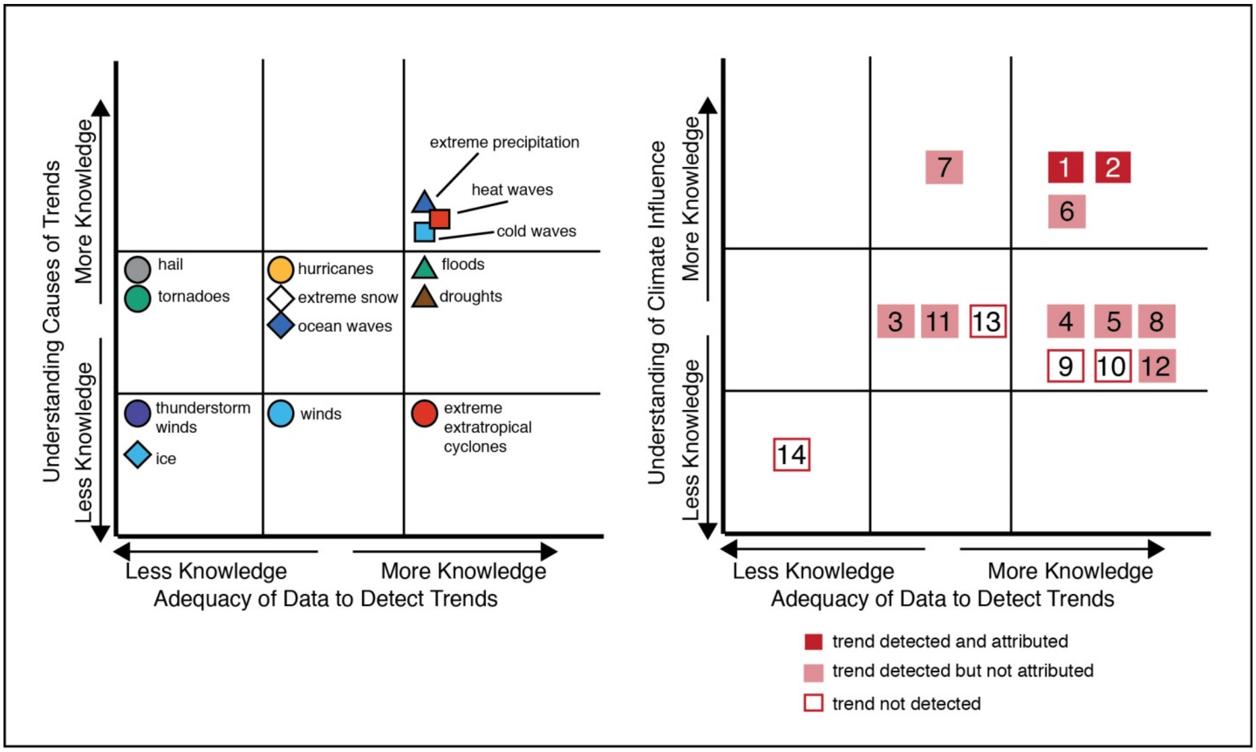


Figure 26-1 Detection and attribution of climate change impacts. Comparisons of the adequacy of currently available data to detect trends and the degree of understanding of causes of those changes in climatic extreme events in the United States (left; Peterson *et al.*, 2013) and degree of understanding of the climate influence in key impacts in North America (right). Note that "climate influence" means that the impact has been documented to be sensitive to climate, not that it has been attributed to climate change. Filled boxes indicate that formal detection and attribution to climate change has been performed for the given impact; shaded boxes indicate that a trend has been detected from background variability in the given impact, but formal attribution to climate change has not occurred and the trend could be due to other drivers; and open boxes indicate that a trend has not currently been detected. Key impacts are: 1) earlier peak flow of snowmelt run-off in snow-dominated streams and rivers in western North America [26.3.1], 2) declines in the amount of water stored in spring snowpack in snow-dominated areas of western North America [26.3.1], 3) northward and upward shifts in species' distributions in multiple taxa of terrestrial species, although not all taxa and regions [26.4.1], 4) increases in coastal flooding [26.8.1], 5) increases in wildfire activity, including fire season length and area burned by wildfires in the western United States and boreal Canada [Box 26-2], 6) storm-related disaster losses in the United States (most of the increase in insurance claims paid has been attributed to increasing exposure of people and assets in areas of risk) [26.7.6.1, 26.8.1], 7) increases in bark beetle infestation levels in pine tree species in western North America [26.4.2.1], 8) yield increases due in part to increasing temperatures in Canada and higher precipitation in the US; yield variances attributed to climate variability in Ontario and Quebec; yield losses attributed to climate-related extremes across North America [26.5.1], 9) changes in storm-related mortality in the United States [26.6.1.2], 10) changes in heat-related mortality in the United States [26.6.1.2], 11) increases in tree mortality rates in old-growth forests in the western United States and western Canada from 1960-2007 [26.4.2.1], 12) changes in flooding in some urban areas due to extreme rainfall [26.3.1, 26.8.2.1], 13) increase in water supply shortages due to drought [26.8.1, 26.3], and 14) changes in cold-related heat mortality [26.6.1.2]. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

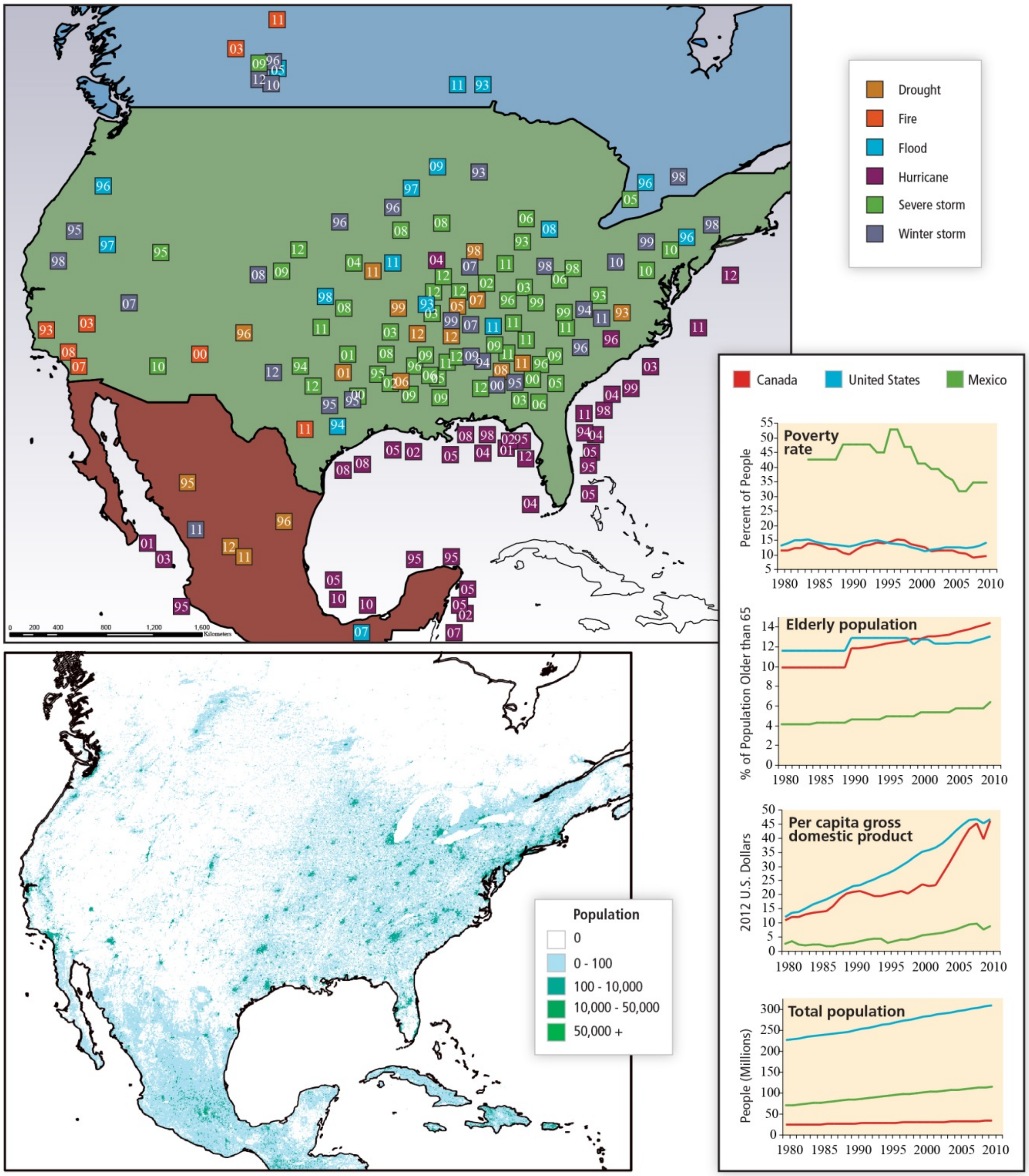

Drought
Fire
Flood
Hurricane
Severe storm
Winter storm
Population
0
0 - 100
100 - 10,000
10,000 - 50,000
50,000 +
Canada
United States
Mexico
Poverty rate
Percent of People
Elderly population
% of Population Older than 65
Per capita gross domestic product
2012 U.S. Dollars
Total population
People (Millions)
1980 1985 1990 1995 2000 2005 2010

Figure 26-2: Extreme events illustrating vulnerabilities for Mexico, the United States, and Canada. This figure offers a graphic illustration of location of extreme events and relevant vulnerability trends. The observed extreme events have not been attributed to anthropogenic climate change, yet they are climate-sensitive sources of impact illustrating vulnerability of exposed systems, particularly if projected future increases in the frequency and/or intensity of such events should materialize. The figure includes:

a) A map (bottom) with population density at 1km resolution highlighting exposure and represented using 2011 Landscan data (Bright *et al.*, 2012).
b) A map (top) with significant weather events taking place during 1993-2012. The map only includes disasters with overall losses of more than $1 billion US dollars in US, or more than $500 million US dollars in Mexico and Canada, adjusted to 2012 values (Source: (NatCatSERVICE, 2010). Hence, it does not include the occurrence of disasters of small and medium impact, and it does not capture the impacts of disasters on populations' livelihoods and wellbeing. Disasters represented by points that are located at the approximate geographic center of affected regions, frequently span more than one subnational jurisdiction (e.g., the 2012 drought affected 12 Mexican states, Annex Table).
c) Four panels (right) with trends in socio-demographic indicators used in the literature to measure vulnerability to hazards (Romero-Lankao *et al.*, 2012): poverty rates, percentage of elderly, GDP per capita and total population (Sources: Comisión Económica para América Latina y el Caribe; U.S. Census Bureau, 2011; Statistics Canada, 2012).

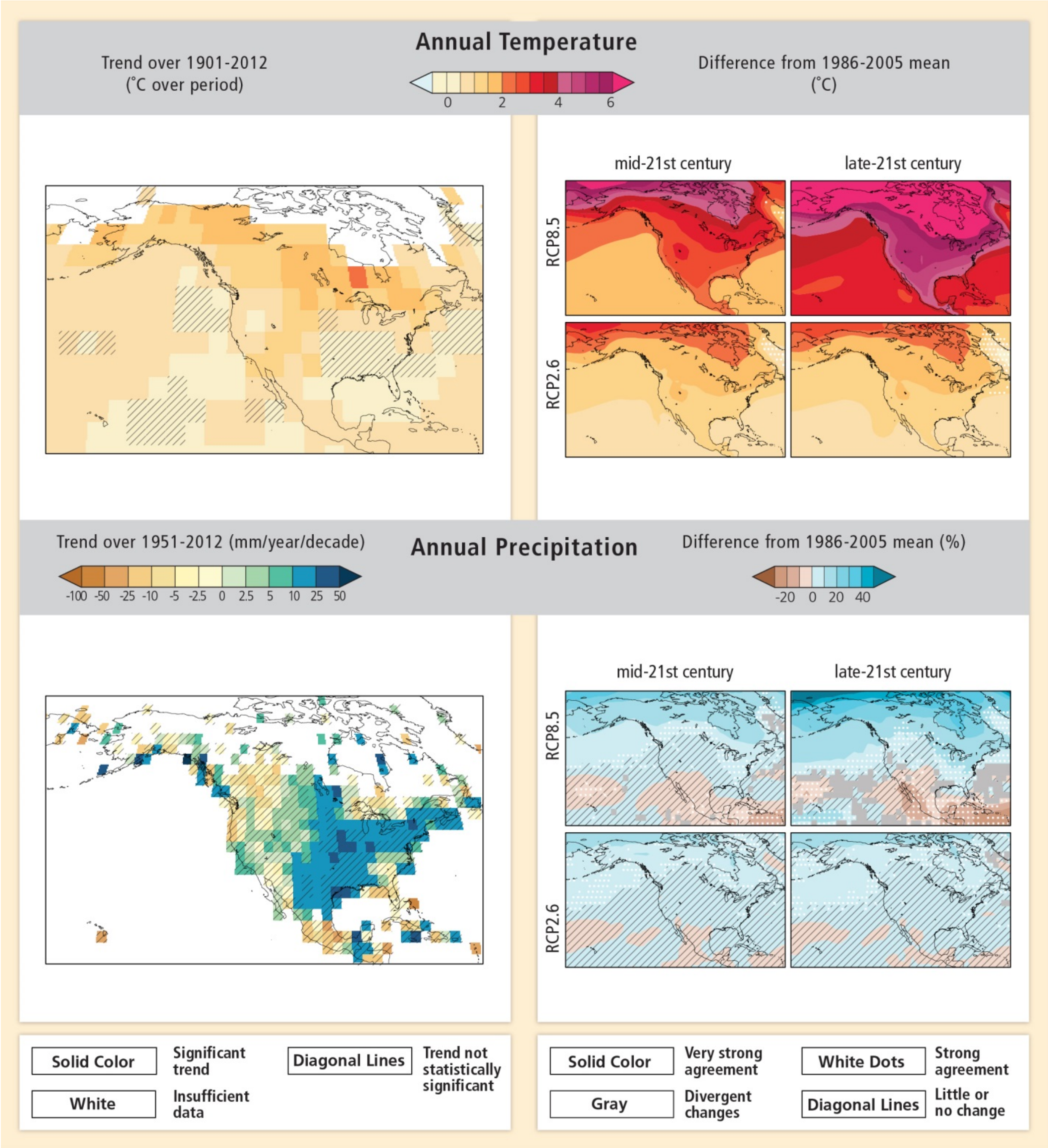


Figure 26-3: Observed and projected Changes in annual temperature and precipitation. (Top panel, left) observed temperature trends from 1901-2012 determined by linear regression [WGI AR5 Figures SPM.1 and 2.21]. (Bottom panel, left) Observed precipitation change from 1951-2010 determined by linear regression. [WGI AR5 Figure SPM.2] For observed temperature and precipitation, trends have been calculated where sufficient data permits a robust estimate (i.e., only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Solid colors indicate areas where change is significant at the 10% level. Diagonal lines indicate areas where change is not significant (Top and bottom panel, right) CMIP5 multi-model mean projections of annual average temperature changes and average percent change in annual mean precipitation for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline

variability, and >90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where >66% of models show change greater than the baseline variability and >66% of models agree on sign of change. Gray indicates areas with divergent changes, where >66% of models show change greater than the baseline variability, but <66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in >66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-3 and CC-RC]

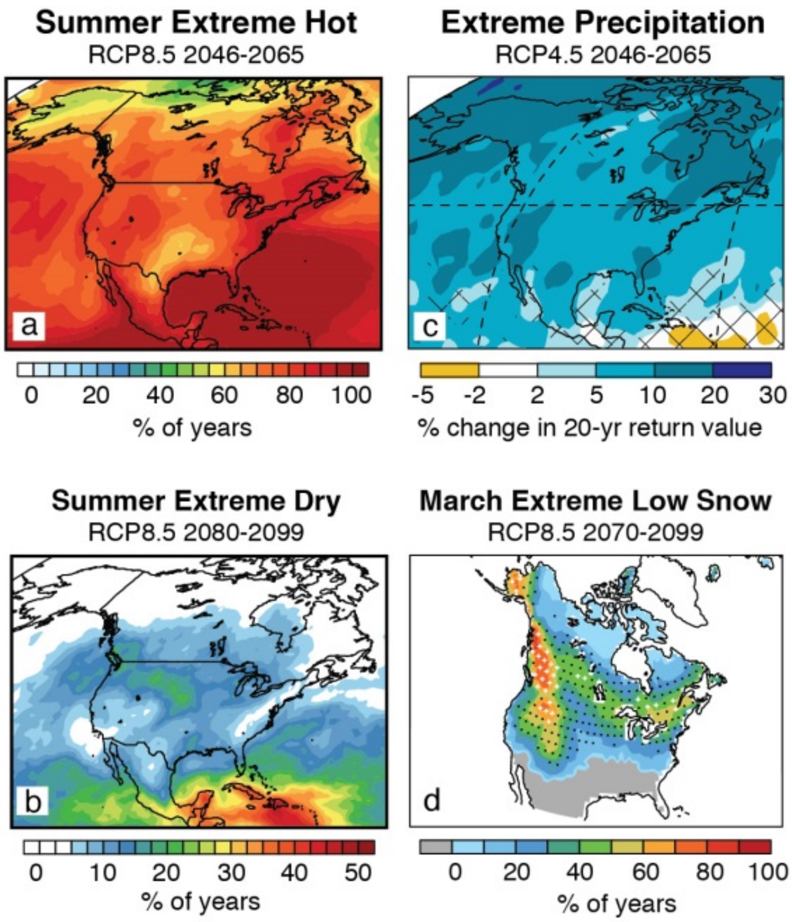


Figure 26-4: Projected changes in extremes in North America. (a) The percentage of years in the 2046–2065 period of RCP8.5 in which the summer temperature is greater than the respective maximum summer temperature of the 1986–2005 baseline period (Diffenbaugh and Giorgi, 2012). (b) The percentage of years in the 2080-2099 period of RCP8.5 in which the summer precipitation is less than the respective minimum summer precipitation of the 1986-2005 baseline period (Diffenbaugh and Giorgi, 2012) (c) The percentage difference in the 20-year return value of annual precipitation extremes between the 2046-2065 period of RCP4.5 and the 1986-2005 baseline period (from (Kharin *et al.*, 2013). The hatching indicates areas where the differences are not significant at the 5% level. (d) The percentage of years in the 2070-2099 period of RCP8.5 in which the March snow water equivalent is less than the respective minimum March snow water equivalent of the 1976–2005 period (Diffenbaugh *et al.*, 2012). The black (white) stippling indicate areas where the multimodel mean exceeds 1.0 (2.0) standard deviations of the multi-model spread. (a-d) The RCPs and time periods are those used in the peer-reviewed studies in which the panels appear. The 2046-2065 period of RCP8.5 and the 2046-2065 period of RCP4.5 exhibit global warming in the range of 2-3˚C above the pre-industrial baseline (WGI Fig. 12.40). The 2080-2099 and 2070-2099 periods of RCP8.5 exhibit global warming in the range of 4-5˚C above the pre-industrial baseline (WGI Fig. 12.40).
[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 27. Central and South America

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Contents

Executive Summary

Significant trends in precipitation and temperature have been observed in Central America (CA) and South America (SA) (*high confidence*). Besides, changes in climate variability and in extreme events have severely affected the region (*medium confidence*). Increasing trends in annual rainfall in Southeastern South America (SESA; 0.6 mm/day/50years during 1950-2008) contrast with decreasing trends in CA and Central-Southern Chile (-1mm/day /50 years during 1950-2008). Warming has been detected throughout CA and SA (near to 0.7-1°C/40 years since the mid-1970’s), except for a cooling off the Chilean coast of about -1 C°/40 years. Increases in temperature extremes have been identified in CA and most of tropical and subtropical SA (*medium confidence*), while more frequent extreme rainfall in SESA has favoured the occurrence of landslides and flash floods (*medium confidence*). (27.2.1.1, Table 27-1, Box 27-1)

Climate projections suggest increases in temperature, and increases or decreases in precipitation for CA and SA by 2100 (*medium confidence*). Post-AR4 climate projections, derived from dynamic downscaling forced by CMIP3 models for various SRES scenarios, and to different global climate models from the CMIP5 for various

RCPs (4.5 and 8.5), warming varies from +1.6°C to +4.0°C in CA, and +1.7°C to +6.7°C in SA (*medium confidence*). Rainfall changes for CA range between -22% to +7% by 2100, while in SA rainfall varies geographically, most notably showing a reduction of -22% in Northeast Brazil, and an increase of +25% in SESA (*low confidence*). By 2100 projections show an increase in dry spells in tropical SA east of the Andes, and in warm days and nights in most of SA (*medium confidence*) (27.2.1.2, Table 27-2).

Changes in stream flow and water availability have been observed and projected to continue in the future in CA and SA, affecting already vulnerable regions (*high confidence*). The Andean cryosphere is retreating affecting the seasonal distribution of streamflows (Table 27-3) (*high confidence*). Increasing runoffs in the La Plata River basin and decreasing ones in the Central Andes (Chile, Argentina) and in CA in the second half of the 20th century were associated with changes in precipitation (*high confidence*). Risk of water supply shortages will increase owing to precipitation reductions and evapotranspiration increases in semi-arid regions (*high confidence*) (Table 27-4), thus affecting water supply for cities (*high confidence*) (27.3.1.1; 27.3.5), hydropower generation (*high confidence*) (27.3.6; 27.6.1) and agriculture (27.3.1.1). Current practices to reduce the mismatch between water supply and demand could be used to reduce future vulnerability (*medium confidence*). Ongoing constitutional and legal reforms towards more efficient and effective water resources management and coordination constitute another adaptation strategy (*medium confidence*) (27.3.1.2).

Land use change contributes significantly to environmental degradation exacerbating the negative impacts of climate change (*high confidence*). Deforestation and land degradation are mainly attributed to increased extensive and intensive agriculture. The agricultural expansion, in some regions associated with increases in precipitation, has affected fragile ecosystems, such as the edges of the Amazon forest and the tropical Andes. Even though deforestation rates in the Amazon have decreased substantially since 2004 to a value of 4,656 km^2/yr in 2012, other regions like the Cerrado still present high levels of deforestation with average rates as high as 14,179 km^2/yr for the period 2002-2008 (27.2.2.1).

Conversion of natural ecosystems is the main cause of biodiversity and ecosystem loss in the region, and is a driver of anthropogenic CC (*high confidence*). CC is expected to increase the rates of species extinction (*medium confidence*). For instance, vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains. In Brazil, distribution of some groups of birds and plants will be dislocated southwards, where there are less natural habitats remaining. However, CA and SA have still large extensions of natural vegetation cover for which the Amazon is the main example (27.3.2.1). Ecosystem-based adaptation practices are increasingly common across the region, such as the effective management and establishment of protected areas, conservation agreements and community management of natural areas (27.3.2.2).

Socioeconomic conditions have improved since AR4; however there is still a high and persistent level of poverty in most countries resulting in high vulnerability and increasing risk to climate variability and change (*high confidence*). Poverty levels in most countries remain high (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade. Human Development Index varies greatly between countries, from Chile and Argentina with the highest values, and Guatemala and Nicaragua with the lowest values in 2007. The economic inequality translates into inequality in access to water, sanitation and adequate housing, particularly for the most vulnerable groups translating into low adaptive capacities to climate change (27.2.2.2).

Sea-level rise (SLR) and human activities on coastal and marine ecosystems pose threats to fish stocks, corals, mangroves, recreation and tourism, and control of diseases (*high confidence*). SLR varied from 2 to 7 mm/yr between 1950 and 2008**.** Frequent coral bleaching events associated to ocean warming and acidification occur in the Mesoamerican Coral Reef. In CA and SA, the main drivers of mangrove loss are deforestation and land conversion to agriculture and shrimp ponds (27.3.3.1). Brazilian fisheries' co-management (a participatory multi-stakeholder process) is an example of adaptation since it favours a balance between conservation of marine biodiversity, the improvement of livelihoods, and the cultural survival of traditional populations (27.3.3.2).

Changes in agricultural productivity with consequences for food security associated to CC are expected to exhibit large spatial variability (*medium confidence*). In SESA, where projections indicate more rainfall, average productivity could be sustained or increased until the mid-century (SRES: A2, B2) (Table 27-5) (*medium confidence*). In CA, northeast of Brazil and parts of the Andean region increases in temperature and decreases in rainfall could decrease the productivity in the short-term (by 2030), threatening the food security of the poorest population (Table 27-5) (*medium confidence*). Considering that SA will be a key food producing region in the future, one of the challenges will be to increase the food and bioenergy quality and production while maintaining environmental sustainability under CC (27.3.4.1). Some adaptation measures include crop, risk, and water use management along with genetic improvement (27.3.4.2) (*high confidence*).

Renewable energy (RE) based on biomass has a potential impact on land use change and deforestation and could be affected by CC (*medium confidence*). Sugarcane and soy are likely to respond positively to CO_2 and temperature changes, even with a decrease in water availability, with an increase in productivity and production (*high confidence*). The expansion of sugarcane, soy and oil palm may have some effect on land use, leading to deforestation in parts of Amazon, CA among other regions, and loss of employment in some countries (*medium confidence*) (27.3.6.1). Advances in second-generation bioethanol from sugarcane and other feedstocks will be important as a measure of mitigation (27.3.6.2).

Changes in weather and climatic patterns are negatively affecting human health in CA and SA, either by increasing morbidity, mortality, and disabilities (*high confidence*), and through the emergence of diseases in previously non-endemic areas (*high confidence*). With *very high confidence* climate-related drivers are associated with respiratory and cardiovascular diseases, vector- and water-borne diseases (malaria, dengue, yellow fever, leishmaniasis, cholera, and other diarrheal diseases), Hantaviruses and Rotaviruses, chronic kidney diseases, and psychological trauma. Air pollution is associated with pregnancy-related outcomes and diabetes, among others (27.3.7.1). Vulnerabilities vary with geography, age, gender, race, ethnicity, and socio-economic status, and are rising in large cities (27.3.7.2) (*very high confidence*). Climate change will exacerbate current and future risks to health, given the region's population growth rates and vulnerabilities in existing health, water, sanitation and waste collection systems, nutrition, pollution and food production in poor regions (*medium confidence*).

In many CA and SA countries, a first step toward adaptation to future climate changes is to reduce the vulnerability to present climate. Long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the CA and SA population. Various examples demonstrate possible synergies between development, adaptation and mitigation planning, which can help local communities and governments to allocate efficiently available resources in the design of strategies to reduce vulnerability. However, the generalization of such actions at continental scale requires that both the CA and SA citizens and governments are faced with the challenge of building a new governance model, where imperative development needs, vulnerability reduction and adaptation strategies to climate stresses will be truly intertwined. (27.3.4, 27.4.1, 27.4.2, 27.4.3, 27.4.4, 27.5).

27.1. Introduction

27.1.1. The Central and South America Region

The CA and SA region harbors unique ecosystems, the highest biodiversity in the planet and has a variety of eco-climatic gradients. Unfortunately, this natural wealth is threatened by advancing agricultural frontiers resulting from a rapidly growing agricultural and cattle production (Grau and Aide, 2008). The region experienced a steady economic growth in the last decade, accelerated urbanization and important demographic changes; poverty and inequality are decreasing continuously, but at a low pace (ECLAC, 2011c). Adaptive capacity is improving in part thanks to poverty alleviation and development initiatives (McGray *et al.*, 2007).

The region has multiple stressors on natural and human systems derived in part from significant land use changes and exacerbated by climate variability/climate change. Climate variability at various time scales has been affecting social and natural systems, and extremes in particular have affected large regions. During 2000-2010, almost 630 weather and climate extreme events occurred in CA and SA, leaving near to 16,000 fatalities and 46.6 million people affected; and generating economical losses amounting to US$ 208 million (CRED, 2011). Land is facing increasing pressure from competing uses like cattle ranching, food production and bioenergy.

The region is regarded as playing a key role in future world economy because countries like Brazil, Chile, Colombia and Panama, among others, are rapidly developing and becoming economically important in the world scenario. The region is bound to be exposed to the pressure related to increasing land use and industrialization. Therefore, it is expected to have to deal with increasing emission potentials. Thus, science-based decision-making is thought to be an important tool to control innovation and development of the countries in the region.

Two other important contrasting features characterize the region: having the biggest tropical forest of the planet on the one side, and possessing the largest potential for agricultural expansion and development during the next decades on the other. This is the case because the large countries of SA, especially, would have a major role in food and bioenergy production in the future, as long as policies towards adaptation to global climate change (GCC) will be strategically designed. The region is already one of the top producers and user of bioenergy and this experience will serve as an example to other developing regions as well as developed regions.

27.1.2. Summary of the AR4 and SREX Findings

27.1.2.1. AR4 Findings

According to AR4-Chapter 13 (Latin America), during the last decades of the 20th century, unusual extreme weather events have been severely affecting the LA region contributing greatly to the strengthening of the vulnerability of human systems to natural disasters. In addition, increases in precipitation were observed in SESA, northwest Peru and Ecuador; while decreases were registered in southern Chile, southwest Argentina, southern Peru and western CA since 1960. Mean warming was near to 0.1ºC/decade. The rate of SLR has accelerated over the last 20 years reaching 2-3mm/year. The glacier-retreat trend has intensified, reaching critical conditions in the Andean countries. Rates of deforestation have been continuously increasing mainly due to agricultural expansion, and land degradation has been intensified for the entire region.

Mean warming for LA at the end of 21st century could reach 1ºC to 4ºC (SRES B2) or 2ºC to 6ºC (SRES A2) (*medium confidence*) (AR4-Ch13-pp583). Rainfall anomalies (positive or negative) will be larger for the tropical part of LA. The frequency and intensity of weather and climate extremes is *likely* to increase (*medium confidence*).

Future impacts include: “Significant species extinctions, mainly in tropical LA” (*high confidence*). “Replacement of tropical forest by savannas, and semi-arid vegetation by arid vegetation” (*medium confidence*). “Increases in the number of people experiencing water stress” (*medium confidence*). “Probable reductions in rice yields and possible increases of soy yield in SESA (AR4-Ch13-pp583); and increases in crop pests and diseases” (*medium confidence*) (AR4-Ch13-pp607). “Some coastal areas affected by sea level rise, weather and climatic variability and extremes” (*high confidence*) (AR4-Ch13-pp584).

Some countries have made efforts to adapt to climate change and variability, for example through the conservation of key ecosystems (e.g. biological corridors in Mesoamerica, Amazonia, and Atlantic forest; compensation for ecosystem services in Costa Rica,), the use of early warning systems and climate forecast (e.g. fisheries in eastern Pacific, subsistence agriculture in NE Brazil), and the implementation of disease surveillance systems (e.g. Colombia) (AR4-Ch13-pp 591). However, several constraints like the lack of basic information, observation and monitoring systems; the lack of capacity-building and appropriate political, institutional and technological frameworks; low income; and settlements in vulnerable areas, outweigh the effectiveness of these efforts.

27.1.2.2. SREX Findings

As reported *on Chapter 3.4 of* the IPCC *Special* Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC, 2012b), a changing climate leads to changes in the frequency, intensity, spatial extent or duration of weather and climate extremes, and can result in unprecedented extremes. Levels of confidence in historical changes depend on the availability of high quality and homogeneous data, and relevant model projections. This has been a major problem in CA and SA, where a lack of long-term homogeneous and continuous climate and hydrological records, and of complete studies on trends have not allowed for an identification of trends in extremes, particularly in CA. Recent observational studies and projections from global and regional models suggest changes in extremes. With *medium confidence*, increases in warm days and decreases in cold days, as well as increases on warm nights and decreases in cold nights have been identified in CA, Northern SA, NEB, SESA and west coast of SA. In CA, there is *low confidence* that any observed long-term increase in tropical cyclone activity is robust, after accounting for past changes in observing capabilities. In other regions, such as the Amazon region, *insufficient evidence*, inconsistencies among studies and detected trends result in *low confidence* of observed rainfall trends. While it *is likely* that there has been an anthropogenic influence on extreme temperature in the region, there is *low confidence* in attribution of changes in tropical cyclone activity to anthropogenic influences.

Projections for the end of the 21st century for differing emissions scenarios (SRES A2 and A1B) show that for all CA and SA, models project substantial warming in temperature extremes. It is *likely* that increases in the frequency and magnitude of warm daily temperature extremes and decreases in cold extremes will occur in the 21st century on the global scale. With *medium confidence*, it is *very likely* that the length, frequency and/or intensity of heat waves will experience a large increase over most of SA, with weaker tendency towards increasing in SESA. With *low confidence*, the models also project an increase of the proportion of total rainfall from heavy falls for SESA and the West coast of SA; while for Amazonia and the rest of SA and CA there are not consistent signals of change. In some regions, there is *low confidence* in projections of changes in fluvial floods. Confidence is low due to limited evidence and because the causes of regional changes are complex. There *is medium confidence* that droughts will intensify along the 21st century in some seasons and areas due to reduced precipitation and/or increased evapotranspiration in Amazonia and NEB.

The character and severity of the impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability. These are influenced by a wide range of factors, including anthropogenic climate change, natural climate variability, and socioeconomic development.

27.2. Major Recent Changes and Projections in the Region

27.2.1. Climatic Stressors

27.2.1.1. Climate Trends, Long-term Changes in Variability, and Extremes

In CA and SA, decadal variability and changes in extremes have been affecting large sectors of the population, especially those more vulnerable and exposed to climate hazards. Observed changes in some regions have been attributed to natural climate variability, while in other regions they have been attributed to land use change, e.g. increase urbanization, meaning that land use change is a result of anthropogenic drivers. Table 27-1 summarizes observed trends in the region's climate.

[INSERT TABLE 27-1 HERE
Table 27-1: Regional observed changes in temperature, precipitation and climate extremes in various sectors of CA and SA. Additional information on changes in observed extremes can be found in the IPCC SREX (Seneviratne *et al.*, 2012) and Chapter 2 IPCC WGI AR5 [2.4, 2.5, 2.6]]

Since around 1950, in CA and the North American Monsoon System (NAMS), rainfall has been starting increasingly later and has become more irregular in space and time, while rainfall has been increasing and the intensity of rainfall has been increasing during the onset season (see references in Table 27-1). Arias *et al.* (2012) relate those changes to decadal rainfall variations in NAMS.

The West coast of SA experienced a prominent but localized coastal cooling of about 1 C during the past 30-50 years extending from central Peru down to central Chile. This occurs in connection with an increased upwelling of coastal waters favored by the more intense trade winds (Falvey and Garreaud, 2009; Gutiérrez *et al.*, 2011a; Gutiérrez *et al.*, 2011b; Kosaka and Xie, 2013; Narayan *et al.*, 2010; Schulz *et al.*, 2012). In the extremely arid northern coast of Chile, rainfall, temperature and cloudiness show strong interannual and decadal variability, and since the mid-70s, the minimum daily temperature, cloudiness and precipitation have decreased. In central Chile, a negative precipitation trend was observed over the period 1935-1976, and an increase after 1976, while further south, the negative trend in rainfall that prevailed since the 1950s has intensified by the end of the 20th century (Quintana and Aceituno, 2012).

To the east of the Andes, northeast Brazil (NEB) exhibits large interannual rainfall variability, with a slight decrease since the 1970s (Marengo *et al*. 2013a). Droughts in this region (e.g. 1983, 1987, 1998) have been associated with El Niño and/or a warmer Tropical North Atlantic Ocean. However, not all El Nino years result on drought in NEB, as the drought 2012-2013 occurred during La Niña (Marengo *et al.*, 2013a).

In the La Plata Basin in SESA, various studies have documented interannual and decadal scale circulation changes that have led to decreases in the frequency of cold nights in austral summer, as well as to increases in warm nights and minimum temperatures during the last 40 years. Simultaneously, a reduction in the number of dry months in the warm season is found since the mid-1970s, while heavy rain frequency is increasing in SESA (references in Table 27-1). In SESA, increases in precipitation are responsible for changes in soil moisture (Collini *et al.*, 2008; Saulo *et al.*, 2010), and although feedback mechanisms are present at all scales, the effect on atmospheric circulation is detected at large scales. Moreover, land use change studies in the Brazilian southern Amazonia for the last decades showed that the impact on the hydrological response is time lagged at larger scales (Rodriguez *et al.*, 2010)

In the central Andes, in the Mantaro Valley (Peru), precipitation shows a strong negative trend, while warming is also detected (SENAMHI, 2007). In the southern Andes of Peru air temperatures have increased during 1964-2006, but no clear signal on precipitation changes has been detected (Marengo *et al.*, 2009a). In the northern Andes (Colombia, Ecuador), changes in temperature and rainfall in 1961-90 have been identified by Villacís (2008). In the Patagonia region, Masiokas *et al.* (2008) have identified an increase of temperature together with precipitation reductions during 1912-2002. Vuille *et al.* (2008a) found that climate in the tropical Andes has changed significantly over the past 50–60 years. Temperature in the Andes has increased by approximately 0.1 °C/ decade, with only two of the last 20 years being below the 1961–90 average. Precipitation has slightly increased in the second half of the 20th century in the inner tropics and decreased in the outer tropics. The general pattern of moistening in the inner tropics and drying in the subtropical Andes is dynamically consistent with observed changes in the large-scale circulation, suggesting a strengthening of the tropical atmospheric circulation. Moreover, a positive significant trend in mean temperature of 0.09 ^{o}C per decade during 1965-2007 has been detected over the Peruvian Andes by Lavado *et al.* (2012).

For the Amazon basin, Marengo (2004) and Satyamurty *et al.* (2010) concluded that no systematic unidirectional long-term trends towards drier or wetter conditions in both the northern and southern Amazon have been identified since the 1920s. Rainfall fluctuations are more characterized by inter-annual scales linked to ENSO or decadal variability. Analyzing a narrower time period, Espinoza *et al.* (2009a; 2009b) found that mean rainfall in the Amazon basin for 1964–2003 has decreased, with stronger amplitude after 1982, especially in the Peruvian western Amazonia (Lavado *et al.*, 2012), consistent with reductions in convection and cloudiness in the same region (Arias *et al.*, 2011). Recent studies by Donat *et al.* (2013) suggest that heavy rains are increasing in frequency in Amazonia. Regarding seasonal extremes in the Amazon region, two major droughts and three floods have affected the region from 2005 to 2012, although these events have been related to natural climate variability rather than to deforestation (Espinoza *et al.*, 2013; Espinoza *et al.*, 2011; Espinoza *et al.*, 2012; Lewis *et al.*, 2011; Marengo *et al.*, 2008; Marengo *et al.*, 2012; Marengo *et al.*, 2013a; Satyamurty *et al.*, 2013). On the impacts of land use changes on changes in the climate and hydrology of Amazonia, Zhang *et al.* (2009) suggest that biomass-burning aerosols can work against the seasonal monsoon circulation transition, thus re-inforce the dry season rainfall pattern for Southern Amazonia, while Wang *et al.* (2011) suggests the importance of deforestation and vegetation dynamics on decadal variability of rainfall in the region. Costa and Pires (2010) have suggested a possible decrease in precipitation due to soybean expansion in Amazonia, mainly as a consequence of its very high albedo. In the SAMS region, positive trends in rainfall extremes have been identified in the last 30 years with a pattern of increasing frequency and intensity of heavy rainfall events, and earlier onsets and late demise of the rainy season (see Table 27-1).

______START BOX 27-1 HERE______

Box 27-1. Extreme Events, Climate Change Perceptions, and Adaptive Capacity in Central America

Central America has traditionally been characterized as a region with high exposure to geo-climatic hazards derived from its location and topography and with high vulnerability of its human settlements (ECLAC, 2010c). It has also been identified as the most responsive tropical region to climate change (Giorgi, 2006). Evidence for this has been accumulating particularly in the last 30 years with a steady increase in extreme events including storms, floods and droughts. In the period 2000-2009, 39 hurricanes occurred in the Caribbean basin compared to 15 and 9 in the decade of 1980 and 1990 respectively (UNEP-ECLAC, 2010). The impacts of these events on the population and the economy of the region have been tremendous: the economic loss derived from 11 recent hydrometereological events evaluated added to US $13,642 millions and the number of people impacted peaked with hurricane Mitch in 1998 with over 600,000 persons affected (ECLAC, 2010c). A high percentage of the population in CA live on or near highly unstable steep terrain with sandy, volcanic soils prone to mudslides which are the main cause of casualties and destruction (Restrepo and Alvarez, 2006).

The increased climatic variability in the past decade certainly changed the perception of people in the region with respect to climate change. In a survey to small farmers in 2003, Tucker *et al.* (2010) found that only 25% of respondents included climate events as a major concern. A subsequent survey in 2007 (Eakin *et al.*, 2013) found that over 50% of respondents cited drought conditions and torrential rains as their greatest concern. Interestingly, there was no consensus on the direction in climate change pattern: the majority or households in Honduras reported an increase in the frequency of droughts but in Costa Rica and Guatemala a decrease or no trend at all was reported; a similar discrepancy in answers was reported with the issue of increase rainfall. But there was general agreement in all countries that rainfall patterns were more variable resulting in higher difficulty in recognizing the start of the rainy season.

The high levels of risk to disasters in CA are the result of high exposure to hazards and the high vulnerability of the population and its livelihoods derived from elevated levels of poverty and social exclusion (Programa Estado de la Nación-Región, 2011). Disaster management in the region has focused on improving early warning systems and emergency response for specific extreme events (Saldaña-Zorrilla, 2008) but little attention has been paid to strengthening existing social capital in the form of local organizations and cooperatives. These associations can be central in increasing adaptive capacity through increased access to financial instruments and strategic information on global markets and climate (Eakin *et al.*, 2011). There is a need to increase the communication of the knowledge from local communities involved in processes of autonomous adaptation to policy makers responsible for strengthening the adaptive capacities in CA (Castellanos *et al.*, 2013).

______END BOX 27-1 HERE______

27.2.1.2. Climate Projections

Since the AR4, substantial additional regional analysis has been carried out using the CMIP3 model ensemble. In addition, projections from CMIP5 models and new experiences using regional models (downscaling) have allowed for a better description of future changes in climate and extremes in CA and SA. Using CMIP3 and CMIP5 models, Giorgi (2006), Diffenbaugh *et al.* (2008), Xu *et al.* (2009), Diffenbaugh and Giorgi (2012) and Jones and Carvalho (2013) have identified areas of CA/western North America and the Amazon as persistent regional climate change hotspots throughout the 21st century of the RCP8.5 and RCP4.5. Table 27-2 summarizes projected climatic changes derived from global and regional models for the region, indicating the projected change, models, emission scenarios, time spans and references.

[INSERT TABLE 27-2 HERE
Table 27-2: Regional projected changes in temperature, precipitation, and climate extremes in different sectors of CA and SA. Various studies used A2 and B2 scenarios from CMIP3 and various RCPs scenarios for CMIP5, and different time slices from 2010 to 2100. In order to make results comparable, the CMIP3 and CMIP5 at the time slice ending in 2100 are included. Additional information on changes in projected extremes can be found in the IPCC SREX (see IPCC, 2012b), and Chapters 9 and 14 from IPCC WG1AR5 [9.5, 9.6 and 14.2, 14.7]]

In CA and Northern Venezuela, projections from CMIP3 models and from downscaling experiments suggest precipitation reductions and warming together with an increase in evaporation, and reductions in soil moisture for most of the land during all seasons by the end of the 21th century (see references in Table 27-2). However, the spread of projections is high for future precipitation.

Analyses from global and regional models in tropical and subtropical SA show common patterns of projected climate in some sectors of the continent. Projections from CMIP3 regional and high resolution global models show by the end of the 21st century for the A2 emission scenario, a consistent pattern of increase of precipitation in SESA, Northwest of Peru and Ecuador and western Amazonia, while decreases are projected for northern SA, Eastern Amazonia, central eastern Brazil, NEB, the Altiplano and southern Chile (Table 27-2). For some regions, projections show mixed results in rainfall projections for the Amazonia and the SAMS region suggesting high uncertainties on the projections (Table 27-2).

As for extremes, CMIP3 models and downscaling experiments show increases in dry spells are projected for Eastern Amazonia and NEB, while rainfall extremes are projected to increase in SESA, in western Amazonia, Northwest Peru and Ecuador, while over southern Amazonia, northeastern Brazil and eastern Amazonia, the maximum number of consecutive dry days tends to augment, suggesting a longer dry season. Increases in warm nights throughout SA are also projected by the end of the 21st century (see references in Table 27-2). Shiogama *et al.* (2011) suggest that although the CMIP3 ensemble mean assessment suggested wetting across most of SA, the observational constraints indicate a higher probability of drying in the eastern Amazon basin.

The CMIP5 models project an even larger expansion of the monsoon regions in NAMS in future scenarios (Jones and Carvalho, 2013; Kitoh *et al.*, 2013). A comparison from eight models from CMIP3 and CMIP5 identifies some improvements in the new generation models. For example, CMIP5 inter-model variability of temperature in summer was lower over northeastern Argentina, Paraguay and northern Brazil, in the last decades of the 21st century, as compared to CMIP3. Although no major differences were observed in both precipitation datasets, CMIP5 inter-model variability was lower over northern and eastern Brazil in summer by 2100 (Blázquez and Nuñez, 2013; Jones and Carvalho, 2013).

The projections from the CMIP5 models at regional level for CA and SA (using the same regions from the IPCC SREX) are shown in Figure 27-1, and update some of these previous projections based on SRES A2 and B2 emission scenarios from CMIP3. Figure 27-1 shows that in relation to the baseline period 1986-2005, for CA and northern South America-Amazonia, temperatures are projected to increase approximately by 0.6 °C and 2 °C for the RCP2.6 scenario, and by 3.6 C and 5.2 °C for the RCP8.5 scenario. For the rest of South America, increases by about 0.6 °C to 2 °C are projected for the RCP4.5 and by about 2.2 °C to 7 °C for the RCP8.5 scenario. The observed records show increases of temperature from 1900 to 1986 by about 1 °C. For precipitation, while for CA and northern South America-Amazonia precipitation is projected to vary between +10% to -25% (with large spread among models). For NEB, there is a spread among models between +30 to -30% making hard to identify any projected rainfall change. This spread is much lower in the western coast of South America and SESA, where the spread is between +20 and -10% (IPCC WG2 Chapter 21, Box 21-3).

Figure 27-2 shows that by late-21st century, the CMIP5 derived projections for RCP8.5 projected: CA: mean annual warming of 2.5ºC and rainfall reduction of 10%, and reduction in summertime precipitation. SA: mean warming of 4ºC, with rainfall reduction up to 15% in tropical SA east of the Andes, and an increase of about 15-20% in SESA, and in other regions of the continent. Changes in mid-21st century are small. Both Figures 27-1 and 27-2 show that there is some degree of uncertainty on climate change projections for regions, particularly for rainfall in CA and tropical SA.

[INSERT FIGURE 27-1 HERE
Figure 27-1: Observed and simulated variations in past and projected future annual average temperature over the Central and South American regions defined in IPCC (2012a). Black lines show various estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the "RCP2.6" emissions scenario (63), and the "RCP8.5" (63). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.]

[INSERT FIGURE 27-2 HERE
Figure 27-2: Projected changes in annual average temperature and precipitation. CMIP5 multi-model mean projections of annual average temperature changes (left panel) and average percent change in annual mean precipitation (right panel) for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and>90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where>66% of models show change greater than the baseline variability and>66% of models agree on sign of change. Gray indicates areas with divergent changes, where>66% of models show change greater than the baseline variability, but<66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in>66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-3 and CC-RC]]

27.2.2. Non-Climatic Stressors

27.2.2.1. Trends and Projections in Land Use and Land Use Change

Land use change is a key driver of environmental degradation for the region that exacerbates the negative impacts from climate change (Lopez-Rodriguez and Blanco-Libreros, 2008; Sampaio *et al.*, 2007). The high levels of deforestation observed in most of the countries in the region have been widely discussed in the literature as a deliberate development strategy based on the expansion of agriculture to satisfy the growing world demand for food, energy and minerals (Benhin, 2006; Grau and Aide, 2008; Mueller *et al.*, 2008). Land is facing increasing pressure from competing uses, among them cattle ranching, food and bioenergy production. The enhanced competition for land increases the risk of land use changes, which may lead to negative environmental and socio-economic impacts. Agricultural expansion has relied in many cases on government subsidies, which have often resulted in lower land productivity and more land speculation (Bulte *et al.*, 2007; Roebeling and Hendrix, 2010). Some of the most affected areas due to the expansion of the agricultural frontier are fragile ecosystems such as the edges of the Amazon forest in Brazil, Colombia, Ecuador and Peru, and the tropical Andes including the Paramo, where activities such as deforestation, agriculture, cattle ranching and gold mining are causing severe environmental degradation (ECLAC, 2010d), and the reduction of environmental services provided by these ecosystems.

Deforestation rates for the region remain high in spite of a reducing trend in the last decade (Fearnside, 2008; Ramankutty *et al.*, 2007). Brazil is by far the country with the highest area of forest loss in the world according to the latest FAO statistics (2010): 21,940 km^2 per year equivalent to 39% of the world deforestation for the period 2005-2010. Bolivia, Venezuela and Argentina follow in deforested area (Figure 27-3) with 5.5%, 5.2% and 4.3% of the total world deforestation respectively. The countries of CA and SA lost a total of 38,300 km^2 of forest per year in that period (69% of the total world deforestation) (FAO, 2010). These numbers are limited by the fact that many countries do not have comparable information through time, particularly for recent years. Aide *et al.* (2013) completed a wall-to-wall analysis for the region for the period 2001-2010 analyzing not only deforestation but also reforestation and reported very different results than FAO (2010) for some countries where reforestation seems to be higher than deforestation, particularly in Honduras, El Salvador, Panama, Colombia and Venezuela. For Colombia and Venezuela, these results are contradictory with country analyses that align better with the FAO data (Armenteras *et al.*, 2013; Rodríguez *et al.*, 2010).

[INSERT FIGURE 27-3 HERE
Figure 27-3: Area deforested per year for selected countries in CA and SA (2005-2010). Notice three countries listed with a positive change in forest cover (based on data from FAO, 2010).]

Deforestation in the Amazon forest has received much international attention in the last decades, both because of its high rates, and its rich biodiversity. Brazilian Legal Amazon is now one of the best-monitored ecosystems in terms of deforestation since 1988 (INPE, 2011). Deforestation for this region peaked in 2004 and has steadily declined since then to a lowest value of 4,656 Km^2/yr for the year 2012 (see Figure 27-4). Such reduction results from a series of integrated policies to control illegal deforestation particularly enforcing protected areas, which now shelter 54% of the remaining forests of the Brazilian Amazon (Soares-Filho *et al.*, 2010). Deforestation in Brazil is now highest in the Cerrado (drier ecosystem south of Amazon) with an average value of 14,179 Km^2/yr for the period 2002-2008 (FAO, 2009).

[INSERT FIGURE 27-4 HERE
Figure 27-4: Deforestation rates in the Brazilian Amazonia (km^2/year) based on measurements by the PRODES project (INPE, 2011).]

The area of forest loss in CA is considerably less than in SA, owing to smaller country sizes (Carr *et al.*, 2009), but when relative deforestation rates are considered, Honduras and Nicaragua show the highest values for CA and SA (FAO, 2010). At the same time, CA includes some countries where forest cover shows a small recovery trend in the last years: Costa Rica, El Salvador, Panama and possibly Honduras where data is conflicting in the literature (Aide *et al.*, 2013; FAO, 2010). This forest transition is the result of: (1) economies less dependent on agriculture, and more on industry and services (Wright and Samaniego, 2008); (2) processes of international migration with the associated remittances (Hecht and Saatchi, 2007), and (3) a stronger emphasis on the recognition of environmental services of forest ecosystems (Kaimowitz, 2008). The same positive trend is observed in some SA countries (Figure 27-3). However, a substantial amount of forest is gained through (single-crop) plantations, most noticeably in Chile (Aguayo *et al.*, 2009), which has a much lower ecological value than the depleted natural forests (Echeverría *et al.*, 2006; Izquierdo *et al.*, 2008).

Land degradation, is also an important process compromising extensive areas of CA and SA very rapidly. According to data from the Global Land Degradation Assessment and Improvement (GLADA) project of the Global Environmental Facility (GEF), additional degraded areas reached 16.4% of the entire territory of Paraguay, 15.3% of Peru and 14.2% of Ecuador for the period 1982-2002. In CA, Guatemala shows the highest proportion of degraded land, currently at 58.9% of the country’s territory, followed by Honduras (38.4%) and Costa Rica (29.5%); only El Salvador shows a reversal of the land degradation process, probably due to eased land exploitation following intensive international migratory processes (ECLAC, 2010d).

Deforestation and land degradation are mainly attributed to increased extensive and intensive agriculture. Two activities have traditionally dominated the agricultural expansion: soy production (only in SA) and beef; but more recently, biomass for biofuel production has become as important (Nepstad and Stickler, 2008) with some regions also affected by oil and mining extractions. Deforestation by small farmers, mainly coming from families who migrate in search for land is relatively low: extensive cattle production is the predominant land use in deforested areas of tropical and subtropical Latin America (Wassenaar *et al.*, 2007). Cattle is the only land use variable correlated with deforestation in Colombia (Armenteras *et al.*, 2013) and in the Brazilian Amazon the peak of deforestation in 2004 (Figure 27-4) was primarily the result of increased cattle ranching (Nepstad *et al.*, 2006). Mechanized farming, agro-industrial production and cattle ranching are the major land use change drivers in eastern Bolivia but subsistence agriculture by indigenous colonists is also important (Killeen *et al.*, 2008).

In recent years, soybean croplands have expanded continuously in SA, becoming increasingly more important in the agricultural production of the region. Soybean-planted area in Amazonian states (mainly Mato Grosso) in Brazil expanded 12.1% per year during the 1990s, and 16.8% per year from 2000 to 2005 (Costa *et al.*, 2007). This landscape-scale conversion from forest to soy and other large-scale agriculture can alter substantially the water balance for large areas of the region resulting in important feedbacks to the local climate (Hayhoe *et al.*, 2011; Loarie *et al.*, 2011) (see section 27.3.4.1).

Soybean and beef production have also impacted other ecosystems next to the Amazon, such as the Cerrado (Brazil) and the Chaco dry forests (Bolivia, Paraguay, Argentina and Brazil). Gasparri *et al.* (2008) estimated carbon emissions from deforestation in Northern Argentina, and concluded that deforestation in the Chaco forest has accelerated in the past decade from agricultural expansion and is now the most important source of carbon emission for that region. In northwest Argentina (Tucumán and Salta provinces) 14,000 km^2 of dry forest were cleared from 1972 to 2007 as a result of technological improvements and increasing rainfall (Gasparri and Grau, 2009). Deforestation continued during the 1980s and 1990s resulting in cropland area covering up to 63% of the region by 2005 (Viglizzo *et al.*, 2011). In central Argentina (northern Córdoba province), cultivated lands have increased from 3% to 30% (between 1969 and 1999); and the forest cover has decreased from 52.5% to 8.2%. This change has also been attributed to the synergistic effect of climatic, socioeconomic, and technological factors (Zak *et al.*, 2008). Losses in the Atlantic forest are estimated in 29% of the original area in 1960, and in 28% of the Yunga forest area, mainly due to cattle ranching migration from the Pampas and Espinal (Viglizzo *et al.*, 2011).

Oil palm is a significant biofuel crop also linked to recent deforestation in tropical CA and SA. Its magnitude is still small compared with deforestation related to soybean and cattle ranching, but it is considerable for specific countries and expected to increase due to increasing demands for biofuels (Fitzherbert *et al.*, 2008). The main producers of palm oil in the region are Colombia and Ecuador, followed by Costa Rica, Honduras, Guatemala and Brazil; this country has the largest potential for expansion, as nearly half of the Amazonia is suitable for oil palm cultivation (Butler and Laurance, 2009). Oil palm production is also growing in the Amazonian region of Peru, where 72% of new plantations have expanded into forested areas representing 1.3% of the total deforestation for that country for the years 2000-2010 (Gutiérrez-Vélez *et al.*, 2011).

However, forests are not the only important ecosystems threatened in the region. An assessment of threatened ecosystems in SA by Jarvis *et al.* (2010) concluded that grasslands, savannas and shrublands are more threatened than forests, mainly from excessively frequent fires (>1/year) and grazing pressure. An estimation of burned land in Latin America by Chuvieco *et al.* (2008) also concluded that herbaceous areas presented the highest occurrence of fires. In the Río de la Plata region (Central-East Argentina, southern Brazil, and Uruguay), grasslands decreased from 67.4% to 61.4% between 1985 and 2004. This reduction was associated with an increase in annual crops, mainly soybean, sunflower, wheat, and maize (Baldi and Paruelo, 2008).

Even with technological changes that might result in agricultural intensification, the expansion of pastures and croplands is expected to continue in the coming years (Kaimowitz and Angelsen, 2008; Wassenaar *et al.*, 2007), particularly from an increasing global demand for food and biofuels (Gregg and Smith, 2010) with the consequent increase in commodity prices. This agricultural expansion will be mainly in Latin America and Sub-Saharan Africa as these regions hold two-thirds of the global land with potential to expand cultivation (Nepstad and Stickler, 2008). It is important to consider the policy and legal needs to keep this process of large-scale change under control as much as possible; Takasaki (2007) showed that policies to eliminate land price distortions and promote technological transfers to poor colonists could reduce deforestation. It is also important to consider the role of indigenous groups; there is a growing acknowledgment that recognizing the land ownership and authority of indigenous groups can help central governments to better manage many of the natural areas remaining in the region (Larson, 2010; Oltremari and Jackson, 2006). The impact of indigenous groups on land use change can vary: Oliveira *et al.* (2007) found that only 9% of the deforestation in the Peruvian Amazon between 1999 and 2005 happened in indigenous territories but Killeen *et al.* (2008) found that Andean indigenous colonists in Bolivia were responsible for the largest land cover changes in the period 2001-2004. Indigenous groups are important stakeholders in many territories in the region and their well-being should be considered when designing responses to pressures on the land by a globalized economy (Gray *et al.*, 2008; Killeen *et al.*, 2008).

27.2.2.2. Trends and Projections in Socioeconomic Conditions

Development in the region has traditionally displayed four characteristics: low growth rates, high volatility, structural heterogeneity and a very unequal income distribution (Bárcena, 2010; ECLAC, 2008). This combination of factors has generated high and persistent poverty levels (45% for CA and 30% for SA for year 2010), with the rate of poverty being generally higher in rural than urban areas (ECLAC, 2009b). SA has based its economic growth in natural resource exploitation (mining, energy, agricultural), which involves direct and intensive use of land and water, and in energy-intensive and, in many cases, highly polluting natural-resource-based manufactures. In turn, CA has exploited its proximity to the North American market and its relatively low labor costs (ECLAC, 2010e). The region shows a marked structural heterogeneity, where modern production structures coexist with large segments of the population with low productivity and income levels (ECLAC, 2010g). The GDP per capita in SA is twice that of CA; in addition, in the latter poverty is 50% higher (see Figure 27-5).

[INSERT FIGURE 27-5 HERE
Figure 27-5: Evolution of GDP per capita and poverty (income below US$ 2 per day) from 1990-2010: CA and SA (US-Dollars per inhabitant at 2005 prices and percentages) (ECLAC on the basis of CEPALSTAT (2012) and ECLAC (2011c)).]

The 2008 financial crisis reached CA and SA through exports and credits, remittances and worsening expectations by consumers and producers (Bárcena, 2010; Kacef and López-Monti, 2010). This resulted in the sudden stop of six consecutive years of robust growth and improving social indicators (ECLAC, 2010e), which contributed to higher poverty in 2009 after six years where poverty had declined by 11%. Poverty rates fell from 44% to 33% of the total population from 2003 to 2008 (Figure 27-5), leaving 150 million people in this situation while extreme poverty diminished from 19.4% to 12.9% (which represents slightly more than 70 million people) (ECLAC, 2009b).

In the second half of 2009 industrial production and exports began to recover and yielded a stronger economic performance (GDP growth of 6.4% in SA and 3.9% in CA in 2010) (ECLAC, 2012). SA benefited the most because of the larger size of their domestic markets and the greater diversification of export markets. Conversely, slower growth was observed in CA with more open economies and a less diversified portfolio of trading partners and a greater emphasis on manufacturing trade (ECLAC, 2010g).

The region is expected to continue to grow in the short term, albeit at a pace that is closer to potential GDP growth, helped by internal demand as the middle class becomes stronger and as credit becomes more available. In SA, this could be boosted by external demand from the Asian economies as they continue to grow at a rapid pace. The macroeconomic challenge is to act counter cyclically creating conditions for productive development that is not based solely on commodity exports (ECLAC, 2010f).

In spite of its economic growth, CA and SA still display high and persistent inequality: most countries have Gini coefficients between 0.5 and 0.6, whereas the equivalent figures in a group of 24 developed countries vary between under 0.25 and around 0.4. The average per capita income of richest 10% of households is approximately 17 times that of the poorest 40% of households (ECLAC, 2010g). Nevertheless, during the first decade of the century, prior to the financial crisis, the region has shown a slight but clear trend towards a more equitable distribution of income and a stronger middle class population resulting in a higher demand for goods (ECLAC, 2010g; ECLAC, 2011b; UN, 2010). Latin American countries also reported gains in terms of human development, although these gains have slowed down slightly over recent years. In comparative terms, the performance of countries as measured by the Human Development Index (HDI) varied greatly in 2007 (from Chile with 0.878 and Argentina with 0.866 to Guatemala with 0.704 and Nicaragua with 0.699) although those with lower levels of HDI showed notably higher improvements than countries with the highest HDI (UNDP, 2010).

Associated with inequality are disparities in access to water, sanitation and adequate housing for the most vulnerable groups - for example indigenous peoples, Afro-descendants, children and women living in poverty- and in their exposure to the effects of climate change. The strong heterogeneity of subnational territorial entities in the region takes the form of high spatial concentration and persistent disparities in the territorial distribution of wealth (ECLAC, 2010g; ECLAC, 2011b; UN, 2010).

The region faces significant challenges in terms of environmental sustainability and adaptability to a changing climate (UN, 2010), resulting from the specific characteristics of its population and economy already discussed and aggravated with a significant deficit in infrastructure development. The countries in CA and SA have made progress in incorporating environmental protection into decision-making processes, and particularly in terms of environmental institutions and legislation, but there are still difficulties to effectively incorporate environmental issues into relevant public policies (UN, 2010). While climate change imposes new challenges, it also provides an opportunity to shift development and economic growth patterns towards a more environmentally friendly course.

27.3. Impacts, Vulnerabilities, and Adaptation Practices

27.3.1. Freshwater Resources

CA and SA are regions with a high average but unevenly distributed water resources availability (Magrin *et al.*, 2007a). The main user of water is agriculture followed by the region's 580 million inhabitants (including the Caribbean), of which 86% had access to water supply by 2006 (ECLAC, 2010b). According to the International Energy Agency (IEA), the region meets 60% of its electricity demand through hydropower generation, which contrast with the 20% average contribution of other regions (see Table 27-6 and case study 27.6.1).

27.3.1.1. Observed and Projected Impacts and Vulnerabilities

In CA and SA there are many evidences of changing hydrologic related conditions. The most robust trend for major rivers is found in the sub-basins of the La Plata River basin (*high confidence* based on *high agreement, robust evidence*). This basin, second only to the Amazon in size, shows a positive trend in streamflow in the second half of the 20th century at different sites (Amsler and Drago, 2009; Conway and Mahé, 2009; Dai *et al.*, 2009; Dai, 2011; Doyle and Barros, 2011; Krepper *et al.*, 2008; Krepper and Zucarelli, 2010a; Pasquini and Depetris, 2007; Saurral *et al.*, 2008). An increase in precipitation and a reduction in evapotranspiration from land use changes have been associated with the trend in streamflows (Doyle and Barros, 2011; Saurral *et al.*, 2008), with the former being more important in the southern sub-basins and the latter in the northern ones (Doyle and Barros, 2011) (see section 27.2.1). Increasing trends in streamflows have also been found in the Patos Lagoon in southern Brazil (Marques, 2012) and Laguna Mar Chiquita (a closed lake), and in the Santa Fe Province, both in Argentina, with ecological and erosive consequences (Bucher and Curto, 2012; Pasquini *et al.*, 2006; Rodrigues Capítulo *et al.*, 2010; Troin *et al.*, 2010; Venencio and García, 2011).

There is no clear long-term trend for the Amazon River. Espinoza *et al.* (2009a; 2011) showed that the 1974-2004 apparent stability in mean discharge at the main stem of the Amazon in Obidos is explained by opposing regional features of Andean rivers (e.g. increasing trends during the high-water period in Peruvian and Colombian Amazons and decreasing trend during the low-water period in Peruvian and Bolivian Amazons (Lavado *et al.*, 2012). In recent years extremely low levels were experienced during the droughts of 2005 and 2010, while record high levels were detected during the 2009 and 2012 floods (see section 27.2.1). Major Colombian rivers draining to the Caribbean Sea (Magdalena and Cauca) exhibit decreasing trends along their main channels (Carmona and Poveda, 2011), while significant trends are absent for all other major large rivers in the Brazilian North East, and northern SA (Dai *et al.*, 2009). Dai (2011) showed a drying trend in CA rivers.

A rapid retreat and melting of the tropical Andes glaciers of Venezuela, Colombia, Ecuador, Peru and Bolivia has been further reported following the IPCC AR4, through use of diverse techniques (*high confidence* based on *high agreement* and *robust evidence*). Rabatel *et al*. (2013) provides a synthesis of these studies (specific papers are presented in Table 27-3a). Tropical glaciers' retreat has accelerated in the second half of the 20th century (area loss between 20-50%), especially since the late 1970s in association with increasing temperature in the same period (Bradley *et al.*, 2009). In early stages of glacier retreat associated streamflow tends to increase due to an acceleration of glacier melt, but after a peak in streamflow as the glacierized water reservoir gradually empties, runoff tends to decrease, as evidenced in the Cordillera Blanca of Peru (Baraer *et al.*, 2012; Chevallier *et al.*, 2011), where seven out of nine river basins have probably crossed a critical threshold, exhibiting a decreasing dry-season discharge

(Baraer *et al.*, 2012). Likewise, glaciers and icefields in the extra tropical Andes located in Central-South Chile and Argentina face significant reductions (see review in Masiokas *et al.* (2009) and details in Table 27-3b), with their effect being compounded by changes in snowpack extent, thus magnifying changes in hydrograph seasonality by reducing flows in dry seasons and increasing them in wet seasons (Pizarro *et al.*, 2013; Vicuña *et al.*, 2013). Central-South Chile and Argentina also face significant reductions in precipitation as shown in section 27.2.1, contributing to runoff reductions in the last decades of the 20th century (Rubio-Álvarez and McPhee, 2010; Seoane and López, 2007; Urrutia *et al.*, 2011; Vicuña *et al.*, 2013), corroborated with long-term trends found through dendrochronology (Lara *et al.*, 2007; Urrutia *et al.*, 2011). Trends in precipitation and runoff are less evident in the Central-North region in Chile (Fiebig-Wittmaack *et al.*, 2012; Souvignet *et al.*, 2012).

[INSERT TABLE 27-3 HERE
Table 27-3: Observed trends related to Andean cryosphere: a) Andean tropical glacier trends, and b) extra tropical Andean cryosphere (glaciers, snowpack, runoff effects) trends.]

As presented in Table 27-4, the assessment of future climate scenarios implications in hydrologic related conditions shows a large range of uncertainty across the spectrum of climate models (mostly using CMIP3 simulations with the exception of Demaria *et al.* (2013) and scenarios considered. Nohara *et al.* (2006) studied climate change impacts on 24 of the main rivers in the world considering a large number of GCMs, and found no robust change for the Paraná (La Plata Basin) and Amazon Rivers. Nevertheless, in both cases the average change showed a positive value consistent at least with observations for the La Plata Basin. In a more recent work Nakaegawa *et al.* (2013a) showed statistically significant increase for both basins in a study that replicated that of Nohara *et al.* (2006) but with different hydrologic model. Focusing in extreme flows Guimberteau *et al.* (2013) show that by the middle of the century no change is found in high flow on the main stem of the Amazon River but there is a systematic reduction in low-flow streamflow. In contrast the northwestern part of the Amazon River shows a consistent increase in high flow and inundated area (Guimberteau *et al.*, 2013; Langerwisch *et al.*, 2013). On top of such climatic uncertainty, future streamflows and water availability projections are confounded by the potential effects of land use changes (Coe *et al.*, 2009; Georgescu *et al.*, 2013; Moore *et al.*, 2007).

[INSERT TABLE 27-4 HERE
Table 27-4: Synthesis of projected climate change impacts on hydrologic related variables in CA and SA basins and major glaciers.]

The CA region shows a consistent future runoff reduction. Maurer *et al.* (2009)studied climate change projections for the Lempa River basin, one of the largest basins in CA, covering portions of Guatemala, Honduras and El Salvador. They showed that future climate projections (increase in evaporation and reduction in precipitation) imply a reduction of 20% in inflows to major reservoirs in this system (see Table 27-4). Imbach *et al.* (2012) found similar results using a modeling approach that also considered potential changes in vegetation. These effects could have large hydropower generation implications as discussed in the case study (see section 27.6.1).

The evolution of tropical Andes glaciers associated future climate scenarios has been studied using trend (e.g. Poveda and Pineda (2009), regression (e.g. Juen *et al.* (2007) and Chevallier *et al.* (2011) and explicit modeling (e.g. Condom *et al.*, 2012) analysis. These studies indicate that glaciers will continue their retreat (Vuille *et al.*, 2008a) and even disappear as glacier Equilibrium Line Altitudes rises, with larger hydrological effects during the dry season (Gascoin *et al.*, 2011; Kaser *et al.*, 2010). This is expected to happen during the next 20-50 years (Chevallier *et al.*, 2011; Juen *et al.*, 2007) (see Table 27-4). After that period water availability during the dry months is expected to diminish. A projection by Baraer *et al.* (2012) for the Santa River in the Peruvian Andes finds that once the glaciers are completely melt, annual discharge would decrease by 2%–30%, depending on the watershed. Glacier retreat can exacerbate current water resources related vulnerability (Bradley *et al.*, 2006; Casassa *et al.*, 2007; Mulligan *et al.*, 2010; Vuille *et al.*, 2008b), diminishing the mountains' water regulation capacity, making it more expensive and less reliable the supply of water for diverse purposes, as well as for ecosystems integrity (Buytaert *et al.*, 2011). Impacts on economic activities associated with conceptual scenarios of glacier melt reduction have been monetized (Vergara *et al.*, 2007), representing about US$100 million in the case of water supply for Quito, and between US$212 million to US$ 1.5 billion in the case of the Peruvian electricity sector due to losses of hydropower generation (see case study 27.6.1). Andean communities will face an important increase in their vulnerability, as documented by Mark *et al.* (2010), Pérez *et al.* (2010) and Buytaert and De Bièvre (2012).

In Central Chile, Vicuña *et al.* (2011) project changes in the seasonality of streamflows of the upper snowmelt-driven watersheds of the Limarí River, associated with temperature increases and reductions in water availability owing to a reduction (increase) in precipitation (evapotranspiration). Similar conclusions are derived across the Andes on the Limay River in Argentina by Seoane and López (2007). Under these conditions, semiarid highly populated basins (e.g. Santiago, Chile) and with extensive agriculture irrigation and hydropower demands are expected to increase their current vulnerability (ECLAC, 2009a; Fiebig-Wittmaack *et al.*, 2012; Souvignet *et al.*, 2010; Vicuña *et al.*, 2012) (*high confidence*) (see Table 27-4). Projected changes in the cryosphere conditions of the Andes could affect the occurrence of extreme events, such as extreme low and high flows (Demaria *et al.*, 2013). Glacial-lake outburst floods occurring in the icefields of Patagonia (Dussaillant *et al.*, 2010; Marín *et al.*, 2013), volcanic collapse and debris flow associated with accelerated glacial melting in the tropical Andes (Carey, 2005; Carey *et al.*, 2012b; Fraser, 2012), and with volcanoes in southern Chile and Argentina (Tormey, 2010), as well as scenarios of water quality pollution by exposure to contaminants owing to glaciers retreat (Fortner *et al.*, 2011).

Another semiarid region that has been studied thoroughly is the NEBian (Hastenrath, 2012). De Mello *et al.* (2008), Gondim *et al.* (2008), Souza *et al.* (2010) and Montenegro and Ragab (2010) have shown that future climate change scenarios would decrease water availability for agriculture irrigation owing to reductions in precipitation and increases in evapotranspiration (*medium confidence*). Krol and Bronstert (2007) and Krol *et al.* (2006) presented an integrated modeling study that linked projected impacts on water availability for agriculture with economic impacts that could potentially drive full-scale migrations in the Brazilian northeast region.

27.3.1.2. Adaptation Practices

At an institutional level, a series of policies have been developed to reduce vulnerability to climate variability as faced today in different regions and settings. In 1997, Brazil instituted the National Water Resources Policy and created the National Water Resources Management System under the shared responsibility between the States and the Federal government. Key to this new regulation has been the promotion of decentralization and social participation through the creation of National Council of Water Resources and their counterparts in the states, the States Water Resources Councils. The challenges and opportunities dealing with water resources management in Brazil in the face of climate variability and climate change have been well studied (Abers, 2007; Engle *et al.*, 2011; Kumler and Lemos, 2008; Lorz *et al.*, 2012; Medema *et al.*, 2008). Other countries in the region are following similar approaches. In the last years, there have been constitutional and legal reforms towards more efficient and effective water resources management and coordination among relevant actors in Honduras, Nicaragua, Ecuador, Peru, Uruguay, Bolivia and Mexico; although in many cases, these innovations have not been completely implemented (Hantke –Domas, 2011). Institutional and governance improvements are required to assure an effective implementation of these adaptation measures (e.g. Halsnæs and Verhagen, 2007; Engle and Lemos, 2010; Lemos *et al.*, 2010; Zagonari, 2010; Pittock, 2011; and Kirchhoff *et al.* 2013).

With regards to region specific freshwater resources issues it is important to consider adaptation to reduce vulnerabilities in the communities along the tropical Andes and the semi-arid basins in Chile-Argentina, North East Brazil, and the northern CA basins. Different issues have been addressed in the assessment of adaptation strategies for tropical Andean communities such as the role of governance and institutions (Lynch, 2012; Young and Lipton, 2006), technology (Carey *et al.*, 2012a), and the dynamics of multiple stressors (Bury *et al.*, 2013; McDowell and Hess, 2012). Semiarid regions are characterized by pronounced climatic variability and often by water scarcity and related social stress (Krol and Bronstert, 2007; Scott *et al.*, 2012; 2013). Adaptation tools to face the threats of climate change for the most vulnerable communities in the Chilean semi-arid region are discussed by Young *et al.* (2010) and Debels *et al.* (2009). In CA, Benegas *et al.* (2009), Manuel-Navarrete *et al.* (2007) and Aguilar *et al.* (2009) provide different frameworks to understand vulnerability and adaptation strategies to climate change and variability in urban and rural contexts, although no specific adaptation strategies are suggested. The particular experience in NEB provides other examples of adaptation strategies to manage actual climate variability. Broad *et al.* (2007) and Sankarasubramanian *et al.* (2009) studied the potential benefits of streamflow forecast as a way to reduce the impacts of climate change and climate variability on water distribution under stress conditions. An historical review and analysis of drought management in this region are provided by Campos and Carvalho (2008). Souza Filho and Brown (2009) studied different water distribution policy scenarios finding that the best option depended on the degree of water scarcity. The study by Nelson and Finan (2009) provides a critical perspective of drought-related policies, arguing that they constitute an example of maladaptation as they do not try to solve the causes of vulnerability and instead undermine resilience. Tompkins *et al.* (2008) are also critical of risk reduction practices in this region because they have fallen short of addressing the fundamental causes of vulnerability needed for efficient longer-term drought management. Other types of adaptation options that stem from studies on arid and semiarid regions are related to: a) increase in water supply from groundwater pumping (Burte *et al.*, 2011; Döll, 2009; Kundzewicz and Döll, 2009; Nadal *et al.*, 2013; Zagonari, 2010); fog interception practices (Holder, 2006; Klemm *et al.*, 2012), and reservoirs and irrigation infrastructure (Fry *et al.*, 2010; Vicuña *et al.*, 2010; 2012); b) improvements in water demand management associated with increased irrigation efficiency and practices (Bell *et al.*, 2011; Geerts *et al.*, 2010; Jara-Rojas *et al.*, 2012; Montenegro and Ragab, 2010; Van Oel *et al.*, 2010), and changes towards less water intensive crops (Montenegro and Ragab, 2010).

Finally flood management practices also provide a suite of options to deal with actual and future vulnerabilities related to hydrologic extremes, such as the management of ENSO-related events in Peru via participatory (Warner and Oré, 2006) or risk reduction approaches (Khalil *et al.*, 2007), the role of land use management (Bathurst *et al.*, 2010; 2011; Coe *et al.*, 2011), and flood hazard assessment (Mosquera-Machado and Ahmad, 2006) (*medium confidence*).

27.3.2. Terrestrial and Inland Water Systems

27.3.2.1. Observed and Projected Impacts and Vulnerabilities

CA and SA house the largest biological diversity and several of the world's megadiverse countries (Guevara and Laborde, 2008; Mittermeier *et al.*, 1997). However, land use change has led to the existence of six biodiversity hotspots, i.e. places with a great species diversity that show high habitat loss and also high levels of species endemism: Mesoamerica, Chocó-Darien-Western Ecuador, Tropical Andes, Central Chile, Brazilian Atlantic forest, and Brazilian Cerrado (Mittermeier *et al.*, 2005). Thus, conversion of natural ecosystems is the main proximate cause of biodiversity and ecosystem loss in the region (Ayoo, 2008). Tropical deforestation is the second largest driver of anthropogenic climate change on the planet, adding up to 17%-20% of total greenhouse gas emissions during the 1990s (Gullison *et al.*, 2007; Strassburg *et al.*, 2010). In parallel, the region has still large extensions of wilderness areas for which the Amazon is the most outstanding example. Nevertheless, some of these areas are precisely the new frontier of economic expansion. For instance, between 1996 and 2005 Brazil deforested about 19,500 km^2 per year, which represented 2% to 5% of global annual CO_2 emissions (Nepstad *et al.*, 2009). Between 2005 and 2009, deforestation in the Brazilian Amazon dropped by 36%, which is partly related to the network of protected areas that now covers around 45.6% of the biome in Brazil (Soares-Filho *et al.*, 2010). Using LandSHIFT modeling framework for land use change and the IMPACT projections of crop/livestock production, Lapola *et al.* (2011) projected that zero deforestation in the Brazilian Amazon forest by 2020 (and of the Cerrado by 2025) would require either a reduction of 26%–40% in livestock production until 2050 or a doubling of average livestock density from 0.74 to 1.46 head per hectare. Thus, climate change may imply reduction of yields and entail further deforestation.

Local deforestation rates or rising greenhouse gases globally drive changes in the regional SA that during this century might lead the Amazon rainforest into crossing a critical threshold at which a relatively small perturbation can qualitatively alter the state or development of a system (Cox *et al.*, 2000; Lenton *et al.*, 2008; Nobre and Borma, 2009; Salazar *et al.*, 2007; Sampaio *et al.*, 2007). Various models are projecting a risk of reduced rainfall and higher temperatures and water stress, that may lead to an abrupt and irreversible replacement of Amazon forests by savanna-like vegetation, under a high emission scenario (A2), from 2050-2060 to 2100 (Betts *et al.*, 2004; 2008; Cox *et al.*, 2004; Malhi *et al.*, 2008; Malhi *et al.*, 2009; Marengo *et al.*, 2011c; Nobre and Borma, 2009; Salazar *et al.*, 2007; Sampaio *et al.*, 2007; Sitch *et al.*, 2008). The possible 'savannization' or 'die-back' of the Amazon region would potentially have large-scale impacts on climate, biodiversity and people in the region. The possibility of this die-back scenario occurring, however, is still an open issue and the uncertainties are still very high (Rammig *et al.*, 2010; Shiogama *et al.*, 2011).

Plant species are rapidly declining in CA, SA, Central and West Africa, and Southeast Asia (Bradshaw *et al.*, 2009). Risk estimates of plant species extinction in the Amazon, which do not take into account possible climate change impacts, range from 5%-9% by 2050 with a habitat reduction of 12%-24% (Feeley and Silman, 2009) to 33% by 2030 (Hubbell *et al.*, 2008). The highest percentage of rapidly declining amphibian species occurs in CA and SA. Brazil is among the countries with most threatened bird and mammal species (Bradshaw *et al.*, 2009).

A similar scenario is found in inland water systems. Among the components of aquatic biodiversity, fish are the best-known organisms (Abell *et al.*, 2008) with Brazil accounting for the richest icthyofauna of the planet (Nogueira *et al.*, 2010). For instance, the 540 Brazilian small microbasins host 819 fish species with restrict distribution. However, 29% of these microbasins have historically lost more than 70% of their natural vegetation cover and only 26% show a significant overlap with protected areas or indigenous reserves. Moreover, 40% of the microbasins overlap with hydrodams (see 27.6.1 and Chapter 3) or have few protected areas and high rates of habitat loss (Nogueira *et al.*, 2010).

The faster and more severe the rate of climate change, the more severe the biological consequences such as species decline (Brook *et al.*, 2008). Vertebrate fauna in North and South America is projected to suffer species losses until 2100 of at least 10%, as forecasted in over 80% of the climate projections based on low emissions scenario (Lawler *et al.*, 2009). Vertebrate species turnover until 2100 will be as high as 90% in specific areas of CA and the Andes Mountains for emission scenarios varying from low B1 to mid-high A2 (Lawler *et al.*, 2009). Elevational specialists, i.e. a small proportion of species with small geographic ranges restricted to high mountains, are most frequent in the Americas (e.g. Andes and Sierra Madre) and might be particularly vulnerable to global warming because of their small geographic ranges and high energetic and area requirements, particularly birds and mammals (Laurance *et al.*, 2011). In Brazil, projections for Atlantic forest birds (Anciães and Peterson, 2006), endemic bird species (Marini *et al.*, 2009), and plant species (by 2055, scenarios HHGSDX50 and HHGGAX50; Siqueira and Peterson, 2003) of the Cerrado indicate that distribution will dislocate towards the South and Southeast, precisely where fragmentation and habitat loss are worse. Global climate change is also predicted to increase negative impacts worldwide, including SA, on freshwater fisheries due to alterations in physiology and life histories of fish (Ficke *et al.*, 2007).

In addition to climate change impacts at individual species level, biotic interactions will be affected. Modifications in phenology, structure of ecological networks, predator-preys interactions and non-trophic interactions among organisms have been forecasted (Brooker *et al.*, 2008; Walther, 2010). The outcome of non-trophic interactions among plants is expected to shift along with variation in climatic parameters, with more facilitative interactions in more stressful environments, and more competitive interactions in more benign environments (Anthelme *et al.*, 2012; Brooker *et al.*, 2008). These effects are expected to have a strong influence of community and ecosystem (re-) organization given the key engineering role played by plants on the functioning of ecosystems (Callaway, 2007). High Andean ecosystems, especially those within the tropics, are expected to face exceptionally strong warming effects during the 21th century because of their uncommonly high altitude (Bradley *et al.*, 2006). At the same time they provide a series of crucial ecosystem services for millions people (Buytaert *et al.*, 2011). For these reasons shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in this region.

Although in the region biodiversity conservation is largely confined to protected areas, with the magnitude of climatic changes projected for the century, it is expected that many species and vegetational types will lose representativeness inside such protected areas (Heller and Zavaleta, 2009).

27.3.2.2. Adaptation Practices

The sub-set of practices that are multi-sectoral, multi-scale, and based on the premise that ecosystem services reduce the vulnerability of society to climate change are known as Ecosystem-based Adaptation (EbA) (Vignola *et al.*, 2009; see also Glossary and CC-EA). Schemes such as the payment for environmental services (PES) and community management fit the concept of EbA that begins to spread in CA and SA (Vignola *et al.*, 2009). The principle behind these schemes is the valuation of ecosystem services that should reflect both the economic and cultural benefits derived from the human-ecosystem interaction and the capacity of ecosystems to secure the flow of these benefits in the future (Abson and Termansen, 2011).

Since PES schemes have developed more commonly in CA and SA than in other parts of the world (Balvanera *et al.*, 2012), this topic will be covered as a case study (see 27.6.2).

Ecological restoration, conservation in protected areas, and community management can all be important tools for adaptation. A meta-analysis of 89 studies by Benayas *et al.* (2009) (with timescale of restoration varying from <5 to 300 years), including many in SA, showed that ecological restoration enhances the provision of biodiversity and environmental services by 44% and 25%, respectively, as compared to degraded systems (Benayas *et al.*, 2009). Moreover, ecological restoration increases the potential for carbon sequestration and promotes community organization, economic activities and livelihoods in rural areas (Chazdon, 2008), as seen in examples of the Brazilian Atlantic Forest (Calmon *et al.*, 2011; Rodrigues *et al.*, 2011). In that sense, Locatelli *et al.* (2011) revised several ecosystem conservation and restoration initiatives in CA and SA that simultaneously help mitigate and adapt to climate change. Chazdon *et al.* (2009) also highlight the potential of restoration efforts to build ecological corridors (see Harvey *et al.*, 2008, for example in Central America).

The effective management of natural protected areas and the creation of new protected areas within national protected area systems and community management of natural areas are also efficient tools to adapt to climate change and to reconcile biodiversity conservation with socio-economic development (e.g., Bolivian Andes - Hoffmann *et al*., 2011; Panama – Oestreicher *et al*. 2009). Porter-Bolland *et al.* (2012) compared protected areas with areas under community management in different parts of the tropical world, including CA and SA, and found that protected areas have higher deforestation rates than areas with community management. Similarly, Nelson and Chomitz (2011) found for the region that (i) protected areas of restricted use reduced fire substantially, but multi-use protected areas are even more effective; and that (ii) in indigenous reserves the incidence of forest fire was reduced by 16% as compared to non-protected areas. This contrasts with the findings of Miteva *et al*. (2012) that found protected areas more efficient in constraining deforestation than other schemes. Other good examples of adaptive community management in the continent include community forest concessions (e.g., Guatemala; Radachowsky *et al.*, 2012), multiple-use management of forests (Guariguata *et al.*, 2012 ; see also examples in Brazil – Klimas *et al.*, 2012, Soriano *et al.*, 2012, and Bolívia – Cronkleton *et al.*, 2012); and local communities where research and monitoring protocols are in place to pay the communities for collecting primary scientific data (Luzar *et al.*, 2011).

27.3.3. Coastal Systems and Low-Lying Areas

27.3.3.1. Observed and Projected Impacts and Vulnerabilities

Climate change is altering coastal and marine ecosystems (Hoegh-Guldberg and Bruno, 2010). Coral reefs (Chapter 5, Cross-Chapter Box CC-CR), seagrass beds, mangroves, rocky reefs and shelves, and seamounts have few to no areas left in the world that remain unaffected by human influence (Halpern *et al.*, 2008). Anthropogenic drivers associated with climate change decreased ocean productivity, altered food web dynamics, reduced abundance of habitat-forming species, shifting species distributions, and greater incidence of disease (Hoegh-Guldberg and Bruno, 2010). Coastal and marine impacts and vulnerability are often associated with collateral effects of climate change such as sea-level rise, ocean warming and ocean acidification (Cross-Chapter Box CC-OA). Overfishing, habitat pollution and destruction, and the invasion of species also negatively impact biodiversity and the delivery of ecosystem services (Guarderas *et al.*, 2008; Halpern *et al.*, 2008). Such negative impacts lead to losses that pose significant challenges and costs for societies, particularly in developing countries (Hoegh-Guldberg and Bruno, 2010). For instance, the Ocean Health Index (Halpern *et al.*, 2012) that measures how healthy the coupling of the human-ocean system is for every coastal country (including parameters related to climate change), indicates that CA countries rank amongst the lowest values. For SA, Suriname stands out with one of the highest scores.

Coastal states of Latin America and the Caribbean have a human population of more than 610 million, 3/4 of who live within 200 km of the coast (Guarderas *et al.*, 2008). For instance, studying seven countries in the region (El Salvador, Nicaragua, Costa Rica, Panama, Colombia, Venezuela, Ecuador), Lacambra and Zahedi (2011) found that more than 30% of the population lives in coastal areas directly exposed to climatic events. Large coastal populations are related to the significant transformation marine ecosystems have been undergoing in the region. Fish stocks, places for recreation and tourism, and controls of pests and pathogens are all under pressure (Guarderas *et al.*, 2008; Mora, 2008). Moreover, SLR varied from 2 to 7 mm/yr between 1950 and 2008 in CA and SA. The Western equatorial border, influenced by the ENSO phenomenon, shows a lower variation (of about 1 mm yr^{-1}) and a range of variation under El Niño events of the same order of magnitude that the sustained past changes (Losada *et al.*, 2013). The distribution of population is a crucial factor for inundation impact, with coastal areas being non-homogeneously impacted. A scenario of 1m SLR would affect some coastal populations in Brazil and the Caribbean islands (see Figure 27-6). (ECLAC, 2011a)

[INSERT FIGURE 27-6 HERE
Figure 27-6: Current and predicted coastal impacts and coastal dynamics in response to climate change.]

Coastal impacts - based on trends observed and projections, the figure shows how potential impacts may be distributed in the region. Three cases: a) flooding: since flooding probability increases with increasing sea-level, one may expect a higher probability of flooding in locations showing >40% of change over the last 60 years in the 100-years total sea-level (excluding hurricanes). The figure also identifies urban areas where the highest increase in flooding level has been obtained.; b) beach erosion: it increases with potential sediment transport, thus locations where changes in potential sediment transport have increased over a certain threshold have a higher probability to be eroded; c) sea-ports and reliability of coastal structures: the figure shows locations where, in the case of having a protection structure in place, there is a reduction in the reliability of the structures due to the increase in the design wave height estimates (ECLAC, 2011a).
Coastal dynamics - information based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information and satellite information. Advanced statistical techniques have been used for obtaining trends including uncertainties (Izaguirre *et al.*, 2013; Losada *et al.*, 2013).]

The greatest flooding levels (hurricanes not considered) in the region are found in Rio de La Plata area, which combine a 5 mm yr^{-1} change in storm surge with SLR changes in extreme flooding levels (ECLAC, 2011a; Losada *et al.*, 2013). Extreme flooding events may become more frequent since return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected, while at the same time beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast. (ECLAC, 2011a)

The majority of literature concerning climate change impacts for coastal and marine ecosystems considers coral reefs (see also Chapter 5, Cross-Chapter Box CC-CR), mangroves and fisheries. Coral reefs are particularly sensitive to climate-induced changes in the physical environment (Baker *et al.*, 2008) to an extent that 1/3 of the more than 700 species of reef-building corals worldwide are already threatened with extinction (Carpenter *et al.*, 2008). Coral bleaching and mortality are often associated with ocean warming and acidification (Baker *et al.*, 2008). If extreme sea surface temperatures are to continue, the projections of scenarios SRES (A1FI, 3ºC sensitivity, and A1B with 2ºC and 4.5ºC sensitivity) indicate that it is possible that the Mesoamerican coral reef will collapse by mid-century (between 2050 and 2070), causing major economic losses (WB, 2009). Extreme high sea surface temperatures have been increasingly documented in the western Caribbean near the coast of CA and have resulted in frequent bleaching events (1993, 1998, 2005, and again in 2010) of the Mesoamerican coral reef, located along the coasts of Belize, Honduras and Guatemala (Eakin *et al.*, 2010). Reef but also mangrove ecosystems are estimated to contribute greatly to goods and services in economic terms. In Belize, for example, this amount is approximately US$395-US$559 million annually, primarily through marine-based tourism, fisheries and coastal protection (Cooper *et al.*, 2008). In the Eastern Tropical Pacific, seascape trace abundance of cement and elevated nutrients in upwelled waters are factors that help explain high bioerosion rates of local coral reefs (Manzello *et al.*, 2008). In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years Francini-Filho *et al.* (2008). This estimate is based on coral disease prevalence and progression rate, along with growth rate of *Mussismilia braziliensis* - a major reef-building coral species that is endemic in Brazil. These authors also pointed out that coral diseases intensified between 2005 and 2007 based on qualitative observations since the

1980s and regular monitoring since 2001. They have also predicted that - the studied coral species will be nearly extinct in less than a century if the current rate of mortality due to disease is not reversed.

Mangroves are largely affected by anthropogenic activities whether or not they are climate driven. All mangrove forests, along with important ecosystem goods and services, could be lost in the next 100 years if the present rate of loss continues (1-2% a year) (Duke *et al.*, 2007). Moreover, estimates are that climate change may lead to a maximum global loss of 10–15% of mangrove forest by 2100 (Alongi, 2008). In CA and SA, some of the main drivers of loss are deforestation and land conversion, agriculture and shrimp ponds (Polidoro *et al.*, 2010). The Atlantic and Pacific coasts of CA are some of the most endangered in the planet with regards to mangroves, since approximately 40% of the present mangroves' species are threatened with extinction (Polidoro *et al.*, 2010). Approximately 75% of the mangrove extension of the planet is concentrated in 15 countries, among which Brazil is included (Giri *et al.*, 2011). The rate of survival of original mangroves lies between 12.8% and 47.6% in the Tumaco Bay (Colombia), resulting in ecosystem collapse, fisheries reduction and impacts on livelihoods (Lampis, 2010). Gratiot *et al.* (2008) project for the current decade an increase of mean high water levels of 6 cm followed by 90m shoreline retreat implying flooding of thousands of hectares of mangrove forest along the coast of French Guiana.

Peru and Colombia are two of the eight most vulnerable countries to climate change impacts on fisheries, due to the combined effect of observed and projected warming, to species and productivity shifts in upwelling systems, to the relative importance of fisheries to national economies and diets, and limited societal capacity to adapt to potential impacts and opportunities (Allison *et al.*, 2009). Fisheries production systems are already pressured by overfishing, habitat loss, pollution, invasive species, water abstraction and damming (Allison *et al.*, 2009). In Brazil, a decadal rate of 0.16 trophic level decline (as measured by the Marine Trophic Index, which refers to the mean trophic level of the catch) has been detected through most of the northeastern coast, between 1978 and 2000, which is one of the highest rates documented in the world (Freire and Pauly, 2010).

Despite the focus in the literature on corals, mangroves and fisheries, there is evidence that other benthic marine invertebrates that provide key services to reef systems, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change (Przeslawski *et al.*, 2008). The same applies for seagrasses for which a worldwide decline has accelerated from a median of 0.9% yr^{-1} before 1940 to 7% yr^{-1} since 1990, which is comparable to rates reported for mangroves, coral reefs, tropical rainforests and place seagrass meadows among the most threatened ecosystems on earth (Waycott *et al.*, 2009).

A major challenge of particular relevance at local and global scales will be to understand how these physical changes will impact the biological environment of the ocean (e.g., Gutiérrez *et al.*, 2011b), as the Humboldt Current system -flowing along the west coast of SA- is the most productive upwelling system of the world in terms of fish productivity.

27.3.3.2. Adaptation Practices

Designing marine protected areas (MPAs) that are resilient to climate change is a key adaptation strategy in coastal and marine environments (McLeod *et al.*, 2009). By 2007, Latin America and the Caribbean (which includes CA and SA countries) had over 700 MPAs established covering around 1.5% of the coastal and shelf waters, most of which allow varying levels of extractive activities (Guarderas *et al.*, 2008). This protected area cover, however, is insufficient to preserve important habitats or connectivity among populations at large biogeographic scales (Guarderas *et al.*, 2008).

Nevertheless, examples of adaptation in CA and SA are predominantly related to MPAs. In Brazil, a protected area type known as "Marine Extractive Reserves" currently benefits 60,000 small-scale fishermen along the coast (Moura *et al.*, 2009). Examples of fisheries' co-management, a form of a participatory process involving local fishermen communities, government, academia and NGOs, are reported to favor a balance between conservation of marine fisheries, coral reefs and mangroves on the one hand (Francini-Filho and Moura, 2008), and the improvement of livelihoods, as well as the cultural survival of traditional populations on the other (Hastings, 2011; Moura *et al.*, 2009).

Significant financial and human resources are expended annually in the marine reserves to support reef management efforts. These actions, including the creation of marine reserves to protect from overfishing, improvement of watershed management, and protection or replanting of coastal mangroves, are proven tools to improve ecosystem functioning. In Mesoamerican reefs, (Carilli *et al.*, 2009) found out that such actions may also actually increase the thermal tolerance of corals to bleaching stress and thus the associated likelihood of surviving future warming.

In relation to mangroves, in addition to marine protected areas that include mangroves and functionally linked ecosystems, Gilman *et al.* (2008) list a number of other relevant adaptation practices: coastal planning to facilitate mangrove migration with sea-level rise, management of activities within the catchment that affect long-term trends in the mangrove sediment elevation, better management of non-climate stressors, and the rehabilitation of degraded areas. However, such types of practices are not frequent in the region.

On the other hand, the implementation of adaptation strategies to sea level rise or to address coastal erosion is more commonly seen in many countries in the region (Lacambra and Zahedi, 2011). For instance, redirecting new settlements to better-protected locations and to promote investments in appropriate infrastructure shall be required in the low elevation coastal zones (LECZ) of the region, particularly in lower income countries with limited resources, which are especially vulnerable. The same applies to countries with high shares of land (e.g., Brazil ranking 7th worldwide of the total land area in the LECZ) and/or population (e.g., Guyana and Suriname rank 2nd and 5th by the share of population in the LECZ, having respectively 76% and 55% of their populations in such areas (McGranahan *et al.*, 2007). Adaptation will demand effective and enforceable regulations and economic incentives, all of which require political will as well as financial and human capital (McGranahan *et al.*, 2007). Adaptive practices addressing river flooding are also being made available as in the study of Casco *et al.* (2011) for the low Parana river, in Argentina; (see also Chapters 5 and 6 for coastal and marine adaptation).

27.3.4. Food Production Systems and Food Security

27.3.4.1. Observed and Projected Impacts and Vulnerabilities

Increases in the global demand for food and biofuels promoted a sharp increase in agricultural production in SA and CA mainly associated with the expansion of planted areas (see Chapter 7), and this trend is predicted to continue in the future (see 27.2.2.1). Ecosystems are being and will be affected in isolation and synergistically by climate variability/change and land use changes, which are comparable drivers of environmental change (see 27.2.2.1; 27.3.2.1). By the end of 21th century (13 GCMs, under SRES A1B and B1) SA could lose between 1% and 21% of its arable land due to CC and population growth (Zhang and Cai, 2011).

Optimal land management could combine efficient agricultural and biofuels production with ecosystem preservation under CC, however current practices are leading to a deterioration of ecosystems throughout the continent (see section 27.3.2). In southern Brazilian Amazonia water yields (mean daily discharge (mm.day^{-1})) were near four times higher in soy than forested watersheds, and showed greater seasonal variability (Hayhoe *et al.*, 2011). In the Argentinean Pampas current land use changes disrupt water and biogeochemical cycles and may result in soil salinization, altered C and N storage, surface runoff and stream acidification (Berthrong *et al.*, 2009; Farley *et al.*, 2009; Nosetto *et al.*, 2008). In central Argentina flood extension was associated with the dynamics of groundwater level that has been influenced by precipitation and land use change (Viglizzo *et al.*, 2009).

Observed impacts: The SESA region has shown significant increases in precipitation and wetter soil conditions during the 20th century (Giorgi, 2002) (see Table 27-1) that benefited summer crops and pastures productivity, and contributed to the expansion of agricultural areas (Barros, 2010; Hoyos *et al.*, 2012). Wetter conditions observed during 1970-2000 (in relation to 1930-1960) led to increases in maize and soybean yields (9% to 58%) in Argentina, Uruguay and Southern Brazil (Magrin *et al.*, 2007b). Even if rainfall projections estimate increases of about 25% in SESA for 2100, agricultural systems could be threatened if climate reverts to a drier situation due to interdecadal variability. This could put at risk the viability of continuous agriculture in marginal regions of the Argentina's Pampas (Podestá *et al.*, 2009). During the 30's and 40's, dry and windy conditions together with deforestation, overgrazing, overcropping, and non-suitable tillage produced severe dust storms, cattle mortality, crop failure, and rural migration (Viglizzo and Frank, 2006).

At the global scale (see Chapter 7), warming since 1981 has reduced wheat, maize and barley productivity, although the impacts were small compared with the technological yield gains over the same period (Lobell and Field, 2007). In central Argentina, simulated potential wheat yield –without considering technological improvements- has been decreasing at increasing rates since 1930 (1930-2000: -28 kg/ha/year; 1970-2000: -53 kg/ha/year) in response to increases in minimum temperature during October-November (1930-2000: +0.4°C/decade; 1970-2000: +0.6°C/decade) (Magrin *et al.*, 2009). The observed changes in the growing season temperature and precipitation between 1980 and 2008 have slowed the positive yield trends due to improved genetics in Brazilian wheat, maize and soy, as well as Paraguayan soy. In contrast, rice in Brazil and soybean in Argentina have benefited from precipitation and temperature trends (2011). In Argentina, increases in soybean yield may be associated with weather types that favour the entry of cold air from the south reducing thermal stress during flowering and pod set, and weather types that increase the probability of dry days at harvest (Bettolli *et al.*, 2009).

Projected impacts: The assessment of future climate scenarios implications in food production and food security (see Table 27-5) shows a large range of uncertainty across the spectrum of climate models and scenarios. One of the uncertainties is related to the effect of CO_2 on plant physiology. Many crops (such as soybean, common bean, maize and sugarcane) can probably respond with an increasing productivity as a result of higher growth rates and better water use efficiency. However, food quality could decrease due to higher sugar contents in grain and fruits, and decreases in the protein content in cereals and legumes (DaMatta *et al.*, 2010). Uncertainties associated with climate and crop models, as well as with the uncertainty in human behavior, potentially lead to large error bars on any long-term prediction of food output. However, the trends presented here represent the current available information.

In SESA, some crops could be benefited until mid-21st-century if CO_2 effects are considered (see Table 27-5), although interannual and decadal climate variability could provoke important damages. In Uruguay and Argentina productivity could increase or remain almost stable until the 2030s-2050s depending on the SRES scenario (ECLAC, 2010c). Warmer and wetter conditions may benefit crops towards the southern and western zone of the Pampas (ECLAC, 2010c; Magrin *et al.*, 2007c). In South Brazil, irrigated rice yield (Walter *et al.*, 2010) and bean productivity (Costa *et al.*, 2009) is expected to increase. If technological improvement is considered, the productivity of common bean and maize could increase between 40% and 90% (Costa *et al.*, 2009). Sugarcane production could benefit as warming could allow the expansion of planted areas towards the south, where low temperatures are a limiting factor (Pinto *et al.*, 2008). Increases in crop productivity could reach 6% in São Paulo state towards 2040 (Marin *et al.*, 2009). In Paraguay the yields of soybean, maize and wheat could have slight variations (-1.4% to +3.5%) until 2020 (ECLAC, 2010a).

In Chile and western Argentina, yields could be reduced by water limitation. In central Chile (30ºS to 42ºS) temperature increases, reduction in chilling hours and water shortages may reduce productivity of winter crops, fruits, vines and radiata pine. Conversely, rising temperatures, more moderate frosts and more abundant water will *very likely* benefit all species towards the South (ECLAC, 2010a; Meza and Silva, 2009). In northern Patagonia (Argentina) fruit and vegetable growing could be negatively affected because of a reduction in rainfall and in average flows in the Neuquén River basin. In the north of the Mendoza basin (Argentina) increases in water demand, due to population growth, may compromise the availability of subterranean water for irrigation, pushing up irrigation costs and forcing many producers out of farming towards 2030. Also, water quality could be reduced by the worsening of existing salinization processes (ECLAC, 2010a).

In CA, NEB and parts of the Andean region (Table 27-5) CC could affect crop yields, local economies and food security. It is *very likely* that growing season temperatures in parts of tropical SA, east of the Andes and CA exceed the extreme seasonal temperatures documented from 1900 to 2006 at the end of this century (23 GCMs), affecting regional agricultural productivity and human welfare (Battisti and Naylor, 2009). For NEB, declining crop yields in subsistence crops such as beans, corn and cassava are projected (Lobell *et al.*, 2008; Margulis *et al.*, 2010). In addition, increases in temperature could reduce the areas currently favorable to cowpea bean (Silva *et al.*, 2010). The highest warming foreseen for 2100 (5.8 °C, under SRES A2 scenario) could make the coffee crop unfeasible in Minas Gerais and São Paulo (SE Brazil) if no adaptation action is accomplished. Thus, the coffee crop may have to be transferred to southern regions where temperatures are lower and the frost risk will be reduced (Camargo, 2010). With +3ºC, Arabica coffee is expected to expand in the extreme south of Brazil, the Uruguayan border and North of Argentina (Zullo *et al.*, 2011). Brazilian potato production could be restricted to a few months in currently warm areas, which today allow potato production all around the year (Lopes *et al.*, 2011). Large losses of suitable environments for the "Pequi" tree (*Caryocar brasiliense*; an economically important Cerrado fruit tree) are projected by 2050, mainly affecting the poorest communities in Central Brazil (Nabout *et al.*, 2011). In the Amazon region soybean yields would be reduced by 44% in the worst scenario (HadCM3 and no CO_2 fertilization) by 2050 (Lapola *et al.* (2011). By 2050, according to 17GCMs under SRES A2 scenario, 80% of crops will be impacted in more than 60% of current areas of cultivation in Colombia, with severe impacts in perennial and exportable crops (Ramirez-Villegas *et al.*, 2012).

Teixeira *et al.* (2013) identified hot spots for heat stress towards 2071-2100 under the A1B scenario and suggest that rice in South East Brazil, maize in CA and SA, and soybean in Central Brazil will be the crops and zones most affected by increases in temperature.

In CA, changes projected in climate could severely affect the poorest population and specially their food security increasing the current rate of chronic malnutrition. Currently, Guatemala is the most food insecure country by percentage of the population (30.4%) and the problem has been increasing in recent years (FAO, 2012). The impact of climate variability and change is a great challenge in the region. As an example, the recent rust problem on the coffee sector of 2012/2013 has affected near to 600.000 ha (55% of the total area) (ICO, 2013) and will reduce employment by 30% to 40% for the harvest 2013/2014 (FEWS NET, 2013). At least 1.4 million people in Guatemala, El Salvador, Honduras and Nicaragua depend on the coffee sector, which is very susceptible to climate variations. In Panamá, the large interannual climate variability will continue to be the dominant influence on seasonal maize yield into the coming decades (Ruane *et al.*, 2013). In the future, warming conditions combined with more variable rainfall are expected to reduce maize, bean and rice productivity (ECLAC, 2010c); rice and wheat yields could decrease up to 10% by 2030 (Lobell *et al.,* 2008 (*medium confidence*) (see Table 26-7). In CA, near to 90% of agricultural production destined to internal consumption is composed by maize (70%), bean (25%) and rice (6%) (ECLAC, 2011d).

[INSERT TABLE 27-5 HERE
Table 27-5: Impacts on agriculture.]

CC may also alter the current scenario of plant diseases and their management, having effects on productivity (Ghini *et al.*, 2011). In Argentina, years with severe infection of late cycle diseases in soybean could increase; severe outbreaks of the Mal de Rio Cuarto virus in maize (natural vectors: D*elphacodes kuscheli* and *Delphacodes hayward*) could be more frequent; and wheat head fusariosis will increase slightly in the south of the Pampas region by the end of the century (ECLAC, 2010a). In Brazil favorable areas for soybean and coffee rusts will move toward the south, particularly for the hottest scenario of 2080 (Alves *et al.*, 2011). Potato late blight (*Phytophtora infestans*) severity is expected to increase in Perú (Giraldo *et al.*, 2010).

The choice of livestock species could change in the future. For example, by 2060, under a hot and dry scenario, beef and dairy cattle, pigs and chickens production choice could decrease between 0.9 and 3.2%, while sheep election could increase by 7% mainly in the Andean countries (Seo *et al.*, 2010). Future climate could strongly affect milk production and feed intake in dairy cattle in Brazil, where substantial modifications in areas suitable for livestock, mainly in the Pernambuco region, are expected (Silva *et al.*, 2009). Warming and drying conditions in Nicaragua could reduce milk production, mainly among farmers that are already seriously affected under average dry season conditions (Lentes *et al.*, 2010).

CC impact on regional welfare will depend not only on changes in yield, but also in international trade. According to Hertel *et al.* (2010), by 2030, global cereal price could change between increases of 32% (low-productivity scenario) or decreases of 16% (optimistic yield scenario). A rise in prices could benefit net exporting countries like Brazil, where gains from terms of trade shifts could outweigh the losses due to CC. Despite experiencing significant negative yield shocks, some countries tend to gain from higher commodity prices. However, most poor household are food purchasers and rising commodity prices tend to have a negative effect on poverty (von Braun, 2007). According to Chapter 7, increases in prices during 2007-2009 led to rising poverty in Nicaragua.

27.3.4.2. Adaptation Practices

Genetic advances and suitable soil and technological management may induce an increase in some crops' yield despite unfavorable future climate conditions. In Argentina, genetic techniques, specific scientific knowledge and land-use planning are viewed as promising sources of adaptation (Urcola *et al.*, 2010). Adjustments in sowing dates and fertilization rates could reduce negative impacts or increase yields in maize and wheat crops in Argentina and Chile (Magrin *et al.*, 2009; Meza and Silva, 2009; Travasso *et al.*, 2009b). Furthermore, in central Chile and southern Pampas in Argentina warmer climates could allow performing two crops per season increasing productivity per unit land (Meza *et al.*, 2008; Monzon *et al.*, 2007). In Brazil, adaptation strategies for coffee crops include: planting at high densities, vegetated soil, accurate irrigation and breeding programs, and shading management system (arborization) (Camargo, 2010). Shading is also used in Costa Rica and Colombia. In South Brazil, a good option for irrigated rice could be to plant early cultivars (Walter *et al.*, 2010).

Water management is other option for a needed better preparedness regarding water scarcity (see section 27.3.1). In Chile, the adoption of water conservation practices depends on social capital, farm size and land use; and the adoption of technologies that require investment depend on the accesses to credit and irrigation water subsidies (Jara-Rojas *et al.*, 2012). Deficit irrigation could be an effective measure for water savings in dry areas such as the Bolivian Altiplano (quinoa), central Brazil (tomatoes) and northern Argentina (cotton) (Geerts and Raes, 2009). In rainfed crops adaptive strategies might need to look at the harvest, storage, temporal transfer and efficient use of rainfall water. In addition, some agronomic practices like: fallowing, crop sequences, groundwater management, no-till operations, cover crops and fertilization could improve the adaptation to water scarcity (Quiroga and Gaggioli, 2011).

One approach to adapting to future CC is by assisting people to cope with current climate variability (Baethgen, 2010), for which the use of climatic forecasts in agricultural planning presents a measure. Increased access and improvement of climate forecast information enhances the ability of the farmers in the Brazilian Amazon to cope with El Niño impacts (Moran *et al.*, 2006). The Southern Oscillation Index for maize, and the South Atlantic Sea Surface Temperature for soybean and sunflower were the best indicators of annual crop yield variability in Argentina (Travasso *et al.*, 2009a). Another possibility to cope with extreme events consists in transferring weather-related risks by using different types of rural insurance (Baethgen, 2010). Index insurance is one mechanism that has been recently introduced to overcome obstacles to traditional agricultural and disaster insurance markets (see chapter 15). For the support of such parametric agricultural insurance, a Central American climate database was recently established (SICA, 2013).

Local and indigenous knowledge have the potential to bring solutions even in the face of rapidly changing climatic conditions (Altieri and Koohafkan, 2008; Folke *et al.*, 2002); although, migration, climate change, and market integration are reducing indigenous capacity for dealing with weather and climate risk (Pérez *et al.*, 2010; Valdivia *et al.*, 2010). Crop diversification is used in the Peruvian Andes to suppress pest outbreaks and dampen pathogen transmission (Lin, 2011). In Honduras, Nicaragua and Guatemala traditional practices have proven more resilient to erosion and runoff and have helped retain more topsoil and moisture (Holt-Gimenez, 2002). In El Salvador, if local sustainability efforts continue the future climate vulnerability index could only slightly increase by 2015 (Aguilar *et al.*, 2009). Studies with indigenous farmers in highland Bolivia and Peru indicate that constraints on access to key resources must be addressed for reducing vulnerability over time (McDowell and Hess, 2012; Sietz *et al.*, 2012). In Guatemala and Honduras adaptive response between coffees farmers is mainly related to land availability, while participation in organized groups and access to information contribute to adaptive decision-making (Tucker *et al.*, 2010). Otherwise, adaptation may include an orientation towards non-farming activities to sustain their livelihoods and be able to meet their food requirements (Sietz, 2011). In NEB increasing vulnerability related to degradation of natural resources (due to over use of soil and water) encouraged farmers toward off-farm activities, however they could not improve their well-being (Sietz *et al.*, 2006; Sietz *et al.*, 2011). Migration is other strategy in ecosystems and regions at high risk of climate hazards (see Section 27.3.1.1). During 1970-2000 LAC has had the great rate of net migration per population in the dryland zones (Sherbinin *et al.*, 2012). In CA near to 25% of the surveyed households reported some type of migration during the coffee crisis (Tucker *et al.*, 2010). Some migrations, e.g. Guatemala 1960s-1990s; El Salvador 1950s-1980s; NEB 1960s-present, have provoked conflict in receiving areas (Reuveny, 2007).

Shifting in agricultural zoning has been an autonomous adaptation observed in SA. In Argentina e.g., increases in precipitation promoted the expansion of the agricultural frontier to the West and North of the traditional agricultural area, resulting in environmental damage that could be aggravated in the future (Barros, 2008; República Argentina, 2007). Adjustment of production practices, like farmers in the semi-arid zones of mountain regions of Bolivia have begun as they noticed strong changes in the climate since the 1980s, including upward migration of crops, selection of more resistant varieties and water capturing, presents a further adaptation measure (PNCC, 2007).

Organic systems could enhance adaptive capacity due to the application of traditional skills and farmers' knowledge, soil fertility-building techniques and a high degree of diversity (ITC, 2007). As mentioned previously, crop diversity, local knowledge, soil conservation, and economic diversity are all documented strategies for managing risk in CA and SA. A controversial, but important issue in relation to adaptation is the use of genetically modified plants to produce food, with biotech crops being a strategy to cope with the needed food productivity increase considering global population trend (see Chapter 7). Brazil and Argentina are the 2nd and 3rd fastest growing biotech crop producers in the world after the US (Marshall, 2012). However, this option is problematic for the small farms (Mercer *et al.*, 2012), which are least favorable towards GMO (??) (Soleri *et al.*, 2008). According to Eakin and Wehbe (2009) some practices could be an adaptive option for specific farm enterprises, but may have maladaptive implications at regional scales, and over time, become maladaptive for individual enterprises.

27.3.5. Human Settlements, Industry, and Infrastructure

According to the World Bank database (WB, 2012) CA and SA are the geographic regions with the second highest urban population (79%), behind North America (82%) and well above the world average (50%). Therefore this section focuses on assessing the literature on climate change impacts and vulnerability of *urban* human settlements. The information provided should be complemented with other sections of the chapter (see 27.2.2.2; 27.3.1; 27.3.3; and 27.3.7)

27.3.5.1. Observed and Projected Impacts and Vulnerabilities

Urban human settlements suffer from many of the vulnerabilities and impacts already presented in several sections of this chapter. The provision of critical resources and services as already discussed in the chapter –water, health and energy– and of adequate infrastructure and housing remain determinants of urban vulnerability that are enhanced by climate change (Roberts, 2009; Romero-Lankao *et al.*, 2013b; Romero-Lankao *et al.*, 2012b; Smolka and Larangeira, 2008; Winchester, 2008).

Water resource management for example (see section 27.3.1), is a major concern for many cities that need to provide both drinking water and sanitation (Henríquez Ruiz, 2009). More than 20% of the population in the region are concentrated in the largest city in each country (WB, 2012), hence water availability for human consumption in the region's megacities (e.g. São Paulo, Santiago, Lima, Buenos Aires) is of great concern. In this context, reduction in glacier and snowmelt related runoff in the Andes poses important adaptation challenges for many cities, e.g. the metropolitan areas of Lima, La Paz/El Alto and Santiago de Chile (Bradley *et al.*, 2006; Hegglin and Huggel, 2008; Melo *et al.*, 2010). Flooding is also a preoccupation in several cities. In São Paulo for example, according to Marengo *et al.* (2009b; 2013b) the number of days with rainfall above 50 mm were almost zero during the 1950s and now they occur between 2 to 5 times per year (2000-2010). The increase in precipitation is one of the expected risks affecting the city of São Paulo as presented in Box 27-2. Increases in flood events during 1980-2000 have been observed also in the Buenos Aires province and Metropolitan Area (Andrade and Scarpati, 2007; Barros *et al.*, 2008; Hegglin and Huggel, 2008; Nabel *et al.*, 2008). There are also the combined effects of climate change impacts, human settlements' features and other stresses, such as more intense pollution events (Moreno, 2006; Nobre *et al.*, 2011; Nobre, 2011; Romero-Lankao *et al.*, 2013b) and more intense hydrological cycles from urban heat-island effects. In terms of these combined effects, peri-urban areas and irregular settlements pose particular challenges to urban governance and risk management given their scale, lack of infrastructure and socio-economic fragility (Romero-Lankao *et al.*, 2012).

______START BOX 27-2 HERE______

Box 27-2. Vulnerability of South American Megacities to Climate Change: The Case of the Metropolitan Region of São Paulo (MRSP)

Research in the Metropolitan Region of São Paulo (MRSP), between 2009 and 2011, represents a comprehensive and interdisciplinary project on the impacts of climate variability and change, and vulnerability of Brazilian megacities. Studies derived from this project (Marengo *et al.*, 2013b; Nobre *et al.*, 2011) identify the impacts of climate extremes on the occurrence of natural disasters and human health. These impacts are linked to a projected increase of 38% in the extension of the urban area of the MRSP by 2030, accompanied by a projected increase in rainfall extremes. These may induce an intensification of urban flash floods and landslides, affecting large populated areas already vulnerable to climate extremes and variability. The urbanization process in the MRSP has been affecting the local climate, and the intensification of the heat island effect to a certain degree may be responsible for the 2°C warming detected in the city during the last 50 years (Nobre *et al.*, 2011). This warming has been further accompanied by an increase in heavy precipitation as well as more frequent warm nights (Marengo *et al.*, 2013b; Silva Dias *et al.*, 2012). By 2100, climate projections based on data from 1933-2010 show an expected warming between 2-3°C in the MRSP, together with a possible doubling of the number of days with heavy precipitation in comparison to the present (Marengo *et al.*, 2013b; Silva Dias *et al.*, 2012).

With the projected changes in climate and in the extension of the MRSP (Marengo *et al.*, 2013b) more than 20% of the total area of the city could be potentially affected by natural disasters. More frequent floods may increase the risk of leptospirosis, which, together with increasing air pollution and worsening environmental conditions that trigger the risk of respiratory diseases, would leave the population of the MRSP more vulnerable. Potential adaptation measures include a set of strategies that need to be developed by the MRSP and its institutions to face these environmental changes. These include improved building controls to avoid construction in risk areas, investment in public transportation, protection of the urban basins and the creation of forest corridors in the collecting basins and slope regions. The lessons learned suggest that the knowledge on the observed and projected environmental changes, as well as on the vulnerability of populations living in risk areas is of great importance for defining adaptation policies that in turn constitute a first step towards building resilient cities that in turn improve urban quality of life in Brazil.

______END BOX 27-2 HERE______

Changes in prevailing urban climates have led to changing patterns of disease vectors, and water-borne disease issues linked to water availability and subsequent quality (see section 27.3.7). The influence of climate change on particulate matter and other local contaminants is another concern (Moreno, 2006; Romero-Lankao *et al.*, 2013b). It is important to highlight the relationship between water and health, given the problems of water stress and intense precipitation events affecting many urban centers. Both relate to changing disease risks, as well as wider problems of event-related mortalities and morbidity, and infrastructure and property damage. These risks are compounded for low-income groups in settlements with little or no service provision, e.g. waste collection, piped drinking water, sanitation, (ECLAC, 2008). Existing cases of flooding, air pollution and heat waves reveal that not only low-income groups are at risk, but also that wealthier sectors are not spared. Factors such as high-density settlement (Barros *et al.*, 2008) and the characteristics of some hazards explain this – e.g., poor and wealthy alike are at risk from air pollution and temperature in Santiago de Chile and Bogota (2013b; Romero-Lankao *et al.*, 2012a).

There are also other climate change risks in terms of economic activity location and impacts on urban manufacturing and service workers, e.g. thermal stress (Hsiang, 2010), and the forms of urban expansion or sprawl into areas where ecosystem services may be compromised and risks enhanced, e.g. floodplains. Both processes are also related to rising motorization rates that facilitate suburban development and new regional agglomerations that bring pressure to bear on land uses that favor infiltration, surface cooling and biodiversity; the number of light vehicles in Latin America and the Caribbean is expected to double between 2000 and 2030, and be three times the 2000 figure by 2050 (ECLAC, 2009c).

While urban populations face diverse social, political, economic and environmental risks in daily life, climate change adds a new dimension to these risk settings (Pielke Jr *et al.*, 2003; Roberts, 2009; Romero-Lankao and Qin, 2011). Since urban development remains fragile in many cases, with weak planning responses, climate change can compound existing challenges. The probabilities and magnitudes of these events in each urban center will differ significantly according to socioeconomic, institutional and physical contexts.

27.3.5.2. Adaptation Practices

The direct and indirect effects of climate change as flooding, heat islands and food insecurity present cities with a set of challenges and opportunities for mainstreaming flood management, warning systems and other adaptation responses with sustainability goals (Bradley *et al.*, 2006; Hardoy and Pandiella, 2009; Hegglin and Huggel, 2008; Romero-Lankao, 2010; Romero-Lankao *et al.*, 2013a; Romero-Lankao, 2012).

Urban populations, economic activities and authorities have a long experience of responding to climate-related hazards, particularly through disaster risk management (e.g., Tucuman and San Martin, Argentina (Plaza and Pasculi, 2007; Sayago *et al.*, 2010)), and land use and economic development planning to a limited extent (Barton, 2009). Climate policies can build on these. Local administrations participate in the ICLEI, C40, IDB Emerging and Sustainable Cities Initiative (ESCI) (IDB, 2013), and other networks, demonstrating their engagement in the generation of more climate-resilient cities. In smaller settlements, there is less capacity for adequate responses (e.g., climate change and vulnerability information (Hardoy and Romero-Lankao, 2011). Policies, plans and programs are required to reduce social vulnerability, and identify and reduce potential economic effects of climate on the local economy. Rio de Janeiro, for example, with its coastline property and high dependence on tourists (and their perceptions of risk), cannot ignore these climate-related hazards (Gasper *et al.*, 2011).

Poverty and vulnerability, as interlinked elements of the adaptation challenge in CA and SA, remain pivotal to understanding how urban climate policies can be streamlined with broader development issues and not solely the capacity to respond to climate change (Hardoy and Pandiella, 2009; Hardoy and Romero-Lankao, 2011; Winchester and Szalachman, 2009). These broader links include addressing the determinants of vulnerability (e.g., access to education, health and infrastructure, and to emergency response systems (Romero-Lankao, 2007a; Romero-Lankao and Qin, 2011). Among these response options, a focus on social assets has been highlighted by Rubin and Rossing (2012), rather than a, purely, physical asset focus.

Much urbanisation involves in-migrating or already resident, low-income groups and their location in risk-prone zones (Costa Fereira *et al.*, 2011). The need to consider land use arrangements, particularly urban growth on risk-prone zones, as part of climate change adaptation highlights the role of green areas that mitigate the heat island effect and reduce risks from landslides and flooding (Krellenberg *et al.*, 2013; Rodríguez Laredo, 2011).

In the case of governance frameworks, there is clear evidence that incorporation of climate change considerations into wider city planning is still a challenge, as are more inter-sectoral and participative processes that have been linked to more effective policies (Barton, 2009; Barton, 2013; De Oliveira, 2009; Romero-Lankao *et al.*, 2013a). Several metropolitan adaptation plans have been generated over the last five years, e.g. Bogotá, Buenos Aires, Esmeraldas, Quito, and São Paulo, although for the most part they have been restricted to the largest conglomerations and are often included as an addition to mitigation plans (Carmin *et al.*, 2009; Luque *et al.*, 2013; Romero-Lankao, 2007b; Romero-Lankao *et al.*, 2013a; Romero-Lankao *et al.*, 2012b).

27.3.6. Renewable Energy

27.3.6.1. Observed and Projected Impacts and Vulnerabilities

Table 27-6 shows the relevance of RE in the Latin America energy matrix as compared to the world for 2009 according to the International Energy Agency statistics (IEA, 2012). Hydropower is the most representative source of RE and therefore analyzed separately from this section and all other RE sources (see case study in section 27.6.1.). Geothermal energy will be not discussed as it is assumed that there is no impact of climate change on the effectiveness of this energy type (Arvizu *et al.*, 2011).

[INSERT TABLE 27-6 HERE
Table 27-6: Comparison of consumption of different energetics in Latin America and the world (in thousand tons of oil equivalent (ktoe) on a net calorific value basis).]

Hydro, wind energy and biofuel production might be sensitive to climate change in Brazil (Lucena *et al.*, 2009). With the vital role that RE plays in mitigating the effects of GCC, being by far the most important sources of non-hydro RE in SA and CA, this sensitivity demands the implementation of RE projects that will increase knowledge on the crops providing bioenergy.

For historical reasons, CA and SA developed sugarcane as bioenergy feedstock. Brazil accounts for the most intensive RE production as bioethanol, which is used by the majority of the cars in the country (Goldemberg, 2008) whereas biodiesel comprises 5% of all diesel nationwide. With the continent's long latitudinal length, the expected impacts of climate change on plants will be complex due to a wide variety of climate conditions, so that different crops would have to be used in different regions. In Brazil, most of the biodiesel comes from soybeans, but there are promising new sources such as palm oil (Lucena *et al.*, 2009). The development of palm oil as well as soybean are important factors that induce land use change, with a potential to influence stability of forests and biodiversity in certain key regions in SA, such as the Amazon (section 27.2.2.1).

Biofuels can help CA and SA to decrease emissions from energy production and use. However, RE might imply potential problems such as those related to positive net emissions of greenhouse gases, threats to biodiversity, an increase in food prices and competition for water resources (section 27.2.3), some of which can be reverted or attenuated (Koh and Ghazoul, 2008). For example, the sugarcane agro-industry in Brazil combusts bagasse to produce electricity, providing power for the bioethanol industry and increasing sustainability. The excess heat energy is then used to generate bioelectricity, thus allowing the biorefinery to be self-sufficient in energy utilization (Amorim *et al.*, 2011; Dias *et al.*, 2012). In 2005/2006 the production of bioelectricity was estimated to be 9.2 kWh per ton of sugarcane (Macedo *et al.*, 2008), approximately 2% of Brazil's total energy generation production.

Most bioenergy feedstocks at present in production in CA and SA are grasses. In the case of sugarcane, the responses to the elevation of CO_2 concentration up to 720 ppmv have been shown to be positive in terms of biomass production and principally regarding water use efficiency (De Souza *et al.*, 2008).

The production of energy from renewable sources such as hydro- and wind power is greatly dependent on climatic conditions and therefore may be impacted in the future by GCC. Lucena *et al.* (2010a) suggests an increasing energy vulnerability of the poorest regions of Brazil to GCC together with a possible negative influence on biofuels production and electricity generation, mainly biodiesel and hydropower respectively. (JAM: we use CC and GCC, I believe that we use should use CC only).

Expansion of biofuel crops in Brazil might cause both direct and indirect land use changes (e.g., biofuel crops replacing rangelands, which previously replaced forests) with the direct land use changes, according to simulation performed by Lapola *et al.* (2010) of the effects for 2020. The same study shows that sugarcane ethanol and biodiesel derived from soybean each contribute with about one half of the indirect deforestation projected for 2020 (121.970 km^2) (Lapola *et al.*, 2010). Thus, indirect land use changes, especially those causing the rangeland frontier to move further into the Amazonian forests, might potentially offset carbon savings from biofuels production.

The increase in global ethanol demand is leading to the development of new hydrolytic processes capable of converting cellulose into ethanol (Dos Santos *et al.*, 2011). The expected increase in the hydrolysis technologies is *very likely* to balance the requirement of land for biomass crops. Thus, the development of these technologies has a strong potential to diminish social (e.g. negative health effects due the burning process, poor labor conditions) and environmental impacts (e.g. loss of biodiversity, water and land uses) whereas at it can improve the economic potential of sugarcane. One adaptation measure will be to increase the productivity of bioenergy crops due to planting in high productivity environments with highly developed technologies, in order to use less land. As one of the main centers of biotech agriculture application in the world (Gruskin, 2012), the region has a great potential to achieve this goal.

As the effects previously reported on crops growing in SESA might prevail (see 27.3.4.1), i.e. that an increase in productivity may happen due to increasing precipitation, future uncertainty will have to be dealt with by preparing adapted varieties of soybean in order to maintain food and biodiesel production, mainly in Argentina as it is one of the main producers of biodiesel from soybean in the world (Chum *et al.*, 2011).

Other renewable energy sources—such as wind power generation—may also be vulnerable, raising the need for further research. According to Lucena *et al.* (2009; 2010b) the projections of changes in wind power in Brazil, may favor the use of this kind of energy in the future.

27.3.6.2. Adaptation Practices

RE will become increasingly more important over time as this is closely related with the emissions of GHG (Fischedick *et al.*, 2011). Thus, RE could have an important role as adaptation means to provide sustainable energy for development in the region (see also *27.6.1*). However, the production of RE requires large available areas for agriculture, which is the case of Argentina, Bolivia, Brazil, Chile, Colombia, Peru and Venezuela, that together represent 90% of the total area of CA and SA. However, for small countries it might not be possible to use bioenergy. Instead, they could benefit in the future from other types of RE, such as geothermal, eolic, photovoltaic etc., depending on policies and investment in different technologies. This is important because economic development is thought to be strongly correlated with an increase in energy use (Smil, 2000), which is itself associated with an increase in emissions (Sathaye *et al.*, 2011).

Latin America is second to Africa in terms of technical potential for bioenergy production from rain-fed lignocellulosic feedstocks on unprotected grassland and woodlands (Chum *et al.*, 2011). Among the most important adaptation measures regarding RE are: (1) management of land use change (LUC); and (2) development of policies for financing and management of science and technology for all types of RE in the region.

If carefully managed, biofuel crops can be used as a means to regenerate biodiversity as proposed by Buckeridge *et al.* (2012) highlighting that the technology for tropical forest regeneration has become available and that forests could share land with biofuel crops (such as sugarcane) taking advantage of forests' mitigating potential. A possible adaptation measure could be to expand the use of reforestation technology to other countries in CA and SA.

One of the main adaptation issues is related to the food *vs*. fuel issues (Valentine *et al.*, 2012). This is important because an increase in bioenergy feedstocks might threaten primary food production in a scenario expected to feed future populations with an increase of 70% in production (Gruskin, 2012; Valentine *et al.*, 2012). This is particularly important in the region as it has one of the highest percentages of arable land available for food production in the world (Nellemann *et al.*, 2009). As CA and SA develop new strategies to produce more RE there might be a pressure for more acreage to produce bioenergy. Because climate change will affect bioenergy and food crops at the same time, their effects, as well as the adaptation measures related to agriculture will be similar. The main risks identified by Arvizu *et al.* (2011) are: (1) business as usual; (2) un-reconciled growth, and (3) environment and food *vs*. fuel. Thus, the most important adaptation measures will be the ones related to the control of economic growth, environmental management and agriculture production. The choice for lignocellulosic feedstocks (e.g. sugarcane second generation technologies) will be an important mitigation/adaptation measure because these feedstocks do not compete with food (Arvizu *et al.*, 2011). In the case of sugarcane, for instance, an increase of ca. 40% in the production of bioethanol is expected as a result of the implantation of second generation technologies coupled with the first generation ones already existent in Brazil (De Souza *et al.*, 2013; Dias *et al.*, 2012).

Biodiesel production has the lowest costs in Latin America (Chum *et al.*, 2011) due to the high production of soybean in Brazil and Argentina. The use of biodiesel to complement oil-derived diesel is a productive choice for adaptation measures regarding this bioenergy source. Also, the cost of ethanol, mainly derived from sugarcane, is the lowest in CA, SA and Latin America (Chum *et al.*, 2011) and as an adaptation measure, such costs, as well as the one of biodiesel, should be lowered even more by improving technologies related to agricultural and industrial production of both. Indeed, it has been reported that in LA the use of agricultural budgets by governments for investment in public goods induces faster growth, decreasing poverty and environmental degradation (López and Galinato, 2007). The pressure of soy expansion due to biodiesel demand can lead to land use change and consequently to economic teleconnections, as suggested by Nepstad *et al.* (2006). These teleconnections may link Amazon deforestation derived from soy expansion to the economic growth in some developing countries due to changes in the demand of soy. These effects may possibly mean a decrease in jobs related to small to big farms in agriculture in Argentina (Tomei and Upham, 2009) on the one hand, and deforestation in the Amazon due to the advance of soybean cropping in the region on the other (Nepstad and Stickler, 2008).

27.3.7. Human Health

27.3.7.1. Observed and Projected Impacts and Vulnerability

Changes in weather extremes and climatic patterns are affecting human health (*high confidence*), by increasing morbidity, mortality, and disabilities, and through the emergence of diseases in previously non-endemic regions (*high confidence*) (Rodríguez-Morales, 2011; Winchester and Szalachman, 2009). Heat waves and cold spells have increased urban mortality rates (Bell *et al.*, 2008; Hajat *et al.*, 2010; Hardoy and Pandiella, 2009; McMichael *et al.*, 2006; Muggeo and Hajat, 2009). Outbreaks of vector- and water-borne diseases were triggered in CA by hurricane Mitch in 1998 (Costello *et al.*, 2009; Rodríguez-Morales *et al.*, 2010), while the 2010-2012 Colombian floods caused hundreds of deaths and thousands of displaced people (Hoyos *et al.*, 2013).

The number of cases of malaria have increased in Colombia during the last five decades alongside air temperatures (Arevalo-Herrera *et al.*, 2012; Poveda *et al.*, 2011), but also in urban and rural Amazonian regions undergoing large environmental changes (Cabral *et al.*, 2010; Da Silva-Nunes *et al.*, 2012; Gil *et al.*, 2007; Tada *et al.*, 2007). Malaria transmission has reached 2,300 m in the Bolivian Andes, and vectors are found at higher altitudes from Venezuela to Bolivia (Benítez and Rodríguez-Morales, 2004; Lardeux *et al.*, 2007; Pinault and Hunter, 2011). Although the incidence of malaria has decreased in Argentina, its vector density has increased in the northwest along with climate variables (Dantur Juri *et al.*, 2011; Dantur Juri *et al.*, 2010). El Niño drives malaria outbreaks in Colombia (Mantilla *et al.*, 2009; Poveda *et al.*, 2011) amidst other factors (Osorio *et al.*, 2007; Restrepo-Pineda *et al.*, 2008; Rodríguez-Morales *et al.*, 2006). Linkages between ENSO and malaria are also reported in Ecuador and Peru (Anyamba *et al.*, 2006; Kelly-Hope and Thomson, 2010), French Guiana (Hanf *et al.*, 2011), Amazonia (Olson *et al.*, 2009), and Venezuela (Moreno *et al.*, 2007).

Unlike malaria, dengue fever (DF) and its hemorrhagic variant (DHF) are mostly urban diseases whose vector is affected by climate conditions. Their incidence have risen in tropical America in the last 25 years, causing annual economic losses of US$ 2.1+[1 to 4] billion (Shepard *et al.*, 2011; Tapia-Conyer *et al.*, 2009; Torres and Castro, 2007). Environmental and climatic variability affect their incidence in CA (Fuller *et al.*, 2009; Mena *et al.*, 2011; Rodríguez-Morales *et al.*, 2010), in Colombia (Arboleda *et al.*, 2009), and in French Guiana alongside malaria (Carme *et al.*, 2009; Gharbi *et al.*, 2011). In Venezuela, DF increases during La Niña (Herrera-Martinez and Rodríguez-Morales, 2010; Rodríguez-Morales and Herrera-Martinez, 2009). Weather and climate variability are also associated with DF in southern SA (Costa *et al.*, 2010; De Carvalho-Leandro *et al.*, 2010; Degallier *et al.*, 2010; Honório *et al.*, 2009; Lowe *et al.*, 2011), involving also demographic and geographic factors in Argentina (Carbajo *et al.*, 2012). In Rio de Janeiro a 1°C increase in monthly minimum temperature led to a 45% increase of DF in the next month, and 10 mm increase in rainfall to a 6% increase (Gomes *et al.*, 2012). Despite large vaccination campaigns, the risk of Yellow Fever (YF) outbreaks has increased mostly in tropical America's densely populated poor urban settings (Gardner and Ryman, 2010), alongside climate conditions (Jentes *et al.*, 2011).

Schistosomiasis (SCH) is endemic in rural areas of Suriname, Venezuela, the Andean highlands, and rural and peripheral urbanized regions of Brazil (Barbosa *et al.*, 2010; Igreja, 2011; Kelly-Hope and Thomson, 2010). It is highly likely that SCH will increase in a warmer climate (Lopes *et al.*, 2010; Mangal *et al.*, 2008; Mas-Coma *et al.*, 2009). Vegetation indices are associated with human fascioliasis in the Andes (Fuentes, 2004).

Hantaviruses (HV) have been recently reported throughout the region (Jonsson *et al.*, 2010; MacNeil *et al.*, 2011), and El Niño and climate change augment their prevalence (Dearing and Dizney, 2010). Variation in HV reservoirs in Patagonia is strongly dependent on climate and environmental conditions (Andreo *et al.*, 2012; Carbajo *et al.*, 2009). In Venezuela, Rotavirus (RV) is more frequent and more severe in cities with minimal seasonality (Kane *et al.*, 2004). The peak of RV in Guatemala occurs in the dry season, causing 60% of total diarrhoea cases (Cortes *et al.*, 2012).

In spite of its rapid decline, climate-sensitive Chagas disease is still a major public health issue (Abad-Franch *et al.*, 2009; Araújo *et al.*, 2009; Gottdenker *et al.*, 2011; Moncayo and Silveira, 2009; Tourre *et al.*, 2008). Climate also affects the most prevalent mycosis (Barrozo *et al.*, 2009), and ENSO is associated with outbreaks of bartonellosis in Peru (Payne and Fitchett, 2010).

The high incidence of cutaneous leishmaniasis (CL) in Bolivia is exacerbated during La Niña (García *et al.*, 2009; Gomez *et al.*, 2006). CL is affected in Costa Rica by temperature, forest cover and ENSO (Chaves *et al.*, 2008), and in Colombia by land cover, altitude, climatic variables, and El Niño (Cárdenas *et al.*, 2006; 2007; 2008; Valderrama-Ardila *et al.*, 2010), and decreases during La Niña in Venezuela (Cabaniel *et al.*, 2005). CL in Suriname peaks during the March dry season (35%) (Van der Meide *et al.*, 2008), and in French Guiana is intensified after the October-December dry season (Rotureau *et al.*, 2007). Incidence of visceral leishmaniasis (VL) has increased in Brazil (highest in LA) in association with El Niño and deforestation (Cascio *et al.*, 2011; Ready, 2008; Sortino-Rachou *et al.*, 2011), as in Argentina, Paraguay, and Uruguay (Bern *et al.*, 2008; Dupnik *et al.*, 2011; Fernández *et al.*, 2012; Salomón *et al.*, 2011). VL transmission in Venezuela is associated with rainfall seasonality (Feliciangeli *et al.*, 2006; Rodríguez-Morales *et al.*, 2007). Besides, the incidence of skin cancer in Chile has increased in recent years, concomitantly with climate and geographic variables (Salinas *et al.*, 2006).

Onchocerciasis (river blindness) vector exhibits seasonal biting rates (Botto *et al.*, 2005; Rodríguez-Pérez *et al.*, 2011), and leptospirosis is prevalent in CA's warm-humid tropical regions (Valverde *et al.*, 2008). Other climate-driven infectious diseases are ascariasis and gram-positive cocci in Venezuela (Benítez *et al.*, 2004; Rodríguez-Morales *et al.*, 2010), and Carrion's disease in Peru (Huarcaya *et al.*, 2004).

Sea water temperature affects the abundance of cholera's bacteria (Hofstra, 2011; Jutla *et al.*, 2010; Koelle, 2009; Marcheggiani *et al.*, 2010), which explains the outbreaks during El Niño in Peru, Ecuador, Colombia and Venezuela (Cerda Lorca *et al.*, 2008; Gavilán and Martínez-Urtaza, 2011; Holmner *et al.*, 2010; Martínez-Urtaza *et al.*, 2008; Murugaiah, 2011; Salazar-Lindo *et al.*, 2008).

The worsening of air quality and higher temperatures in urban settings are increasing chronic respiratory and cardiovascular diseases, and morbidity from asthma and rhinitis (Grass and Cane, 2008; Gurjar *et al.*, 2010; Jasinski *et al.*, 2011; Martins and Andrade, 2008; Rodriguez *et al.*, 2011), but also artherosclerosis, pregnancy-related outcomes, cancer, cognitive deficit, otitis, and diabetes (Olmo *et al.*, 2011). Dehydration from heatwaves increases hospitalizations for chronic kidney diseases (Kjellstrom *et al.*, 2010), affecting construction, sugarcane and cotton workers in CA (Crowe *et al.*, 2009; 2010; Kjellstrom and Crowe, 2011; Peraza *et al.*, 2012).

Extreme weather/climate events affect mental health in Brazil (depression, psychological distress, anxiety, mania and bipolar disorder), in particular in drought-prone areas of NEB (Coêlho *et al.*, 2004; Volpe *et al.*, 2010). Extreme weather, meager crop yields, and low GDP are also associated with increased violence (McMichael *et al.*, 2006).

Multiple factors increase the region's vulnerability to climate change: precarious health systems, malnutrition, inadequate water and sanitation services, poor waste collection and treatment systems, air, soil and water pollution, lack of social participation, and inadequate governance (Luber and Prudent, 2009; Rodríguez-Morales, 2011; Sverdlik, 2011). Human health vulnerabilities in the region depend on geography, age (Graham *et al.*, 2011; Martiello and Giacchi, 2010; Perera, 2008; Åstrom *et al.*, 2011), gender (Oliveira *et al.*, 2011), race, ethnicity, and socio-economic status (Diez Roux *et al.*, 2007; Martiello and Giacchi, 2010). Neglected Tropical Diseases in LA cause 1.5-5.0 million disability-adjusted life years (DALYs) (Hotez *et al.*, 2008). Vulnerability of mega-cities (see 27.3.5) is aggravated by access to clean water, rapid spread of diseases (Borsdorf and Coy, 2009), and migration from rural areas forced by disasters (Borsdorf and Coy, 2009; Campbell-Lendrum and Corvalán, 2007; Hardoy and Pandiella, 2009). Human health vulnerabilities have been assessed in Brazil through composite indicators involving downscaled climate scenarios, epidemiological variables and socio-economic projections (Barbieri and Confalonieri, 2011; Confalonieri *et al.*, 2009; ; FIOCRUZ, 2011). The Andes and CA are among the regions of highest predicted losses [1% to 27%] in labor productivity from future climate scenarios (Kjellstrom *et al.*, 2009).

27.3.7.2. Adaptation Strategies and Practices

Adaptation efforts in the region ((Blashki *et al.*, 2007; Costello *et al.*, 2011) are hampered by lack of political commitment, gaps in scientific knowledge, and institutional weaknesses (Keim, 2008; Lesnikowski *et al.*, 2011; Olmo *et al.*, 2011) (see 27.4.3). Research priorities and current strategies must be reviewed (Halsnæs and Verhagen, 2007; Karanja *et al.*, 2011; Romero and Boelaert, 2010), and preventive/responsive systems must be put in place (Bell, 2011) to foster adaptive capacity (Campbell-Lendrum and Bertollini, 2010; Huang *et al.*, 2011). Colombia established a pilot adaptation program to cope with changes in malaria transmission and exposure (Poveda *et al.*, 2011). The city of São Paulo has implemented local pollution control measures, with the co-benefit of reducing GHG emissions (De Oliveira, 2009; Nath and Behera, 2011).

Human wellbeing indices must be explicitly stated as adaptation policies in LA (e.g., Millennium Development Goals) (Franco-Paredes *et al.*, 2007; Halsnæs and Verhagen, 2007; Mitra and Rodriguez-Fernandez, 2010). South-south cooperation and multidisciplinary research are required to design relevant adaptation and mitigation strategies (Team and Manderson, 2011; Tirado *et al.*, 2010).

27.4. Adaptation Opportunities, Constraints, and Limits

27.4.1. Adaptation Needs and Gaps

During the last years, the study of adaptation to climate change has progressively switched from an impact-focused approach (mainly climate-driven) to include a vulnerability-focused vision (Boulanger *et al.*, 2011). As a consequence, the development and implementation of systemic adaptation strategies, involving institutional, social, ecosystem, environmental, financial and capacity components (see Chapter 14), to cope with present climate extreme events is a key step toward climate change adaptation, especially in SA and CA countries. While different frameworks and definitions of vulnerability exist, a general tendency aims at studying vulnerability to climate change especially in SA and CA focusing on the following aspects: urban vulnerability (e.g. Hardoy and Pandiella, 2009; Heinrichs and Krellenberg, 2011), rural community (McSweeney and Coomes, 2011; Ravera *et al.*, 2011), rural farmer vulnerability (Oft, 2010), and sectoral vulnerability (see 27.3). The approach used can be holistic or systemic (Carey *et al.*, 2012b; Ison, 2010), where climate drivers are actually few with respect to all other drivers related to human and environment interactions including physical, economic, political and social context, as well as local characteristics such as occupations, resource uses, accessibility to water, etc. (Manuel-Navarrete *et al.*, 2007; Young *et al.*, 2010).

In developing and emergent countries, there exists a general consensus that the adaptive capacity is low, strengthened by the fact that poverty is key determinant of vulnerability in Latin America (to climate related natural hazards, see Rubin and Rossing, 2012) and thus a limit to resilience (Pettengell, 2010) leading to a "low human development trap" (UNDP, 2007). However, Magnan (2009) suggests that this analysis is biased by a "relative immaturity of the science of adaptation to explain what are the processes and the determinants of adaptive capacity". Increasing research efforts on the study of adaptation is therefore of great importance to improve our understanding of the actual societal, economical, community and individual drivers defining the adaptive capacity. Especially, a major focus on traditions and their transmission (Young and Lipton, 2006) may actually indicate potential adaption potentials in remote and economically poor regions of SA and CA. Such a potential does not dismiss the fact that the nature of future challenges may actually not be compared to past climate variability (e.g. glacier retreat in the Andes).

Coping with new situations may require new approaches such as a multilevel risk governance (Corfee-Morlot *et al.*, 2011; Young and Lipton, 2006) associated with decentralization in decision-making and responsibility. While the multilevel risk governance and the local participatory approach are interesting frameworks for strengthening adaptation capacity, perception of local and national needs is diverging, challenging the implementation of adaptation strategies in CA/SA (Salzmann *et al.*, 2009). At present, despite an important improvement during the last years, there still exists a certain lack of awareness of environmental changes and mainly their implications for livelihoods and businesses (Young *et al.*, 2010). Moreover, considering the limited financial resources of some states in CA and SA, long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the population. This situation weakens the importance of adaptation planning to climate change in the political agenda (Carey *et al.*, 2012b), and requires therefore international involvement as one facilitating factor in natural hazard management and climate change adaptation, in accordance with the respect to sovereignty, the international conventions including the United Nations Framework Convention on Climate Change. In addition, as pointed out by McGray *et al.* (2007), development, adaptation and mitigation issues are not separate issues. Especially, development and adaptation strategies should be tackled together in developing countries such as SA and CA, focusing on strategies to reduce vulnerability. The poor level of adaptation of present-day climate in SA and CA countries is characterized by the fact that responses to disasters are mainly reactive rather than preventive. Some early warning systems are being implemented, but the capacity of responding to a warning is often limited, particularly among poor populations. Finally, actions combining public communication (and education), public decision-maker capacity-building and a synergetic development-adaptation funding will be key to sustain the adaptation process that CA and SA require to face future climate change challenges.

27.4.2. Practical Experiences of Autonomous and Planned Adaptation, including Lessons Learned

Adaptation processes in many cases have been initiated a few years ago, and there is still a lack of literature to evaluate their efficiency in reducing vulnerability and building resilience of the society against climate change. However, experiences of effective adaptation and maladaptation are slowly being documented (see also 27.4.3), some lessons have already been learned from these first experiences (see section 27.3), and tools, such as the Index of Usefulness of Practices for Adaptation (IUPA) to evaluate adaptation practices have been developed for the region (Debels *et al.*, 2009). Evidenced by these practical experiences, there is a wide range of options to foster adaptation and thus adaptive capacity in CA and SA. In CA and SA, many societal issues are strongly connected to development goals and are often considered priority in comparison to adaptation efforts to climate change. However, according to the 135 case studies analyzed by McGray *et al.* (2007), 21 of which were in CA and SA, the synergy between development and adaptation actions allows to ensuring a sustainable result of the development projects.

Vulnerability and disaster risk reduction may not always lead to long-term adaptive capacity (Nelson and Finan, 2009; Tompkins *et al.*, 2008), except when structural reforms based on good governance (Tompkins *et al.*, 2008) and negotiations (Souza Filho and Brown, 2009) are implemented. While multi-level governance can help to create resilience and reduce vulnerability (Corfee-Morlot *et al.*, 2011; Roncoli, 2006; Young and Lipton, 2006), capacity-building (Eakin and Lemos, 2006), good governance and enforcement (Lemos *et al.*, 2010; Pittock, 2011) are key components.

Autonomous adaptation experience are mainly realized at local levels (individual or communitarian) with examples found for instance for rural communities in Honduras (McSweeney and Coomes, 2011), indigenous communities in Bolivia (Valdivia *et al.*, 2010) and coffee agroforestry systems in Brazil (De Souza *et al.*, 2012). However, such adaptation processes do not always respond specifically to climate forcing. For instance, the agricultural sector adapts rapidly to economic stressors, while, despite a clear perception of climate risks, it may last longer before responding to climate changes (Tucker *et al.*, 2010). In certain regions or communities, such as Anchioreta in Brazil (Bonatti *et al.*, 2012), adaptation is part of a permanent process and is actually tackled through a clear objective of vulnerability reduction, maintaining and diversifying a large set of natural varieties of corn allowing the farmers to diversify their planting. Another kind of autonomous adaptation is the southward displacement of agriculture activities (e.g. wine, coffee) though the purchase of lands, which will become favorable for such agriculture activities in a warmer climate. In Argentina, the increase of precipitation observed during the last 30 years contributed to a westward displacement of the annual crop frontier. However, local adaptation to climate and non-climate drivers may undermine long-term resilience of socio-ecological systems when local, short-term strategies designed to deal with specific threats or challenges do not integrate a more holistic and long-term vision of the system at threat (Adger *et al.*, 2011). Thus, policy should identify the sources of and conditions for local resilience and strengthen their capacities to adapt and learn (Adger *et al.*, 2011; Borsdorf and Coy, 2009; Eakin *et al.*, 2011), as well as to integrate new adapted tools (Oft, 2010). This sets the question of convergence between the local-scale/short-term and broad scale/long-term visions in terms of perceptions of risks, needs to adapt and appropriate policies to be implemented (Eakin and Wehbe, 2009; Salzmann *et al.*, 2009). Even if funding for adaptation is available, the overarching problem is the lack of capacity and/or willingness to address the risks, especially those threatening lower income groups (Satterthwaite, 2011a). Adaptation to climate change cannot eliminate the extreme weather risks, and thus efforts should focus on disaster preparedness and post-disaster response (Sverdlik, 2011). Migration is the last resort for rural communities facing water stress problems in CA and SA (Acosta-Michlik *et al.*, 2008).

In natural hazard management contributing to climate change adaptation, specific cases such as the one in Lake 513 in Peru (Carey *et al.*, 2012b) clearly allowed to identify facilitating factors for a successful adaptation process (technical capacity, disaster events with visible hazards, institutional support, committed individuals, and international involvement) as well as impediments divergent risk perceptions, imposed government policies, institutional instability, knowledge disparities, and invisible hazards). In certain cases, forward-looking learning (anticipatory process), as a contrast to learning by shock (reactive process), has been found as a key element for adaptation and resilience (Tschakert and Dietrich, 2010) and should be promoted as a tool for capacity-building at all levels (stakeholders, local and national governments). Its combination with role-playing game and agent-based models (Rebaudo *et al.*, 2011) can strengthen and accelerate the learning process.

Planned adaptation policies promoted by governments have been strengthened by the participation in international networks, where experience and knowledge can be exchanged. As an example, the C40 Cities- Climate Leadership Group or ICLEI include Bogota (Colombia), Buenos Aires (Argentina), Caracas (Venezuela), Curitiba, Rio de Janeiro and Sao Paulo (Brazil), Lime (Peru) and Santiago de Chile (Chile). Most of these cities have come up with related action and strategy plans (e.g. Action Plan Buenos Aires 2030, Plan of Caracas 2020 or the Metropolitan Strategy to CCA of Lima) (C40 Cities, 2011).

At a regional policy level, an example of intergovernmental initiatives in SA and CA is the ‘Ibero-American Programme on Adaptation to Climate Change’ (PIACC), developed by the Ibero-American Network of Climate Change Offices (RIOCC) (Keller *et al.*, 2011b). For CA specifically, the Central American Commission for Environment and Development (CCAD) brings together the environmental ministries of the Central American Integration System (Sistema de la Integración Centroamericana (SICA)) that released its climate change strategy in 2010 (CCAD-SICA, 2010; Keller *et al.*, 2011a).

These initiatives demonstrate that there has been a growing awareness of CA and SA governments on the need to integrate climate change and future climate risks in their policies. Up to date, in total 18 regional Non-Annex countries, including Argentina, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Nicaragua, Guyana, Panama, Paraguay, Peru, Suriname, Uruguay and Venezuela, have already published their first and/or second National Communication to the UNFCCC (see UNFCCC, 2012) allowing to measure the country’s emissions and to assess its present and future vulnerability.

27.4.3. Observed and Expected Barriers to Adaptation

Adaptation is a dynamic process, which to be efficient requires a permanent evolution and even transformation of the vulnerable system. Such transformation process can be affected by several constraints, including constraints affecting the context of adaptation as well as the implementation of policies and measures (see 16.3.2).

Major constraints related to the capacity and resources needed to support the implementation of adaptation policies and processes comprehend access to (Lemos *et al.*, 2010) and exchange of knowledge (e.g. adaptive capacity can be enhanced by linking indigenous knowledge and scientific knowledge; Valdivia, 2010), the access to and quality of natural resources (López-Marrero, 2010), the access to financial resources, especially for poor households (Hickey and Weis, 2012; Rubin and Rossing, 2012; Satterthwaite, 2011b) as well as for institutions (Pereira *et al.*, 2009), technological resources (López-Marrero, 2010), technical assistance (Eakin *et al.*, 2011; Guariguata, 2009) , as well as the fostering of public-private technology transfer (La Rovere *et al.*, 2009a; Ramirez-Villegas *et al.*, 2012) and promotion of technical skills (Hickey and Weis, 2012), and social asset-based formation at the local level (Rubin and Rossing, 2012).

In terms of framing adaptation, as constraint to affect the adaptation context, it is usually considered that a major barrier to adaptation is the perception of risks and many studies focused on such an issue (Bonatti *et al.*, 2012). Also, new studies (Adger *et al.*, 2009) identified social limits to possible adaptation to climate change in relation with issues of values and ethics, risk, knowledge and culture, even though such limits can evolve in time. Indeed, while being a necessary condition, perception may not be the main driver for initiating an adaptation process. As pointed out by Tucker *et al.* (2010) with a specific focus on CA, exogenous factors (economic, land tenure, cost, etc.) may actually strongly constrain the decision-making process involved in possible adaptation process. In that sense, efficient governance and management are key components in the use of climate and non-climate information in the decision-making and adaptation process. As a consequence, it is difficult to describe adaptation without defining at which level it is thought. Indeed, while a lot of efforts are invested in national and regional policy initiatives, most of the final adaptation efforts will be local. National and international (transborder) governance is key to build adaptive capacity (Engle and Lemos, 2010) and therefore to strengthen (or weaken) local adaptation through efficient policies and delivery of resources. At a smaller scale (Agrawal, 2008), local institutions can strongly contribute to vulnerability reduction and adaptation. However, at all levels, the efficiency in national and local adaptation activities strongly depend on the capacity-building and information transmission to decision-makers (Eakin and Lemos, 2006).

27.5 Interactions between Adaptation and Mitigation

Synergies between adaptation and mitigation strategies on the local level can be reached due to self-organization of communities in cooperatives (see 'The SouthSouthNorth Capacity Building Module on Poverty Reduction" (see SSN, 2006), which manages recycling or renewable energy production, leading to an increase in energy availability, thus production capacity and therefore new financial resources. Moreover, Venema and Cisse (2004) support also the development of decentralized renewable energy solutions for the growth of renewable energy in CA and SA (see also section 27.3.6) next to large infrastructure project (see their case studies for Argentina and Brazil).

In spite of their smaller size (individual or communitarian), these solutions offer adaptation and mitigation benefits. On one hand, fossil-based energy consumption is reduced, while energy availability is increased. On the other hand, reduction of energy precariousness is key in any development strategy. Thus, it allows local community and individuals to growing socially and economically; and therefore to reducing its vulnerability avoiding the poverty trap (UNDP, 2007), and to initiating an adaptation process based on non-fossil fuel energy sources. Such initiatives also depend on local and organizational leaderships (UN-Habitat, 2011).

Such integrated strategies of income generation as adaptation measures as well as production of renewable energy are also identified for vulnerable, small farmers diversifying their crops towards crops for vegetable oil and biodiesel production in Brazil. Barriers identified concern capacity building and logistical requirements making policy tools, credit mechanism, and organization into cooperatives, and fostered research necessary (La Rovere *et al.*, 2009b).

Other promising interactions of mitigation and adaptation are identified e.g. for the management of Brazilian tropical natural and planted forest (Guariguata, 2009).

At national and regional scales, CA and SA countries will require the allocation of human and financial resources to adapt to climate change. While resources are limited, too large an economic dependence of these countries to fossil fuels will reduce their adaptive capacity. The reduction in energy consumption and the integration of renewable energies in their energetic matrix is therefore a key issue for all these countries in order to sustain their development and growth and therefore increase their adaptive capacity (see also section 27.3.6).
Reforestation and avoided deforestation are important practices that contribute to both mitigation and adaptation efforts in the region as in other parts of the world. Maintaining forest cover can provide a suite of environmental services including local climate regulation, water regulation, reduced soil erosion, all of which can reduce the vulnerability of communities to variable climate (see section 27.3.2.2 on Ecosystem-based adaptation) (Vignola *et al.*, 2009).

27.6. Case Studies

27.6.1. Hydropower

Hydropower is the main source of renewable energy in CA and SA (see section 27.3.6). The region is only second to Asia in terms of hydropower energy generation in the world, displaying a 20% share of total annual generation and an average regional capacity factor of over 50% (Table 5-1 SRREN; IPCC, 2011). As a result, the region has by far the largest proportion of electricity generated through hydropower facilities (Table 27-6 in section 27.3.6.1). The hydropower proportion of total electricity production is over 40% in the region, and in some cases is near or close to 80%, as in the case of Brazil, Colombia and Costa Rica (IEA, 2012). Although there is debate, especially in tropical environments, about GHG emissions from hydropower reservoirs (Fearnside and Pueyo, 2012), this form of electricity generation is often seen as a major contributor to mitigating GHG emissions worldwide (see IPCC SRREN [5]; Kumar *et al.*, 2011). But on the other hand, hydropower is a climate-related sector, thus making it prone to the potential effects of changing climate conditions (see section 27.3.1.1). In this regards the CA and SA region constitute a unique example to study these relations between climate change mitigation and adaptation in relation to hydropower generation.

Diverse studies have analyzed the potential impacts of climate change on hydropower generation (see details in Table 27-4 in section 27.3.1.1). Maurer *et al.* (2009) studied future conditions for the Lempa River (El Salvador, Honduras and Guatemala) showing a potential reduction in hydropower capacity of 33% to 53% by 2070-2099 (Maurer *et al.*, 2009). A similar loss is expected for the Sinu-Caribe basin in Colombia were, despite a general projection of increased precipitation, losses due to evaporation enhancement reduces inflows to hydroelectric systems, thus reducing electricity generation up to 35% (Ospina-Noreña *et al.*, 2009a). Further studies (Ospina-Noreña *et al.*, 2011a; 2011b) have estimated vulnerability indices for the hydropower sector in the same basin, and identified reservoir operation strategies to reduce this vulnerability. Overall reductions in hydropower generation capacity are also expected in Chile for the main hydropower generation river basins: Maule, Laja and Biobio (ECLAC, 2009a; McPhee *et al.*, 2010; Stehr *et al.*, 2010), and also in the Argentinean Limay River basin (Seoane and López, 2007). Ecuador, on the other hand, faces an increase in generation capacity associated with an increment in precipitation on its largest hydroelectric generation Paute River basin (Buytaert *et al.*, 2010). Brazil, although being the country with the largest installed hydroelectric capacity in the region, still has unused generation capacity in sub-basins of the Amazon River (Soito and Freitas, 2011). However, future climate conditions plus environmental concerns pose an important challenge for the expansion of the system (Andrade *et al.*, 2012; Finer and Jenkins, 2012; Freitas and Soito, 2009). According to Lucena *et al.* (2009), hydropower systems in southern Brazil (most significantly the Parana River system) could face a slight increase in energy production under an A2 scenario. However, the rest of the country's hydropower system, and especially those located in NEB, could face a reduction in power generation, thus reducing the reliability of the whole system (Lucena *et al.*, 2009).

An obvious implication of the mentioned impacts is the need to replace the energy lost through alternative (see 27.3.6.2) or traditional sources. Adaptation measures have been studied for Brazil (Lucena *et al.*, 2010a), with results implying an increase in natural gas and sugarcane bagasse electricity generation in the order of 300 TWh, increase in operation costs in the order of 7 billion USD annually and 50 billion USD in terms of investment costs by 2035. In Chile, the study by ECLAC (2009a) assumed that the loss in hydropower generation, in the order of 18 TWh for the 2011-2040 period (a little over 10% of actual total hydropower generation capacity) would be compensated by the least operating cost source available, coal-fired power plant, implying an increase of 2 $MTCO_2e$ of total GHG emissions (emissions for the electricity sector in Chile totaled 25 $MTCO_2e$ in 2009). Ospina-Noreña (2011a; 2011b) studied some adaptation options, such as changes in water use efficiency or demand growth that could mitigate the expected impacts on hydropower systems in the Colombian Sinú-Caribe River basin. Changes in seasonality and total availability could also increase complexities in the management of multiple-use dedicated basins in Peru (Condom *et al.*, 2012; Juen *et al.*, 2007), Chile (ECLAC, 2009a), and Argentina (Seoane and López, 2007), that could affect the relationship between different water users within a basin. It is worth noting that those regions which are projected to face an increase in streamflow and associated generation capacity, such as Ecuador or Costa Rica, also share difficulties in managing deforestation, erosion and sedimentation which limits the useful life of reservoirs (see section 27.3.1.1). In these cases it is important to consider these effects in future infrastructure operation (Ferreira and Teegavarapu, 2012) and planning, and also to enhance the on-going process of recognizing the value of the relation between ecosystem services and hydropower system operations (Leguía *et al.*, 2008) (see more on PES in section 27.3.2.2 and 27.6.2).

27.6.2. Payment for Ecosystem Services

Payment for ecosystem services (PES) is commonly described as a set of transparent schemes for securing a well-defined ecosystem service (or a land use capable to secure that service) through conditional payments or compensations to voluntary providers (Engel *et al.*, 2008; Tacconi, 2012). Van Noordwijk *et al.* (2012) provides a broader definition to PES by arguing that it encompasses three complementary approaches, (i) the one above, i.e., commodification of pre-defined ecosystem services so that prices can be negotiated between buyers and sellers; plus (ii) compensation for opportunities forgone voluntarily or by command and control decisions; and (iii) coinvestment in environmental stewardships. Therefore, the terms ´conservation agreements´, ´conservation incentives´ and ´community conservation´ are often used as synonyms or as something different or broader than PES (Cranford and Mourato, 2011; Milne and Niesten, 2009). For simplicity, we refer to PES in its broadest sense (sensu Van Noordwijk *et al.*, 2012).

Services subjected to such types of agreements often include regulation of freshwater flows, carbon storage, provision of habitat for biodiversity, and scenic beauty (De Koning *et al.*, 2011; Montagnini and Finney, 2011). Since the ecosystems that provide the services are mostly privately owned, policies often aim at supporting landowners to maintain the provision of services over time (Kemkes *et al.*, 2010). Irrespective of the debate of as to whether payments or compensations should be designed to focus on actions or results (Gibbons *et al.*, 2011), experiences in Colombia, Costa Rica and Nicaragua show that PES can finance conservation, ecosystem restoration, and better land use practices (Montagnini and Finney, 2011; see also Table 27-5). However, based on examples from Ecuador and Guatemala, Southgate *et al.* (2010) argue that uniformity of payment for beneficiaries can be inefficient if recipients accept less compensation in return for conservation measures, or if recipients that promote greater environmental gains receive only the prevailing payment. Other setbacks to PES schemes might include cases where there is a perception of commoditization of nature and its intangible values (e.g. Bolivia, Cuba, Ecuador and Venezuela); other cases where mechanisms are inefficient to reduce poverty; slowness to build trust between buyers and sellers, as well as gender and land tenure issues that might arise (Asquith *et al.*, 2008; Balvanera *et al.*, 2012; Peterson *et al.*, 2010; Van Noordwijk *et al.*, 2012).

Table 27-7 lists selected examples of PES schemes in Latin America, but a more complete and detailed list is given in Balvanera *et al.* (2012).

[INSERT TABLE 27-7 HERE
Table 27-7: Cases of government-funded PES schemes in CA and SA.]

The PES concept (or ´fishing agreements´) also applies to coastal and marine areas, although only a few cases have been reported. Begossi (2011) argues that this is due to three factors: origin (the mechanism was originally designed for forests), monitoring (marine resources such as fish are more difficult to monitor than terrestrial resources) and definition of resource boundaries in offshore water. One example of a compensation mechanism in the region is the so-called *defeso*, in Brazil. It consists of a period (reproductive season) when fishing is forbidden by the government and fishermen receive a financial compensation. It applies to shrimp, lobster and both marine and freshwater fisheries (Begossi *et al.*, 2011).

27.7. Data and Research Gaps

The scarcity and difficult availability of high resolution high quality and continuous climate, oceanic and hydrological data, together with the availability of only very few complete regional studies, pose challenges for the region to address changes in climate variability and the identification of trends in extremes, in particular for CA. This situation hampers studies on frequency and variability of extremes, as well as impacts and vulnerability analyses of the present and future climates, and the development of vulnerability assessments and adaptation actions.

Related to observed impacts in most sectors, there is an imbalance in information availability among countries. While more studies have been performed for Brazil, Southern SA and SESA region, much less are available for CA and for some regions of tropical SA. An additional problem is poor dissemination of results in peer-reviewed publications since most information is available only as grey literature. There is a need for studies focused on current impacts and vulnerabilities across sectors throughout CA and SA, with emphasis on extremes to improve risk management assessments.

The complex interactions between climate and non-climate drivers difficult the assessment of impacts and projections, as is the case for water availability and streamflows owing to current and potential deforestation; overfishing and pollution regarding the impacts on fisheries, or impacts on hydroenergy production. The lack of interdisciplinary integrated studies limits our understanding of the complex interactions between natural and socio-economic systems. In addition, accelerating deforestation and land use changes, as well as changes in economic conditions, impose a continuous need for updated and available data sets that feed basic and applied studies.

To address the global challenge of food security and food quality, both important issues in CA and SA, investment in scientific agricultural knowledge need to be reinforced, mainly with regard to the integration of agriculture with organic production; and the integration of food and bioenergy production. It is necessary to consider ethical aspects when the competition for food and bioenergy production is analyzed to identify which activity is most important at a given location and time and whether bioenergy production would affect food security for a particular population.

Sea level rise and coastal erosion are also relevant issues; the lack of comparable measurements of sea level rise in CA and SA difficult the present and future integrated assessment of the impacts of SLR in the region. Of local and global importance will be improving our understanding of the physical oceanic processes, in particular of the Humboldt Current system flowing along the west coast of SA, being this one of the most fish productive system worldwide.

More information and research about the impacts of climate variability and change on human health is needed. One problem is the difficulty in accessing health data that are not always archived and ready to be used in integrated studies. Another need refers to building the necessary critical mass of transdisciplinary scientists to tackle the climate change-human health problems in the region. The prevailing gaps in scientific knowledge hamper the implementation of adaptation strategies, thus demanding a review of of research priorities towards better disease control. With the aim of further studying the health impacts of climate change and identifying resilience, mitigation and adaptation strategies, South-South cooperation and multidisciplinary research are considered to be relevant priorities.

In spite of the uncertainty that stems from global and regional climatic projections, the region needs to act in preparation of a possible increase in climate variability and in extremes. It is necessary to undertake research activities leading to public policies to assist societies in coping with current climate variability, as for example, risk assessment and risk management. Other important aspect since the AR4 is the improvement of climate modeling and the generation of high-resolution climate scenarios, that in countries in CA and SA resulted in the first integrated regional studies on impacts and vulnerability assessments of climate change focusing on sectors such as agriculture, energy and human health.

Research on adaptation and the scientific understanding of the various processes and determinants of adaptive capacity is also mandatory for the region, with particular emphasis on increasing adaptation capacity involving the traditional knowledge of ancestral cultures and how this knowledge is transmitted. Linking indigenous knowledge with scientific knowledge is important. Although some adaptation processes have been initiated in the recent years, there is no literature assessing their efficiency so far.

The research agenda needs to address vulnerability and foster adaptation in the region; encompassing an inclusion of the regions' researchers and focusing also on governance structures and action-oriented research that addresses resource distribution inequities.

Regional and international partnerships, and research networks and programs have allowed linking those programs with local strategies for adaptation and mitigation, also providing opportunities to address research gaps and exchange among researchers. Examples are the European Union funded projects CLARIS LPB in SESA and AMAZALERT in Amazonia. Other important initiatives come from the IAI, WHO, GEF, IDB, ECLAC (CEPAL), La Red and BirdLife International, among others. The same holds for local international networks such as ICLEI or C40, of which CA and SA cities form part. The weADAPT initiative is a good example on how CA and SA practitioners, researchers and policy makers can have access to credible, high quality information and to share experiences and lessons learnt in other regions of the world.

27.8. Conclusions

CA and SA harbor unique ecosystems and maximum biodiversity, with a variety of eco-climatic gradients rapidly changing from development initiatives. Agricultural and beef production as well as bioenergy crops are on the raise mostly by expanding agricultural frontiers. Poverty and inequality are decreasing, but at a low pace. Socioeconomic development shows a high level of heterogeneity and a very unequal income distribution, resulting in high vulnerability to climatic conditions. There is still a high and persistent level of poverty in most countries (45% for CA and 30% for SA for year 2010) in spite of the sustained economic growth observed in the last decade.

The IPCC AR4 and SREX reports contain ample evidence of increase in extreme climate events in CA and SA. During 2000-2010, 630 weather and climate extreme events lead to 16,000 fatalities, and 46.6 million people affected, with estimated losses of US$ 208 million. During 2000-2009, 39 hurricanes occurred in the CA-Caribbean basin compared to 15 and 9 in the decade of 1980 and 1990, respectively. In SESA, more frequent and intense rainfall extremes have favored an increase in the occurrence of flash floods and landslides. In Amazonia extreme droughts were reported in 2005 and 2010 and record floods were observed in 2009 and 2012. In 2012-2013 an extreme drought affected NEB.

While warming occurred in most of CA and SA, cooling was detected off the coast of Southern Peru and Chile. There is growing evidence that Andean glaciers (both tropical and extratropical) are retreating in response to warming trends. Increases in precipitation were registered in SESA, CA and the NAMS regions, while decreases were observed in Southern Chile, and a slight decrease in NEB after the middle 1970s. In CA it has been observed a gradual delay of the beginning of the rainfall season. SLR varied from 2 to 7 mm/yr between 1950 and 2008 in CA and SA, which is a reason for concern since a large proportion of the population of the region lives by the coast.

Land use and land cover change are key drivers of regional environmental change in SA and CA. Natural ecosystems are affected by climate variability/change and land use change. Deforestation, land degradation, and biodiversity loss are mainly attributed to increased extensive agriculture for traditional export activities and bioenergy crops. Agricultural expansion has affected fragile ecosystems, causing severe environmental degradation and reducing the environmental services provided by these ecosystems. Deforestation has intensified the process of land degradation, increasing the vulnerability of communities exposed floods, landslides and droughts. Plant species are rapidly declining in CA and SA, with a high percentage of rapidly declining amphibian species. However, the region has still large extensions of natural vegetation cover, with the Amazon being the main example. Ecosystem-based Adaptation practices, such as the establishment of protected areas and their effective management, conservation agreements, community management of natural areas, and payment for ecosystem services are increasingly more common across the region.

Figure 27-7 summarizes of some of the main observed trends in global environmental change drivers across different representative regions of CA and SA. Changes in climate and non-climate drivers have to be compounded with other socioeconomic related trends; such as the rapid urbanization process experienced the region

Some observed impacts on human and natural systems can be directly or indirectly attributed to human influences, and can be summarized as (Figure 27-8):

- Changes in river flow variability in the Amazon River during the last two decades, and robust positive trends in streamflow in sub-basins of the La Plata River basin, and increased dryness for most of the river basins in west coast of South America during the last 50 years.
- Reduction in tropical glaciers and icefields in tropical and extra tropical Andes over the second half of the 20th century that can be attributed to an increase in temperature
- Coastal erosion, bleaching of coral reefs in the coast of CA, and reduction in fisheries stock.
- Increase in agricultural yield in SESA, and shifting in agricultural zoning: significant expansion of agricultural areas, mainly in climatically marginal regions.
- Increase in frequency and extension of dengue fever, yellow fever and malaria.

However, for some impacts the number of concluding studies is still insufficient, leading to low levels of confidence for attribution to human influences.

[INSERT FIGURE 27-7 HERE
Figure 27-7: Summary of observed changes in climate and other environmental factors in representative regions of CA and SA. The boundaries of the regions in the map are conceptual (neither geographic nor political precision). Information and references to changes provided are presented in different sections of the chapter.]

[INSERT FIGURE 27-8 HERE
Figure 27-8: Observed impacts of climate variations and attribution of causes in CA and SA.]

By the end of the century, the CMIP5 derived projections for RCP8.5 projected: CA: mean annual warming of 2.5ºC (range: 1.5°C to 5.0 °C), mean rainfall reduction of 10% (range: -25% to +10%), and reduction in summertime precipitation; SA: mean warming of 4ºC (range: 2.0°C to 5.0 °C), with rainfall reduction up to 15% in tropical SA east of the Andes, and an increase of about 15-20% in SESA, and in other regions of the continent. Increases in warm days and nights are *very likely* to occur in most of SA. SESA: Increases in heavy precipitation. Northeastern South America: increases in dry spell. However, there is some degree of uncertainty on climate change projections for regions, particularly for rainfall in CA and tropical SA.

Current vulnerability in terms of water supply in the semi-arid zones and the tropical Andes is expected to increase even further due to climate change. This would be exacerbated by the expected glacier retreat, precipitation reduction and increase evapotranspiration demands as expected in the semi-arid regions of CA and SA. These scenarios would affect water supply for large cities, small communities, hydropower generation and food production. There is a need for re-assessing current practices to reduce the mismatch between water supply and demand in order to reduce future vulnerability, and to implement constitutional and legal reforms towards more efficient and effective water resources management.

SLR due to climate change and human activities on coastal and marine ecosystems pose threats to fish stocks, corals, mangroves, recreation and tourism, and diseases control in CA and SA. Coral reefs, mangroves, fisheries, and other benthic marine invertebrates that provide key ecosystem services, such as nutrient cycling, water quality regulation, and herbivory, are also threatened by climate change. It is possible that the Mesoamerican coral reef will collapse by mid-century (between 2050 and 2070), causing major economic and environmental losses. In the southwestern Atlantic coast, eastern Brazilian reefs might suffer a massive coral cover decline in the next 50 years. In the Rio de La Plata area extreme-flooding events may become more frequent since return periods are decreasing, and urban coastal areas in the eastern coast will be particularly affected. Beach erosion is expected to increase in southern Brazil and in scattered areas at the Pacific coast.

Urban populations in CA and SA face diverse social, political, economic and environmental risks in daily life, and climate change will add a new dimension to these risks. Since urban development remains fragile in many cases, with weak planning responses, climate change can compound existing challenges, e.g. water supply in cities from glacier, snowmelt and paramos related runoff in the Andes (Lima, La Paz/El Alto, Santiago de Chile, Bogota), flooding in several cities like São Paulo and Buenos, and health related challenges in many cities of the region.

Climate change will affect individual species and biotic interactions. Vertebrate fauna will suffer major species losses especially in high altitude areas; elevational specialists might be particularly vulnerable because of their small geographic ranges and high energetic requirements; freshwater fisheries can suffer alterations in physiology and life histories. In addition, modifications in phenology, structure of ecological networks, predator-preys interactions and non-trophic interactions among organisms will affect biotic interactions. Shifts in biotic interactions are expected to have negative consequences on biodiversity and ecosystem services in High Andean ecosystems. Although in the region biodiversity conservation is largely confined to protected areas it is expected that many species and vegetational types will lose representativeness inside such protected areas.

Changes in food production and food security are expected to have a great spatial variability, with a wide range of uncertainty mainly related to climate and crop models. In SESA average productivity could be sustained or increased until the mid-century, although interannual and decadal climate variability are likely to impose important damages. In other regions like NEB, CA, and some Andean countries agricultural productivity could decrease in the short-term, threatening the food security of the poorest population. The expansion of pastures and croplands is expected to continue in the coming years, particularly from an increasing global demand for food and biofuels. The great challenge for CA and SA will be to increase the food and bioenergy production and at the same time sustain the environmental quality in a scenario of climate change.

Renewable energy provides a great potential for adaptation and mitigation. Hydropower is currently the main source of RE in CA and SA, followed by biofuels. SESA is one of the main sources of production of the feedstocks for biofuels’ production, mainly with sugarcane and soybean, and future climate conditions may lead to an increase in productivity and production. Advances in second generation biofuels will be important as a measure of adaptation, as they have the potential to increase biofuels productivity. In spite of the large amount of arable land available, the expansion of biofuels might have some direct and indirect land use change effects, producing teleconnections that could lead to deforestation of native tropical forests and loss of employment in some countries. This might also affect food security.

Changes in weather and climatic patterns are negatively affecting human health in CA and SA, either by increasing morbidity, mortality, and disabilities, and through the emergence of diseases in previously non-endemic regions. Multiple factors increase the region’s vulnerability to climate change: precarious health systems, malnutrition, inadequate water and sanitation services, population growth, poor waste collection and treatment systems, air, soil and water pollution, food in poor regions, lack of social participation, and inadequate governance. Vulnerabilities vary with geography, age, gender, race, ethnicity, and socio-economic status, and are rising in large cities. Climate change and variability may exacerbate current and future risks to health.

Climate change will bring modifications to environmental conditions in space and time, and the frequency and intensity of weather and climate processes. In many CA and SA countries, a first step toward adaptation to climate change is to reduce the vulnerability to present climate, taking into account future potential impacts, particularly of weather and climate extremes. Long-term planning and the related human and financial resource needs may be seen as conflicting with present social deficit in the welfare of the CA and SA population. Such conditions weaken the importance of adaptation planning to climate change on the political agenda. Currently, there are few experiences on synergies between development, adaptation and mitigation planning, which can help local communities and governments to allocate available resources in the design of strategies to reduce vulnerability and to develop adaptation measures. Facing a new climate system and, in particular, the exacerbation of extreme events, will call for new ways to manage human and natural systems for achieving sustainable development.

[INSERT TABLE 27-8 HERE
Table 27-8: Key risks from climate change and the potential for risk reduction through mitigation and adaptation.]

Frequently Asked Questions

FAQ 27.1: What is the impact of glacier retreat on natural and human systems in the tropical Andes?
[to be inserted at end of Section 27.3.1.2]
The retreat of glaciers in the tropical Andes mountains, with some fluctuations, started after the Little Ice Age (16th to 19th centuries), but the rate of retreat (area reduction between 20-50%) has accelerated since the late 1970s. the changes in runoff from glacial retreat into the basins fed by such runoff vary depending on the size and phase of glacier retreat. In an early phase, runoff tends to increase due to accelerated melting, but after a peak, as the glacierized water reservoir gradually empties, runoff tends to decrease. This reduction in runoff is more evident during dry months when glacier melt is the major contribution to runoff (high confidence).

A reduction in runoff could endanger high Andean wetlands (bofedales) and intensify conflicts between different water users among the highly vulnerable populations in high elevation Andean tropical basins. Glacier retreat has also been associated with disasters such as glacial lake outburst floods that are a continuous threat in the region. Glacier retreat could also impact activities in high mountainous ecosystems such as alpine tourism, mountaineering and adventure tourism (high confidence).

FAQ 27.2: Can payment for ecosystem services (PES) be used as an effective way to help local communities adapt to climate change? *[to be inserted in Section 27.3.3.2]*
Ecosystems provide a wide range of basic services, like providing breathable air, drinkable water, and moderating flood risk (very high confidence). Assigning values to these services and designing conservation agreements based on these (broadly known as PES), can be an effective way to help local communities adapt to climate change. It can simultaneously help protect natural areas, and improve livelihoods and human well-being (medium confidence). However, during design and planning, a number of factors need to be taken into consideration at the local level in order to avoid potentially negative results. Problems can arise if a) the plan sets poor definitions about whether the program should focus just on actions to be taken or the end result of those actions, b) many perceive the initiative as commoditization of nature and its intangible values, c) the action is inefficient to reduce poverty, d) difficulties emerge in building trust between various stakeholders involved in agreements, and e) there are eventual gender or land tenure issues.

FAQ 27.3: Are there emerging and re emerging human diseases as a consequence of climate variability and change in the region? *[to be inserted in Section 27.3.7.2]*
Human health impacts have been exacerbated by variations and changes in climate extremes. Climate-related diseases have appeared in previously non-endemic regions (e.g. malaria in the Andes, dengue in CA and Southern SA) (*high confidence*). Climate variability and air pollution have also contributed to increase the incidence of respiratory and cardiovascular, vector- and water-borne and chronic kidney diseases, Hantaviruses and rotaviruses, pregnancy-related outcomes, and psychological trauma (*very high confidence*). Health vulnerabilities vary with geography, age, gender, ethnicity, and socio-economic status, and are rising in large cities. Without adaptation measures (e.g. extending basic public health services), climate change will exacerbate future health risks, owing to population growth rates and existing vulnerabilities in health, water, sanitation and waste collection systems, nutrition, pollution, and food production in poor regions (*medium confidence*).

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Table 27-1: Regional observed changes in temperature, precipitation and climate extremes in various sectors of CA and SA. Additional information on changes in observed extremes can be found in the IPCC SREX (Seneviratne *et al.*, 2012) and Chapter 2 IPCC WGI AR5 [2.4, 2.5, 2.6]

Region	Period	Observed changes
CA and Northern SA/Variable		
Precipitation in the NAMS (Englehart and Douglas, 2006)	1943-02	+0.94 mm/day/58 years
Rainfall onset in NAMS (Grantz *et al.*, 2007)	1948-04	-10 to -20 days/57 years
Summertime Precipitation in NAMS *(Anderson et al., 2010)*	1931-00	+17.6 mm century^{-1}
Rainfall extremes (P95) in NAMS (Cavazos *et al.*, 2008)	1961-98	+1.3% decade^{-1}
Cold days and nights in CA and Northern SA (Donat *et al.*, 2013)	1951-10	Cold days: -1 day decade^{-1}, Cold nights: -2 day decade^{-1}
Warm days and nigths in Northern SA ((Donat *et al.*, 2013)	1951-10	Warm days: +2 to +4 day decade^{-1}, warm nights: +1 to +3 day decade^{-1}
Heavy precipitation (R10) in Northern SA ((Donat *et al.*, 2013)	1951-10	+1 to +2 day decade^{-1},
Consecutive dry days (CDD) in Northern SA (Donat *et al.*, 2013)	1951-10	-2 day decade^{-1},
West Coast of SA		
SST and air temperatures off coast of Peru and Chile (15S-35S) (Falvey and Garreaud, 2009; Gutiérrez *et al.*, 2011a; Gutiérrez *et al.*, 2011b; Kosaka and Xie, 2013)	1960-10	-0.25 ºC /decade, -0.7 ºC /11 years for 2002-2012
Temperature, precipitation, cloud cover, and number of rainy days since the middle 1970´s off coast of Chile (18S-30S) (Schulz *et al.*, 2012)	1920-09	-1 ºC /40 years, -1.6 mm/40 years, -2 octas/40 years, and -0.3 days/40 years
Wet days until 1970, increase after that, reduction in the precipitation rate in southern Chile (37S-43S) (Quintana and Aceituno, 2012)	1900-07	-0.34% until 1970 and +0.37 after that, -0.12 %
Cold days and nights in all South American coast (Donat *et al.*, 2013)	1951-10	Cold days: -1 days decade^{-1}; cold nights: -2 days decade^{-1}
Warm nights in all South American coast, warm days in the northern coast of South America, warm days off the coast of Chile (Donat *et al.*, 2013)	1951-10	Warm night: -1 days decade^{-1}; warm days: +3 days decade^{-1} ; warm days: -1 days decade^{-1}
Warm nights in the coast of Chile (Dufek *et al.*, 2008)	1961-90	+5 to +9%/31 years
Dryness as estimated by the Palmer Drought Severity Index (PDSI) for most of the west coast of SA (Chile, Ecuador, Northern Chile) (Dai, 2011)	1950-08	-2 to -4 / 50 years
Heavy precipitation (R95) in northern and central Chile (Dufek *et al.*, 2008)	1961-90	-45 to -105 mm/31 years
Temperature and precipitation in southern Chile (Vicuña *et al.*, 2013)	1976-08	-45 to -105 mm/31 years
SESA		
Mean annual air temperature in southern Brazil (Sansigolo and Kayano, 2010)	1913-06	+0.5 to +0.6 ºC /decade, -31.4 - -47.6 mm/decade
Frequency of cold days and nights, warm days in Argentina and Uruguay (Rusticucci and Renom, 2008)	1935-02	-1.2%/decade, -1%/decade/, +0.2%/decade
Highest annual maximum temperature, lowest annual minimum air temperature in Argentina and Uruguay (Rusticucci and Tencer, 2008)	1956-03	+0.8 C/47 years, +0.6C/47 years
Warm nights in Argentina and Uruguay and southern Brazil (Rusticucci, 2012)	1960-09	10-20%/41 years
Warm nights in most of the region (Dufek *et al.*, 2008)	1961-90	+7 to +9%/31 years
Cold nights in most of the region (Dufek *et al.*, 2008)	1961-90	-5 to -9%/31 years
Cold days and nights in most of the region (Donat *et al.*, 2013)	1951-10	warm nights: +3 days decade^{-1}; warm days: +4 days decade^{-1}
Warm days and nights in most of the region (Donat *et al.*, 2013)	1951-10	Cold nights: -3 days decade^{-1}; cold days: -3 days decade^{-1}
Consecutive dry days (CDD) in the La Plata Basin countries (Argentina, Bolivia and Paraguay) and decrease of CDD in SA South of 30 S (Dufek *et al.*, 2008)	1961-90	+15 to +21 days/31 years, -21 to -27 days/31 years
Number of dry months during the warm season October-March in the Pampas region between	1904-00	From 2-3 months in 1904-1920 to 1-2 months from 1980-2000

25S-40S (Barrucand *et al.*, 2007)		
Moister conditions as estimated by the Palmer Drought Severity Index (PDSI) in most of SESA (Dai, 2011)	1950-08	0 to 4/50 years
Rainfall trends in the Parana River Basin (Dai *et al.*, 2009)	1948-08	+1.5 mm/day/50 years
Number of days with precipitation above 10 mm (R10) in most of the region (Donat *et al.*, 2013)	1951-10	+2 days/decade^{-1}
Heavy precipitation (R95) in most of the region (Donat *et al.*, 2013)	1951-10	+1% decade^{-1} and -4 days decade $^{--1}$
Heavy precipitation (R95) in most of the region (Dufek *et al.*, 2008)	1961-90	+45 to +135 mm/31 years
Heavy precipitation (R95) in the state of Sao Paulo (Dufek and Ambrizzi, 2008)	1950-99	+50 to +75 mm/40 years
Consecutive dry days (CDD) in the state of Sao Paulo (Dufek and Ambrizzi, 2008)	1950-90	-25 to-50 days/40 years
Lightning activity significantly with change in temperature in the state of Sao (Pinto and Pinto, 2008; Pinto *et al.*, 2013)	1951-06	+40% per 1ºC for daily and monthly time scales and approximately 30% per 1 ºC for decadal timescale
Number of days with rainfall above 20 mm in the city of Sao Paulo (Marengo *et al.*, 2013; Silva Dias *et al.*, 2012)	2005-11	+5 to +8 days/11 years
Excess rainfall events duration after 1950 (Krepper and Zucarelli, 2010)	1901-03	+ 21 months/53 years
Dry events and events of extreme dryness from 1972 to 1996 (Vargas *et al.*, 2011)	1972-96	-29 days/24 years
Number of dry days in Argentina (Rivera *et al.*, 2013)	1960-05	-2 to -4 days/decade
Extreme daily rainfall in La Plata Basin (Penalba and Robledo, 2010)	1950-00	+33 to +60% increase in Spring, Summer and Autumn, -10 to -25% decrease in winter
Frequency of heavy rainfall in Argentina, Southern Brazil and Uruguay (Re and Barros, 2009)	1959-02	+50 to +150 mm/43 years
Annual precipitation in the La Plata Basin (Doyle *et al.*, 2012)(Doyle and Barros, 2011) (Doyle and Barros, 2011)	1960-05	+5 mm/year
Andes		
Mean maximum temperature along the Andes, and increase in the number of frost days *(Marengo et al., 2011b)*	1921-10	+0.10 to +0.12 ºC /decade in 1921-2010, and +0.23-0.24 ºC /decade during 1976-2010; 8 days/decade during 196-2002
Air temperature and changes in precipitation Northern Andes (Colombia, Ecuador) (Villacís, 2008)	1961-90	+0.1 C to +0.22 ºC /decade, -4 to +4 %/decade years
Temperature and precipitation in northern and central Andes of Peru (SENAMHI, 2005; 2007; 2009a; 2009c; 2009d)	1963-06	+0.2 to +0.45 ºC /decade, -20 to -30%/40 years
Temperature and precipitation in the southern Andes of Peru (Marengo *et al.*, 2011b; SENAMHI, 2007; 2009a; 2009b; 2009c; 2009d)	1964-06	+0.2 to 0.6 ºC /decade, -11 to +2 mm/decade
Air temperature and rainfall over Argentinean and Chilean Andes and Patagonia (Falvey and Garreaud, 2009; Masiokas *et al.*, 2008)	1950-90	+0.2 to 0.45 ºC /decade, -10 to -12%/decade
Number of days with rainfall above 10 mm (R10) (Donat *et al.*, 2013)	1950-10	-3 days decade^{-1}
Dryness in the Andes between 35.65 S-39.9 S using the PDSI (Christie *et al.*, 2011)	1950-03	-7 PDSI/53 years
Rainfall decrease in the Mantaro Valley, central Andes of Peru (SENAMHI, 2009c)	1970-05	-44 mm/decade
Air temperature in Colombian Andes (Poveda and Pineda, 2009)	1959-07	+1 ºC /20 years
Amazon region		
Decadal variability of rainfall in northern and southern Amazonia *(Marengo et al., 2009; Satyamurty et al., 2010)*	1920-08	-3 STD/30 years in northern Amazonia and +4 STD/30 years in southern Amazonia since the middle 1970's
Rainfall in all the region (Espinoza *et al.*, 2009a; 2009b)	1975-03	-0.32 %/28 years
Onset of the rainy season in southern Amazonia (Butt *et al.*, 2011; Marengo *et al.*, 2011b)	1950-10	-1 month since 1976 to 2010

Precipitation in the SAMS core region (Wang *et al.*, 2012)	1979-08	+ 2 mm/day decade^{-1}
Onset becomes steadily earlier from 1948 to early 1970s, demise dates have remained later, and SAMS duration was longer after 1972 (Carvalho *et al.*, 2011)	1948-08	SAMS from 170 days (1948–1972) to 195 days (1972–1982).
Spatially varying trends of heavy precipitation (R95), increase in many areas and insufficient evidence in others (Marengo *et al.*, 2009)	1961-90	+100 mm/31 years in western and extreme eastern Amazonia,
Spatially varying trends in dry spells in (CDD), increase in many areas and decrease in others (Marengo *et al.*, 2009; Marengo *et al.*, 2010)	1961-90	+15 mm/31 years in western Amazonia, -20 mm/ in southern Amazonia
Rainfall in most of Amazonia and in western Amazonia (Dai *et al.*, 2009; Dai, 2011)	1948-08	+1 mm/day/50 years, -1.5 mm/day/50 years
Dryness as estimated by the Palmer Drought Severity Index PDI in southern Amazonia and moister conditions in western Amazonia (Dai, 2011)	1950-08	-2 to -4/50 years, +2 to +4 /50 years
Seasonal mean convection and cloudiness (Arias *et al.*, 2011)	1984-07	+30 W/m2/23 years, -8 %/23 years
Onset of rainy season in southern Amazonia due to land use change (Butt *et al.*, 2011)	1970-10	-0.6 days/30 years
Precipitation in the region (Gloor *et al.*, 2013)	1990-10	-20 mm/21 years
Northeast Brazil		
Rainfall trends interior Northeast Brazil and in northern Northeast Brazil (Dai *et al.*, 2009; Dai, 2011)	1948-08	-0.3 mm/day/50 years, +1.5 mm/day/50 years
Heavy precipitation (R95) in some areas, and in southern Northeast Brazil (Silva and Azevedo, 2008)	1970-06	-2 mm/24 years to + 6 mm/24 years,
Consecutive dry days CDD in most of southern Northeast Brazil (Silva and Azevedo, 2008)	1970-06	-0.99 days/24 years
Total annual precipitation in northern Northeast Brazil (Santos and Brito, 2007)	1970-06	+1 to +4 mm/year/24 years
Spatially varying trends in heavy precipitation (R95) in northern Northeast Brazil (Santos and Brito, 2007)	1970-06	-0.1 to +5 mm/yeas/24 years
Spatially varying trends in heavy precipitation (R95) and consecutive dry days (CDD) in northern Northeast Brazil (Santos *et al.*, 2009)	1935-06	-0.4 to +2.5 mm/year/69 years, -1.5 to +1.5 days/year/69 years,
Dryness in Southern Northeast Brazil as estimated by the PDSI, and northern Northeast Brazil (Dai, 2011)	1950-08	-2 to -4/50 years, 0 to +1/50 years

Table 27-2: Regional projected changes in temperature, precipitation, and climate extremes in different sectors of CA and SA. Various studies used A2 and B2 scenarios from CMIP3 and various RCPs scenarios for CMIP5, and different time slices from 2010 to 2100. In order to make results comparable, the CMIP3 and CMIP5 at the time slice ending in 2100 are included. Additional information on changes in projected extremes can be found in the IPCC SREX (see IPCC, 2012), and Chapters 9 and 14 from IPCC WG1AR5 [9.5, 9.6 and 14.2, 14.7]

Region	Models and scenarios	Projected changes
CA and Northern SA		
Leaf Area Index (LAI), evapotranspiration by 2070-2099 in CA (Imbach *et al.*, 2012)	23 CMIP3 models, A2	Evapotranspiration: +20%; LAI:-20%+0.94 mm/day/58 years
Air temperature by 2075 and 2100 in CA (Aguilar *et al.*, 2009)	9 CMIP3 models, A2	+2.2 C by 2075; +3.3 C by 2100
Rainfall in CA and Venezuela, air temperature in the region (Hall *et al.*, 2013; Kitoh *et al.*, 2011)	20 km MRI-AGCM3.1S model, A1B	Rainfall decrease/increase of about -10%/+10%, by 2079. Temperature increases of about +2.5-+3.5 ºC by 2079
Precipitation and evaporation in most of the region. Soil moisture in most land areas in all seasons (Nakaegawa *et al.*, 2013b)	20 km MRI-AGCM3.1S model, A1B	Precipitation decrease of about -5 mm/day, evaporation increase of about +3 to +5 mm/day; soil moisture to decrease by -5 mm/day.
Rainfall in Nicaragua, Honduras, Northern Colombia and Northern Venezuela, rainfall in Costa Rica and Panama. Temperature in all region by 2071-2100 (Campbell *et al.*, 2011)	PRECIS forced by the HadAM3, A2	Rainfall: -25 to -50%, and +25 to +50%. Temperature: +3 to +6 C
Precipitation and temperature in northern SA, decrease in interior Venezuela, temperature increases by 2071-2100 (Marengo *et al.*, 2011a)	Eta forced with HadCM3, A1B	Increases by +30 to 50%, and reductions between -10 to -20%; temperature: +4 to +5 C
Precipitation and temperature by 2100 in CA (Karmalkar *et al.*, 2011)	PRECIS forced with HadAM3, A2	Precipitation: -24 to -48%; temperature: +4 to +5 C
Warm nights, consecutive dry days and heavy precipitation in Venezuela, by 2100 (Marengo *et al.*, 2009; 2010)	PRECIS forced with HadAM3, A2	Increase by +12 to +18%, +15 to +25 days and reduction of 75 to 105 days
Air temperature and precipitation in CA by 2100 (Giorgi and Diffenbaugh, 2008)	23 CMIP3 models, A1B	Increase by +3 to +5 ºC; reduction by -10 to -30%
Consecutive dry days and in heavy precipitation by 2099 (Kamiguchi *et al.*, 2006)	20 km MRI-AGCM3.1S model, A1B	Increase by +5 days, and between +2 to +8 %
Rainfall over Panama by 2099 (Fábrega *et al.*, 2013)	20 km MRI-AGCM3.1S model, A1B	Increase by +5 %
West Coast of SA		
Precipitation, runoff and temperature at the Limari river basin in semi-arid Chile by 2100 (Vicuña *et al.*, 2011)	PRECIS forced with HadAM3, A2	Precipitation: -15 % to -25%; runoff: -6 to -27%; temperature: + 3 to +4 ºC
Ai temperature and surface winds in west coast of SA (Chile) by 2100 (Garreaud and Falvey, 2009)	15 CMIP3 models, PRECIS forced with HadAM3, A2	Temperature: +1 ºC; coastal winds: +1.5 m/sec
Precipitation in the bands 5N-10S, and 25S-30S, and 10S-25S and 30S-50S; temperature increase between by 2100 (Marengo *et al.*, 2011a)	Eta model forced with HadCM3, A1B	Increases of 30-40%; increases of 3 to 5 ºC
Warm nights, consecutive dry days, and heavy precipitation in 5N-5S by 2100 (Marengo *et al.*, 2009; 2010)	PRECIS forced with HadAM3, A2	Increase of +3 to +18%, reduction of -5 to – 8 days, increase by +75 to +105 days
Air temperature, increase of precipitation between 0 and 10S, and between 20 and 40S by 2100 (Giorgi and Diffenbaugh, 2008)	23 CMIP3 models, A1B	Increase of +2 to +3 ºC; increase by 10%, reduction by -10 to -30%

Consecutive dry days between 5 N and 10 S and south of 30S, heavy precipitation between 5S-20S and south of 20S by 2099 (Kamiguchi *et al.*, 2006)	20 km MRI-AGCM3.1S model, A1B	Increase by 10 days and between +2 to +10%
Precipitation between 15 and 35 S; and south of 40S; temperature by 2100 (Nuñez *et al.*, 2009)	MM5 forced with HadAM3, A2	Precipitation: -2 mm/day; +2 mm/day; temperature: +2.5 ºC
Precipitation in Panama and Venezuela, heavy precipitation in Panama and in Venezuela, consecutive dry days over Panama and Colombia by 2099 (Sörensson *et al.*, 2010)	RCA forced with ECHAM5-MPI OM model, A1B	Precipitation:-1 to -3 mm/day,
SESA		
Precipitation and runoff, an in air temperature by 2100 (Marengo *et al.*, 2011a)	Eta forced with HadCM3, A1B	Precipitation: + 20 to +30%; Runoff: +10 to +20%; air temperature: +2.5 to +3.5 ºC
Precipitation and temperature in the La Plata basin by 2050 (Cabré *et al.*, 2010)	MM5 forced with HadAM3, A2	Precipitation: +0.5 to 1.5 mm/day; temperature: +1.5 ºC to 2.5 ºC.
Warm nights, consecutive dry days and heavy precipitation by 2100 (Menendez and Carril, 2010)	7 CMIP3 models, A1B	Warm nights: +10 to +30%; Consecutive dry days: +1 to +5 days; Heavy precipitation: +3 to +9 %.
Precipitation during summer and spring, and in fall and winter by 2100 (Seth *et al.*, 2010)	9 CMIP3 models, A2	Precipitation: + 0.4 to +0.6 mm/day, -0.02 to -0.04 mm/day
Warm nights, consecutive dry days and heavy precipitation by 2100 (Marengo *et al.*, 2009; 2010)	PRECIS forced with HadAM3, A2	Increase of +6 to +12%, +5 to +20 days, +75 to +105 days
Air temperature and rainfall by 2100 (Giorgi and Diffenbaugh, 2008)	23 CMIP3 models, A1B	Increase by +2 to +4 ºC, increase by +20 to +30 %
Consecutive dry days and in heavy precipitation by 2099 (Kamiguchi *et al.*, 2006)	20 km MRI-AGCM3.1S model, A1B	Increase by +5 to +10% and by +2 to +8 %
Precipitation in north central Argentina, decrease in southern Brazil, increase of air temperature by 2100 (Nuñez *et al.*, 2009)	MM5 forced with HadAM3, A2	Increase of +0.5 to +1 mm/day, reduction of -0.5 mm/day, increase of +3 to +4.5 ºC
Drought frequency, intensity and duration in South America South of 20 S for 2011-40 relative to 1979-2008 (Penalba and Rivera, 2013)	15 CMIP5 models, RCP 4.5 and 8.5	Frequency increase between 10-20%, increase in severity between 5-15% and reduction in duration between 10 and 30%
Precipitation, heavy precipitation, reduction of consecutive dry days in the eastern part of the region, increase in the western part of the region by 2099 (Sörensson *et al.*, 2010)	RCA forced with the ECHAM5 mode, A1B	Increase of +2 mm/day, of +5 to +15 mm, reduction of -10 days and increase of +5 days
Precipitation in SESA by 2100 (Sörensson *et al.*, 2010)	9 CMIP3 models, A1B	Increase between +0.3 to +0.5 mm/day
Andes		
Precipitation and temperature, increase by 2100 in the Altiplano (Minvielle and Garreaud, 2011)	11 CMP3 models, A2	Precipitation: -10 to -30 %; temperature:>3 ºC
Precipitation at 5N-5S, and 30S-45 S, at 5-25 S; temperature by 2100 (Marengo *et al.*, 2011a)	Eta forced with HadCM3, A1B	Increase between +10 and +30%, decrease by -20 to -30%, increase of +3.5 to +4.5 ºC
Warm nights, heavy precipitation and consecutive dry days south of 15 S by 2100 (Marengo *et al.*, 2009)	PRECIS forced with HadAM3, A2	Increase by +3 to +18%, reduction by -10 to -20 days, and -75 to -105 days
Air temperature, rainfall between 0-10S and reduction between 10-40 S (Giorgi and Diffenbaugh, 2008)	23 CMIP3 models, A1B	Increase by +3 to +4 ºC, increase by 10% and reduction by -10%
Consecutive dry days and increase of heavy precipitation by 2099 (Kamiguchi *et al.*, 2006)	20 km MRI-AGCM3.1S model, A1B	Reduction by -5 days, increase by +2 to +4 % south of 20S
Precipitation, heavy precipitation, and consecutive dry days by 2070-99 (Sörensson *et al.*, 2010)	RCA forced with ECHAM5, A1B	Increases of +1 to +3 mm/day, +5 mm and of +5 to +10 days

Summer precipitation and surface air temperature in the Altiplano region by 2099 (Minvielle and Garreaud, 2011)	9 CMIP3 models, A2	Reduction in precipitation between -10% and -30%, an temperature increase of +3 ºC
Temperature and rainfall in lowland Bolivia inn 2070-2999 (Seiler *et al.*, 2013)	5 CMIP3 models (A1B) ad 5 CMIP5 models (RCP4.5, 8.5)	Increase from 2.5 ºC to 5 ºC, reduction of 9% annual precipitation
Precipitation in the dry season, temperature and evapotranspiration 2079-98 (Guimberteau *et al.*, 2013)	CMIP3 models, A1B	-1.1 mm; +2 ºC; +7%
Amazon region		
Rainfall in central and eastern Amazonia, and in western Amazonia, air temperature in all region by 2100 (Marengo *et al.*, 2011a)	Eta forced with HadCM3, A1B	Precipitation: -20 to -30%, +20 to +30%; temperature: +5 to +7 ºC
Intensity of the South Atlantic Convergence Zone and in rainfall in the South American monsoon region, 2081-2100 (Bombardi and Carvalho, 2009)	10 CMIP3 models, A1B	Precipitation: -100 to -200 mm/20 years
Precipitation in western Amazonia during summer and in winter in Amazonia by 2100 (Mendes and Marengo, 2010)	5 CMIP3 models, A2 and ANN	+1.6% in summer and -1.5% in winter
Number of South American Low Level Jet east of the Andes events (SALLJ), and in the moisture transport from Amazonia to the La Plata basin by 2090 (Soares and Marengo, 2009)	PRECIS forced by HadAM3, A2	+50 events of SALLJ during summer, increase in moisture transport by 50%
Precipitation in the South American monsoon during summer and spring, and during fall and winter by 2100 (Seth *et al.*, 2010)	9 CMIP3 models, A2	Increase of +0.15 to +0.4 mm/, reductions of -0.10 to -0.26 mm/day
Warm nights, consecutive dry days in eastern Amazonia, heavy precipitation in western Amazonia and in eastern Amazonia by 2100 (Marengo *et al.*, 2009)	PRECIS forced with HadAM3, A2	Increase of +12 to +15%, by 25-30 days in eastern Amazonia, increase in western Amazonia by 75-105 days and reduction by -15 to 75 days in eastern Amazonia
Increase in air temperature, rainfall increase in western Amazonia and decrease in eastern Amazonia by 2100 (Giorgi and Diffenbaugh, 2008)	CMIP3 models, A1B	Increase of +4 to +6 ºC, increase of +10% and decrease between -10 to -30%
Reduction of consecutive dry days and increase in heavy precipitation by 2099 (Kamiguchi *et al.*, 2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of -5 to -10 days, increase by +2 to +8 %
Onset and late demise of the rainy season in SAMS by 2040-2050 relative to 1951-80 (Jones and Carvalho, 2013)	10 CMIP5 models, RCP8.5	Onset 14 days earlier than present, demise 17 days later than present
Precipitation in SAMS during the monsoon wet season in 2071-2100 relative to 1951-80 (Jones and Carvalho, 2013)	10 CMIP5 models, RCP8.5	Increase of 300 mm during the wet season
Precipitation in western Amazonia, heavy precipitation in northern Amazonia and in southern Amazonia, consecutive dry days in western Amazonia and increase by 2099 (Sörensson *et al.*, 2010)	RCA forced with the ECHAM5 model, A1B	Increase of +1 to +3 mm/day, reduction of -1 to -3 mm, increase of +5 to +10 mm, decrease of -5 to -10 days, increase by +20 to +30 days
Northeast Brazil		
Rainfall and temperature in the entire region by 2100 (Marengo *et al.*, 2011a)	Eta forced with HadCM3, A1B	Precipitation: -20 to -20%; temperature: +3 to +4 ºC
Warm nights, consecutive dry days, heavy precipitation by 2100 (Marengo *et al.*, 2009)	PRECIS forced with HadAM3, A2	Increase by +18 to +24%, by +25 to +30 days and -15 to –75 days
Air temperature and precipitation by 2100 (Giorgi and Diffenbaugh, 2008)	23 CMIP3 models, A1B	Increase of +2 to +4 ºC, reduction -10 to -30%
Consecutive dry days and heavy precipitation by 2099 (Kamiguchi *et al.*, 2006)	20 km MRI-AGCM3.1S model, A1B	Reduction of -5 to -10% and increase of +2 to +6 %
Precipitation, heavy precipitation and consecutive dry days by 2099 (Sörensson *et al.*, 2010)	RCA forced with ECHAM5 model, A1B	Increase of +1 to +2 mm/day, increase by +5 to +10 mm, and increase by +10 to +30 days

Table 27-3: Observed trends related to Andean cryosphere.
a) Andean tropical glacier trends

Country *Documented massifs (latitude)*	**Significant changes recorded** **(Variable code number[a]) Value of trend (period of observed trend)**	**References**
Venezuela *Cordillera de Merida (10°N)*	(1) +300/+500m between Little Ice Age (LIA) maximum and today. (5) Accelerated melting since 1972. Risk of disappearing completely as ELA close to the highest peak (Pico Bolívar, 4979 m)	Polissar *et al.* (2006); Morris *et al.* (2006)
Colombia *Parque Los Nevados (4°50N)* *Sierra Nevada del Cocuy (6°30N)* *Sierra Nevada de Santa Marta (10°40N)*	(3) LIA maximum between AD 1600 and 1850 (3) Many small/low elevation (<5000 m a.s.l.) glaciers have disappeared (3) -60/-84% (1850-2000); -50% (last 50 yrs); -10/-50% (past 15yrs); Retreat 3.0km²/yr (since 2000)	Ruiz *et al.* (2008); Ceballos *et al.* (2006); Poveda and Pineda (2009); IDEAM (2012); Rabatel *et al.* (2013)
Ecuador *Antisana (0°28S)* *Chimborazo and Carihuayrazo (1°S)*	(1) +300 between the middle 18th (maximum LIA) and the last decades of the 20th C; ~+200m (20th C) (3) ~-45% (1976-2006). Glaciers below 5300m in process of extinction	Francou *et al.* (2007); Vuille *et al.* (2008); Jomelli *et al.* (2009); Cáceres (2010); Rabatel *et al.* (2013)
Peru *Cordillera Blanca (9°S)*	(1) ~+100m (between LIA maximum and beginning 20th C); +150m (20th C) (3) -12/-17% (18th C); -17/-20% (19th C); -20/-35% (1960s-2000s); -26% (1962 and 2000) (4) -8 m decade^{-1} since 1970 (Yanamarey glacier) (8) +1.6% (± 1.1) (glaciers with >20 percent glacier area); (7) Seven out of nine watersheds decreasing dry-season discharge	Raup *et al.* (2007); Jomelli *et al.* (2009); UGHR (2010); Bury *et al.* (2011); Mark *et al.* (2010); Baraer *et al.* (2012); Rabatel *et al.* (2013)
Coropuna volcano (15°33S)	(3) -26% (1962-2000)	Racoviteanu *et al.* (2007)
Cordillera Vilcanota (13°55S)	(3) 10 times faster in 1991-2005 compared to 1963-2005 (2-4) about -30% of area and about -45% of volume since 1985	Thompson *et al.* (2006; 2011) Salzmann *et al.* (2013)
Bolivia *Cordillera Real and Cordillera Quimza Cruz (16°S)*	(1) +300 m (between LIA maximum and late 20th C); +180/+200m (20th C) (3) -48% (1976-2006) in the Cordillera Real; Chacaltaya vanished in 2010. (5) Zongo glacier have lost a mean of 0.4m w.e./yr in the 1991-2011 period; glaciers in the Cordillera Real lost -43% of their volume from 1963 to 2006 (maximum from 1976 to 2006). (2) +1.1±0.2°C over the 20th century at ~6340 m a.s.l.	Rabatel *et al.* (2006; 2008); Francou *et al.* (2007); Vuille *et al.* (2008); Jomelli *et al.* (2011); Soruco *et al.* (2009); Gilbert *et al.* (2010); Rabatel *et al.* (2013)
Sur Lipez, Caquella, 21°30S	(7) Evidence of recent degradation of Caquella rock glacier (South Bolivian Altiplano)	Francou *et al.* (1999)

b) Extra tropical Andean cryosphere (glaciers, snowpack, runoff effects) trends.

Region *Documented massifs/latitude*	**Significant changes recorded and reference** **(Variable code number[a]) Value of trend (period of observed trend)**	**References**
Chile, Argentina and Bolivia and Argentinean Patagonia	(6) No significant trend.	Foster *et al.* (2009)
Dessert Andes (17°S-31°S)		

Huasco basin glaciers (29°S)	(5) –0.84 m w.e./yr (2003/2004–2007/2008)	Nicholson *et al.* (2009); Rabatel *et al.* (2011); Gascoin *et al.* (2011)
Central Andes (31°S-36°S)		
Piloto/Las Cuevas (32°S)	(5) - 10.50 m w.e. (last 24 yrs)	Leiva *et al.* (2007)
Aconcagua basin glaciers (33°S)	(3) -20% (last 48 years); (2) -14% (1955-2006). (8) Significant decrease in Aconcagua basin streamflow	Nicholson *et al.* (2009); Bown *et al.* (2008); Pellicciotti *et al.* (2007)
Central Andes glaciers (33–36 °S)	(3) -3% (since 1955); (4) –50/–9my^{-1} (during 20th C); (5) -0.76/-0.56 m/y (during 20th C)	Le Quesne *et al.* (2009)
ELA across central Andes	(1) +122 ± 8 m (winter) and 200 ± 6 m (summer) (1975 and 2001)	Carrasco *et al.* (2005)
Snowpack (30 °S -37°S)	(6) Positive, though nonsignificant, linear trend (1951–2005); (8) Mendoza river streamflow. Possible link to rising temperatures and snowpack/glacier effects. Not conclusive; (8) Increase in high and low flows possibly associated with increase in temperature and effects on snowpack	Masiokas *et al.* (2006) Vich *et al.* (2007) Vicuña *et al.* (2013)
Morenas coloradas rock glacier (32-33°S)	(7) Significant change in active layer possibly associated with warming processes.	Trombotto and Borzotta (2009)
Cryosphere in the Andes of Santiago (33.5°S.)	(5) Expansion of thermokarst depressions	Bodin *et al.* (2010)
Basins (28-47 °S)	(8) Not significant increase in February runoff possible increase of glacier melt (1950–2007).	Casassa *et al.* (2009)
Basins (30-40 °S)	(8) Significant negative timing trend (CT date shifting towards earlier in the year) for 23 out of the 40 analyzed series.	Cortés *et al.* (2011)
Patagonian Andes (36°S-55°S)		
Streamflow from basins (28-47 °S)	(8) Not significant increase in February run-off trends that might suggest an increase of glacier melt in the Andes (1950–2007).	Casassa *et al.* (2009)
NW Patagonia (38°-45°S)	(4) Recession of 6 glaciers based on areal photograph analysis.	Masiokas *et al.* (2008)
Casa Pangue glacier (41°S)	(5) –2.3±0.6 m/y (1961-1998); (4) –3.6±0.6 m/y (1981-1998)	Bown and Rivera (2007)
Manso Glacier (41°S)	(8) Reduction in discharge associated with reduction in melt and precipitation	Pasquini *et al.* (2013)
North Patagonian Icefield (NPI)	(8) Glacial lake outburst flood (GLOF) possible response to retreat of Calafate glacier (20th C)	Harrison *et al.* (2006)
Southern Patagonia Icefield (SPI)	(4) Larger retreating rates observed on the west side coinciding with lower elevations of the ELAs	Barcaza *et al.* (2009)
NPI, SPI, Cordillera Darwin Icefield	(4) 5.7-12.2 km (1945-2005)	Lopez *et al.* (2010)
Gran Campo Nevado (GCN) (53 °S)	(5) Slow retreat from Late LIA. Acceleration started 60 years ago	Strelin and Iturraspe (2007)
	(5) -2.8% of glacier length per decade (1942-2002); (3) -2.4% per decade (1942-2002)	Schneider *et al.* (2007)
Cordón Martial glaciers (54 °S)	(5) -1.6 m/year or -27.9 ± 11 km3/year (2002-2006)	Chen *et al.* (2007)
Proglacial lakes (40-50°S)	(8) Summertime negative trend on lakes indicating that melt water is decreasing	Pasquini *et al.* (2008)

Notes: [a] Variable coding: (1) Increase in Equilibrium line altitude (ELA); (2) Atmospheric warming revealed by englacial temperature measured at high elevation; (3) Area reduction; (4) Frontal retreat; (5) Volume (water equivalent) reduction; (6) Snow cover; (7) Rock glaciers; (8) Runoff change;

Table 27-4: Synthesis of projected climate change impacts on hydrologic related variables in CA and SA basins and major glaciers.

Notes: [a] Variable coding: (1) Runoff/Discharge; (2) Demand; (3) Recharge; (4) Glaciar change; (5) Unmet demand/water availability

Region *Basins studied*	**Hydrologic Variable Projected Change**[a]	**Period**	**GCM (GHG Scenarios)**	**References**
La Plata Basin and SESA				
Paraná	(1): + 4.9% (not robust)	2081-2100	CMIP3 (A1B)	Nohara *et al.* (2006)
	(1): +10 to +20%	2100	Eta-HadCM3 (A1B)	Marengo *et al.* (2011a)
	(1) + 18.4% (significant)	2075-2100	CMIP3 models (A1B)	Nakaegawa *et al.* (2013a)
Grande (Parana)	(1) +20/-20%	Different periods	7 CMIP3 models	Todd *et al.* (2011) ; Gosling *et al.* (2011); Nóbrega *et al.* (2011)
Itaipu (Parana)	(1) 2010–2040: Left bank: –5/ –15%; Right bank: +30%; (1) 2070-2100: 0 to –30%	2010–2040 and 2070-2100	CCCMA-CGCM2 (A2)	Rivarola *et al.* (2011)
Concordia	(1): -40%	2070-2100	HadRM3P	Perazzoli *et al.* (2013)
Carcarañá	(2) Increase (3) Slight reduction	2010-2030	HadCM3 (A2)	Venencio and García (2011)
Amazon Basin				
Peruvian Amazon	(1) Some basins increased, some reduced	Three time slices	BCM2, CSMK3 and MIHR (A1B, B1)	Lavado *et al.* (2011)
Alto Beni-Bolivia	(1) Increase and reduction. (3) Always reduction (5) Increase in water stress	2070-2100	CMIP3 models (A1B)	Fry *et al.* (2012)
Ecuador - Tomebamba/Paute	(1) Some scenarios increase some reduction	2070-2100	CMIP3 models (A1B)	Buytaert *et al.* (2011)
Amazon at Obidos	(1) + 5.4% (not robust)	2081-2100	CMIP3 models (A1B)	Nohara *et al.* (2006)
	(1) +6%	2000-2100	ECBilt-CLIO-VECODE (A2)	Aerts *et al.* (2006)
	(1) + 3.7% (significant)	2075-2100	CMIP3 models (A1B)	Nakaegawa *et al.* (2013a)
	(1) No change in high flow. Reduction in low flow	2046–65/2079–98	8 AR4 GCMs (B1, A1B and A2)	Guimberteau *et al.* (2013)
Amazon -Orinoco	(1) -20%	2050s	HadCM3 (A2)	Palmer *et al.*(2008)
Brazil	(1) Consistent decrease	2050s	HadCM3 (A1b) and CMIP3	Arnel and Gosling (2013)
Tropical Andes				
Colombian glaciers	(4) Disappearance by 2020s	linear extrapolation		Poveda and Pineda (2009)
Cordillera Blanca glaciarized basins	(1) Increase for next 20-50 years, reduction afterwards	2005-2020	Temperature output only (B2)	Chevallier *et al.* (2011)
	(4) 2050: area -38/-60%. Increased seasonality (4) 2080: area -49/-75%. Increased seasonality	2050 (climatology)	Not specified (A1, A2, B1, B2)	Juen *et al.* (2007)
	(4) Increased seasonality	2030	16 CMIP3 (A1B, B1)	Condom *et al.* (2012)
Basins providing water to cities of Bogota, Quito, Lima and La Paz	(5) Inner tropics: Only small change. Increase in precipitation an increase in ET. (5) Outer tropics: Severe reductions. Decrease in precipitation and increase in ET	2010-2039 and 2040-2069	19 CMIP3 models (A1B, A2)	Buytaert and De Bièvre (2012)

Central Andes				
Limari	(1) -20/-40%.	2070-2100	HadCM3 (A2, B2)	Vicuña *et al.* (2011)
	(1) -20% (1) -30/-40%; (1) Change in seasonality	2010-2040 2070-2100	15 CMIP3 (A1B, B2, B1)	Vicuña *et al.* (2012)
Maipo	(1) -30% (5) Unmet demand up to 50%	Three 30-year periods 2070-2090	HadCM3 (A2, B2)	Melo *et al.* (2010); ECLAC (2009); Meza *et al.* (2012)
Mataquito	(1) Reduction in average and low flows. Increase in high flows	Three 30-year periods	CMIP3 (A2, B1) and CMIP5 (RCP4.5 and 8.5)	Demaria *et al.* (2013)
Maule, Laja	(1) -30%	Three 30-year periods	HadCM3 (A2, B2)	McPhee *et al.* (2010); ECLAC (2009)
Bio Bio	(1) (-81%/+ 7%)	2070-2100	8 GCMs (6 SRES)	Stehr *et al.* (2010)
Limay	(1) -10/-20%.	2080s (climatology)	HadCM2 (NS)	Seoane and López (2007)
North East Brazil (NEB)				
Brazilian Federal States of Ceara´ and Piauı´	(1) No significant change up to 2025. (1) After 2025: strong reduction with ECHAM4; slight increase with HadCM2.	2000-2100	HadCM2, ECHAM4 (NS)	Krol *et al.* (2006); Krol and Bronstert (2007)
Paracatu (Sao Francisco)	(1) A2: +31/+131%; (1) B2: no significant change	2000-2100	HadCM3 (A2, B2)	De Mello *et al.* (2008)
Jaguaribe	(2) Demand: +33/+44% (2) Irrigation water needs: +8/+9%	2040 2025-2055	HadCM3 (A2, B2) HadCM3 (B2)	Gondim *et al.* (2012; 2008)(2008)
Parnaiba	(1) -80%	2050s	HadCM3 (A2)	Palmer *et al.* (2008)
Mimoso catchment	(1) Dry scenario: -25/-75%; (2) Wet scenario: +40/+140%; (3) Similar	2010–2039, 2040–2069, and 2070–2099	CSMK3 and HadCM3 (A2, B1)	Montenegro and Ragab (2010)
Tapacurá River	(1) B1: -4.89%, -14.28%, -20.58% (1) A2: +25.25%, 39.48% and 21.95%	Three 30-year periods	CSMK3 and MPEH5 (A2, B1)	Montenegro and Ragab (2012)
Benguê catchment	(1) -15% reservoir yield	Sensitivity scenario in 2100 selected from TAR and AR4 GCMs with good skill. + 15% PET, -10% Precip		Krol *et al.* (2011)
Aquifer in NEB	(3) Reduction	2040-2070	HadCM3, ECHAM4 (A2,B2)	Hirata and Conicelli (2012)
North SA				
Essequibo Guyana	(1) -50%	2050s	HadCM3 (A2)	Palmer *et al.* (2008)
Magdalena (Colombia)	(1) Not significant changes in near future. End of 21st changes in seasonality.	2015–2035 and 2075–2099	CMIP3 multi-model ensemble (A1B)	Nakaegawa and Vergara (2010)
Sinu (Colombia)	(1) -2/-35%	2010-2039	CCSRNIES, CSIROMK2B, CGCM2, HadCM3 (A2)	Ospina-Noreña *et al.*(2009a; 2009b)
CA				
Lempa	(1) B1: -13%; (1) A2: -24%	2070-2100	CMIP3 (A2, B1)	Maurer *et al.* (2009)
Grande de Matagalpa	(1) -70%	2050s	HadCM3 (A2)	Palmer *et al.* (2008)
Mesoamerica	(1) Decrease across the region	2070-2100	CMIP3 (A2, A1B, B1)	Imbach *et al.* (2012)
	(1) Consistent decrease	2050s	HadCM3 and CMIP3 (A1b)	Arnel and Gosling (2013)
	(1) Consistent reduction in Northern CA	2050–2099	30 GMCs (A1b)	Hidalgo *et al.* (2013)
Panama	(1) The Pacific basins: +35/40% (1) Bocas del Toro: -50%	2075–2099	MRI-AGCM3.1 (A1B)	Fábrega *et al.* (2013)

Table 27-5: Impacts on agriculture.

Country/ Region	Activity	Time slice	SRES	CO_2	Changes	Source
Uruguay (SESA)	Annual crops Livestock Forestry	2030/2050/2070/2100 2030/2050 2030/2050/2070/2100 2030/2050 2030/2050/2070/2100 2030/2050/2070	A2 B2 A2 B2 A2 B2		+185/-194/-284/-508 +92/+169 +174/-80/-160/-287 +136/+182 +15/+39/+52/+19 +6/+13/+18	ECLAC (2010) **(*1)**
(Paraguay (SESA)	Cassava Wheat Maize Soybean Bean	2020/2050/2080 2020/2050/2080 2020/2050/2080 2020/2050/2080 2020/2050/2080	A2 A2 B2 A2 B2 A2 B2 A2		+16/+22/+22 +4/-9/-13 -1/+1/-5 +3/+3/+8 +3/+1/+6 A2 0/-10/-15 0/-15/-2 -1/+10/+16	ECLAC (2010)
Argentina (SESA)	Maize Soybean Wheat	2080 2080 2080	A2/B2 A2/B2 A2/B2 A2/B2 A2/B2 A2/B2	N Y N Y N Y	-24/-15 +1/0 -25/-14 +14/+19 -16/-11 +3/+3	ECLAC (2010)
	Soybean Maize	2020/2050/2080 2020/2050/2080	A2 B2 A2 B2	Y Y Y Y	+24/+42/+48 +14/+30/+33 +8/+11/+16 +5/+5/+9	Travasso *et al.* (2008)
Brazil (SESA)	Rice		$2CO_2$/0ºC $2CO_2$/+5ºC	Y Y	+60 +30	Walter *et al.* (2010)
	Bean Maize	2050-2080 2020-2050-2080 2020-2050-2080 2050-2080 2050-2080 2020-2050-2080	A2 A2+CO_2 A2+CO_2+T A2 A2+CO_2 A2+CO_2+T	N Y Y N Y Y	Up to -30% Up to: +30/+30/+45 Up to: +45/+75/+90 Up to -30% Near to -15% Up to: +40/+60/+90	Costa *et al.* (2009) **(*2)**
	Arabica coffee		0 to +1ºC +1 to +2ºC +2 to +3ºC +3 to +4ºC		+1.5% +15.9% +28.6% -12.9%	Zullo *et al.* (2011) **(*3)**
Brazil Sao Pablo	Sugarcane	2040 2040	Pessimistic Optimistic		+6% +2%	Marin *et al.* (2009)
Brazil Northeast	Cassava Maize Rice Wheat	2030 2030 2030 2030		N N N N	0 to -10 0 to -10 -1 to -10 -1 to -14	Lobell *et al.* (2008)
	Maize Bean Rice				-20 to -30 -20 to -30 -20 to -30	Margulis *et al.* (2010)
	Cowpea bean		+1.5ºC +3.0ºC +5.0ºC		-26% -44% -63%	Silva *et al.* (2010) **(*3)**
Central America (CA)	Maize Bean Rice	2030/2050/2070/2100	A2 A2 A2		0/0/-10/-30 -4/-19/-29/-87 +3/-3/-14/-63	ECLAC (2010)
	Rice Wheat	2020-2040 2020-2040		N N	0 to -10 -1 to -9	Lobell *et al.* (2008)
Panamá	Maize	2020-2050-2080 2020-2050-2080	A2 B1	Y Y	-0.5/+2.4/+4.5 -0.1/-0.8/+1.5	Ruane et al. (2011)
Andean Region	Wheat Barley	2020-2040		N N	-14 to +2 -1 to -8	Lobell *et al.* (2008)

	Potato Maize			N N	0 to -5 0 to -14	
Colombia	All main crops	2050	17GCM-A2		80% of crops impacted in more than 60% of current cultivated areas	Ramirez *et al*. (2012)
Chile 34.6ºS/38.5ºS	Maize Wheat	2050 2050	A1FI A1FI	Y Y	-5% to -10% -10% to -20%	Meza and Silva (2009)

Changes are expressed as differences in relative yield (%), except for (*1) and (*3)

N: Without considering CO2 biological effects; Y: Considering CO2 biological effects

(*1) Gross Value of Production (millions of American dollars)

(*2) Huge spatial variability, the values are approximated

(*3) Changes in the percentage of areas with low climate risk

Table 27-6: Comparison of consumption of different energetics in Latin America and the world (in thousand tonnes of oil equivalent (ktoe) on a net calorific value basis).

Energy resource		LATAM						World					
		TFC (non electricity)		TFC (via electricity generation)		Total TFC		TFC (non electricity)		TFC (via electricity generation)		TFC	
Fossil	Coal and Peat	9,008	3%	1,398	2%	10,406	3%	831,897	12%	581,248	40%	1,413,145	17%
	Oil	189,313	55%	8,685	13%	197,998	48%	3,462,133	52%	73,552	5%	3,535,685	44%
	Natural Gas	59,44	17%	9,423	14%	68,863	17%	1,265,862	19%	307,956	21%	1,573,818	19%
Nuclear	Nuclear	0	0%	1,449	2%	1,449	0%	0	0%	193,075	13%	193,075	2%
Renewable	Biofuels and waste	82,997	24%	2,179	3%	85,176	21%	1,080,039	16%	20,63	1%	1,100,669	14%
	Hydro	0	0%	45,92	66%	45,92	11%	0	0%	238,313	17%	238,313	3%
	Geothermal, solar, wind, other renewable	408	0%	364	1%	772	0%	18,265	0%	26,592	2%	44,857	1%
TOTAL		341,166	100%	69,418	100%	410,584	100%	6,658,196	100%	1,441,366	100%	8,099,562	100%

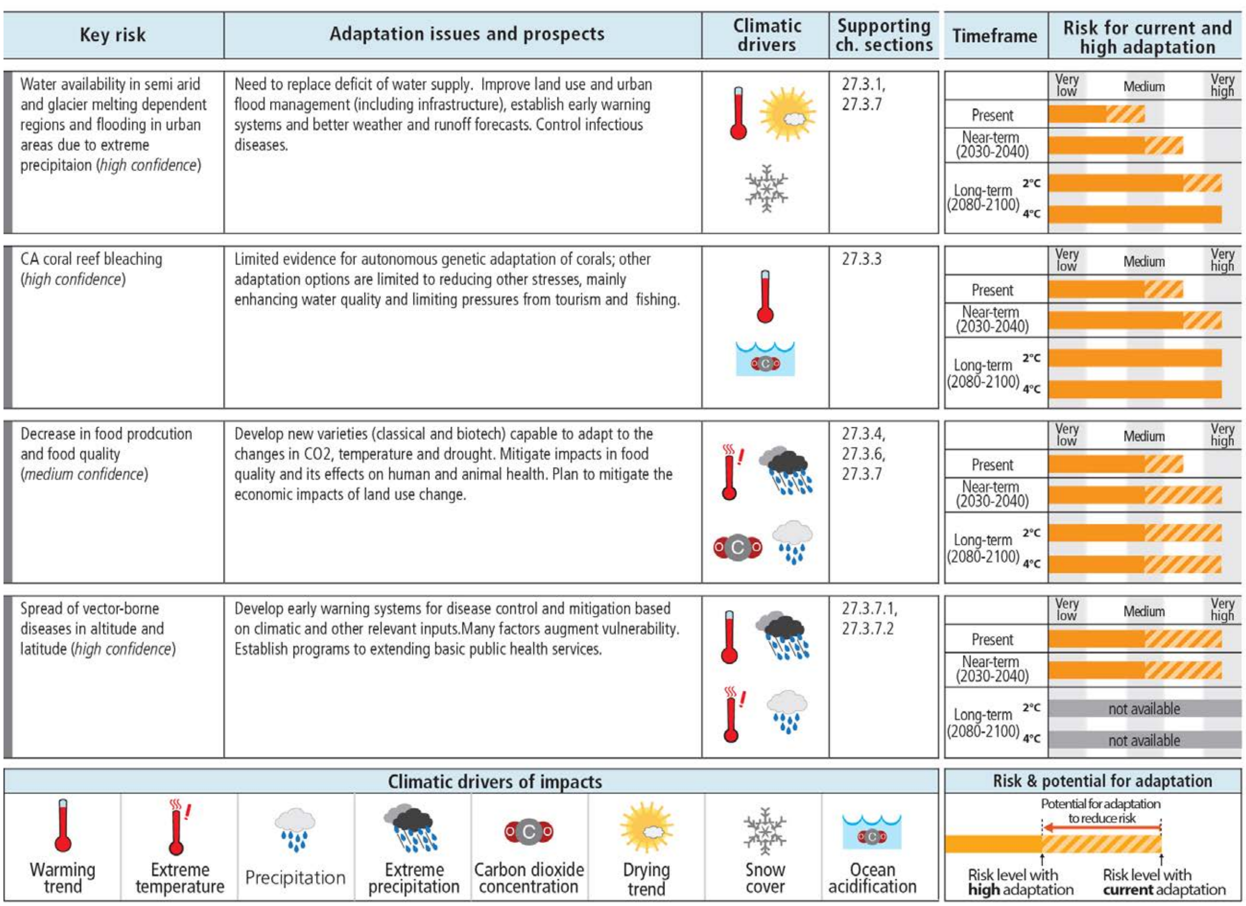
* TFC: Total final consumption

Source: IEA, 2012

Table 27-7: Cases of government-funded PES schemes in CA and SA.

Countries	Level	Start	Name	Benefits	References
Brazil	Sub-national (Amazonas state)	2007	*Bolsa Floresta*	By 2008, 2700 traditional and indigenous families already benefitted: financial compensation and health assistance in exchange for zero deforestation in primary forests.	Viana (2008)
Costa Rica	National	1997	FONAFIFO fund	PES is a strong incentive for reforestation and, for agroforestry ecosystems alone, over 7,000 contracts have been set since 2003, and nearly 2 million trees were planted.	Montagnini and Finney (2011)
Ecuador	National	2008	*Socio-Bosque*	By 2010, the program already included more than half a million hectares of natural ecosystems protected and has over 60,000 beneficiaries.	De Koning *et al.* (2011)
Guatemala	National	1997	Programa de Incentivos Forestales, PINFOR	By 2009, the program included 4,174 beneficiaries who planted 94,151 hectares of forest. In addition, 155,790 hectares of natural forest were under protection with monetary incentives.	Instituto Nacional de Estadística (2011)

Table 27-8: Key risks from climate change and the potential for risk reduction through mitigation and adaptation.



Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Water availability in semi arid and glacier melting dependent regions and flooding in urban areas due to extreme precipitaion (*high confidence*)	Need to replace deficit of water supply. Improve land use and urban flood management (including infrastructure), establish early warning systems and better weather and runoff forecasts. Control infectious diseases.		27.3.1, 27.3.7	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
CA coral reef bleaching (*high confidence*)	Limited evidence for autonomous genetic adaptation of corals; other adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing.		27.3.3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Decrease in food prodcution and food quality (*medium confidence*)	Develop new varieties (classical and biotech) capable to adapt to the changes in CO2, temperature and drought. Mitigate impacts in food quality and its effects on human and animal health. Plan to mitigate the economic impacts of land use change.		27.3.4, 27.3.6, 27.3.7	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Spread of vector-borne diseases in altitude and latitude (*high confidence*)	Develop early warning systems for disease control and mitigation based on climatic and other relevant inputs.Many factors augment vulnerability. Establish programs to extending basic public health services.		27.3.7.1, 27.3.7.2	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high; Long-term 2°C: not available; 4°C: not available

Climatic drivers of impacts: Warming trend; Extreme temperature; Precipitation; Extreme precipitation; Carbon dioxide concentration; Drying trend; Snow cover; Ocean acidification

Risk & potential for adaptation: Potential for adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

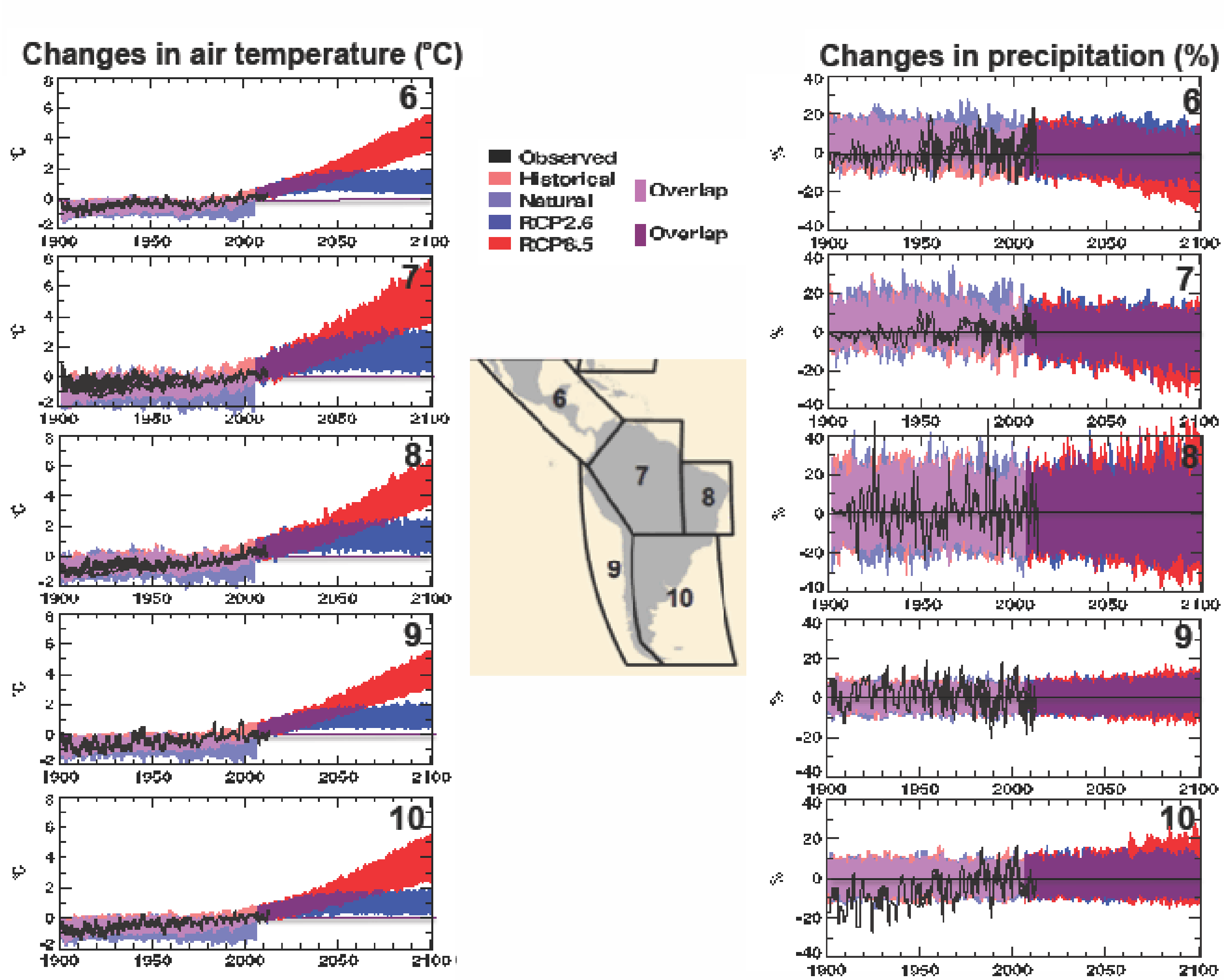


Figure 27-1: Observed and simulated variations in past and projected future annual average temperature over the Central and South American regions defined in IPCC (2012). Black lines show various estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations driven with "historical" changes in anthropogenic and natural drivers (63 simulations), historical changes in "natural" drivers only (34), the "RCP2.6" emissions scenario (63), and the "RCP8.5" (63). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-3.
[Illustration to be redrawn to conform to IPCC publication specifications.]

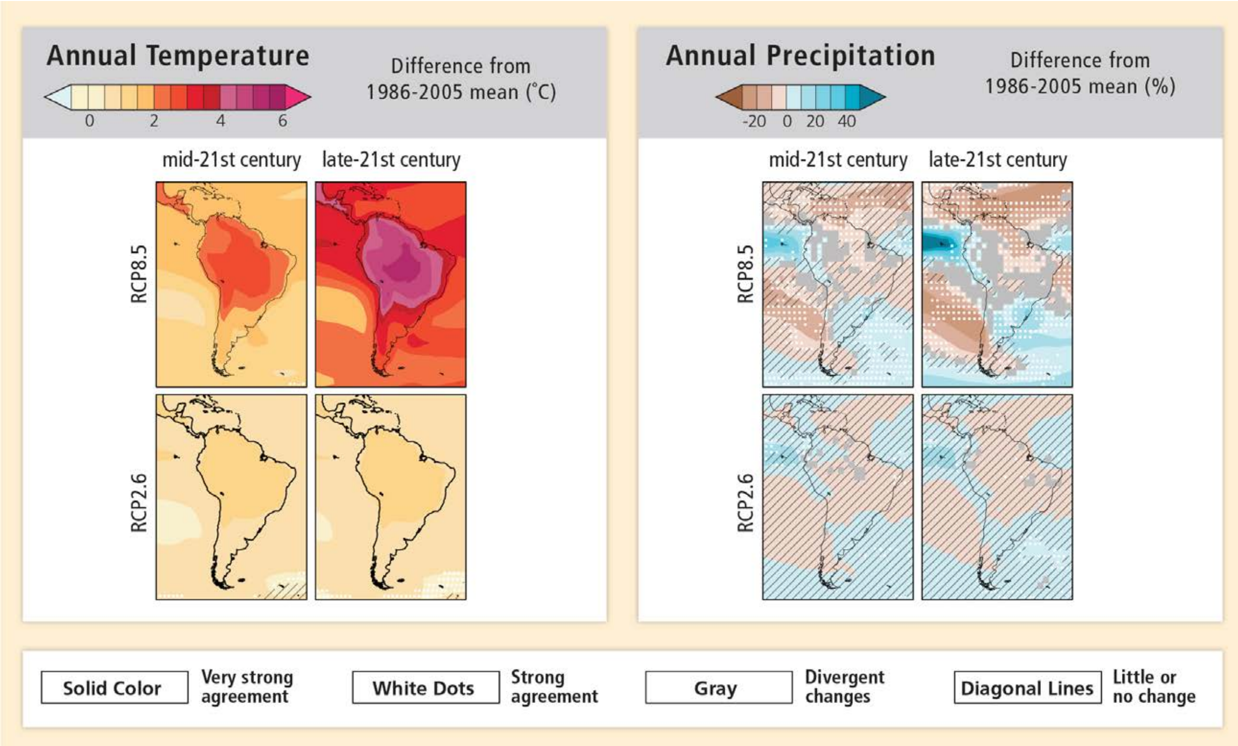


Figure 27-2: Projected changes in annual average temperature and precipitation. CMIP5 multi-model mean projections of annual average temperature changes (left panel) and average percent change in annual mean precipitation (right panel) for 2046-2065 and 2081-2100 under RCP2.6 and 8.5. Solid colors indicate areas with very strong agreement, where the multi-model mean change is greater than twice the baseline variability, and>90% of models agree on sign of change. Colors with white dots indicate areas with strong agreement, where>66% of models show change greater than the baseline variability and>66% of models agree on sign of change. Gray indicates areas with divergent changes, where>66% of models show change greater than the baseline variability, but<66% agree on sign of change. Colors with diagonal lines indicate areas with little or no change, less than the baseline variability in>66% of models. (There may be significant change at shorter timescales such as seasons, months, or days.). Analysis uses model data and methods building from WGI AR5 Figure SPM.8. See also Annex I of WGI AR5. [Boxes 21-3 and CC-RC]

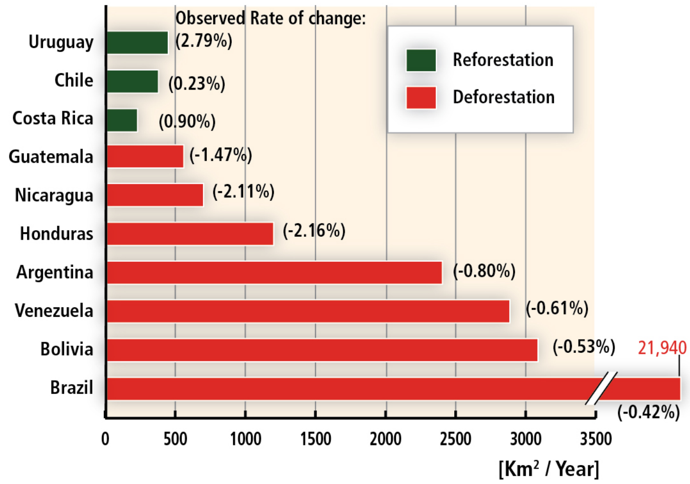


Figure 27-3: Area deforested per year for selected countries in CA and SA (2005-2010). Notice three countries listed with a positive change in forest cover (based on data from FAO, 2010).

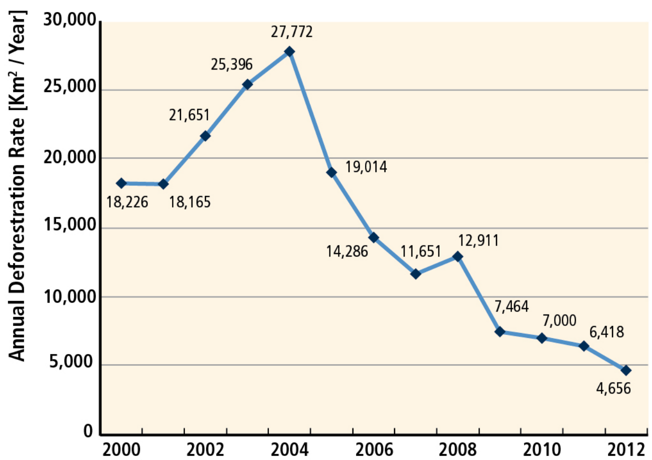


Figure 27-4: Deforestation rates in the Brazilian Amazonia (km²/year) based on measurements by the PRODES project (INPE, 2011).

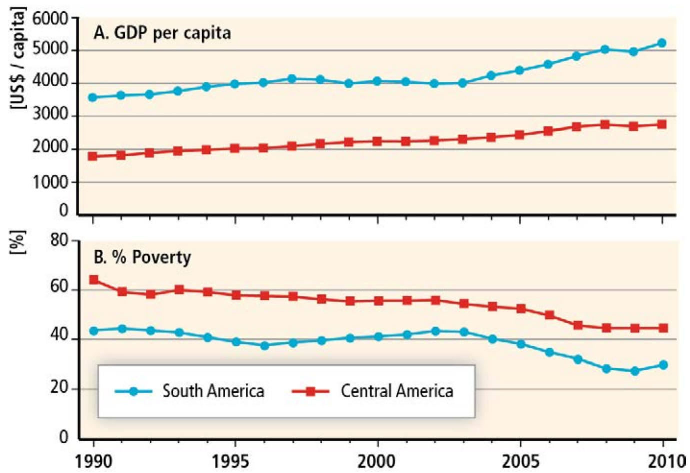


Figure 27-5: Evolution of GDP per capita and poverty (income below US$ 2 per day) from 1990-2010: CA and SA (US-Dollars per inhabitant at 2005 prices and percentages) (ECLAC on the basis of CEPALSTAT (2012) and ECLAC (2011b)).

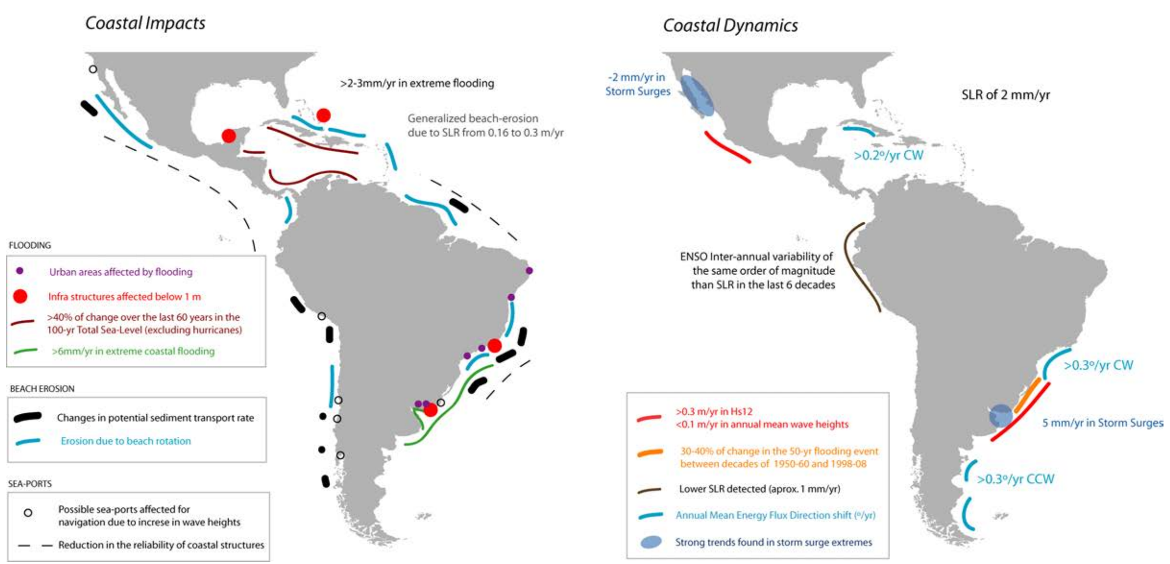


Figure 27-6: Current and predicted coastal impacts and coastal dynamics in response to climate change.

Coastal impacts - based on trends observed and projections, the figure shows how potential impacts may be distributed in the region. Three cases: a) flooding: since flooding probability increases with increasing sea-level, one may expect a higher probability of flooding in locations showing >40% of change over the last 60 years in the 100-years total sea-level (excluding hurricanes). The figure also identifies urban areas where the highest increase in flooding level has been obtained.; b) beach erosion: it increases with potential sediment transport, thus locations where changes in potential sediment transport have increased over a certain threshold have a higher probability to be eroded; c) sea-ports and reliability of coastal structures: the figure shows locations where, in the case of having a protection structure in place, there is a reduction in the reliability of the structures due to the increase in the design wave height estimates (ECLAC, 2011a).

Coastal dynamics - information based on historical time series that have been obtained by a combination of data reanalysis, available instrumental information and satellite information. Advanced statistical techniques have been used for obtaining trends including uncertainties (Izaguirre *et al.*, 2013; Losada *et al.*, 2013).

[Illustration to be redrawn to conform to IPCC publication specifications.]

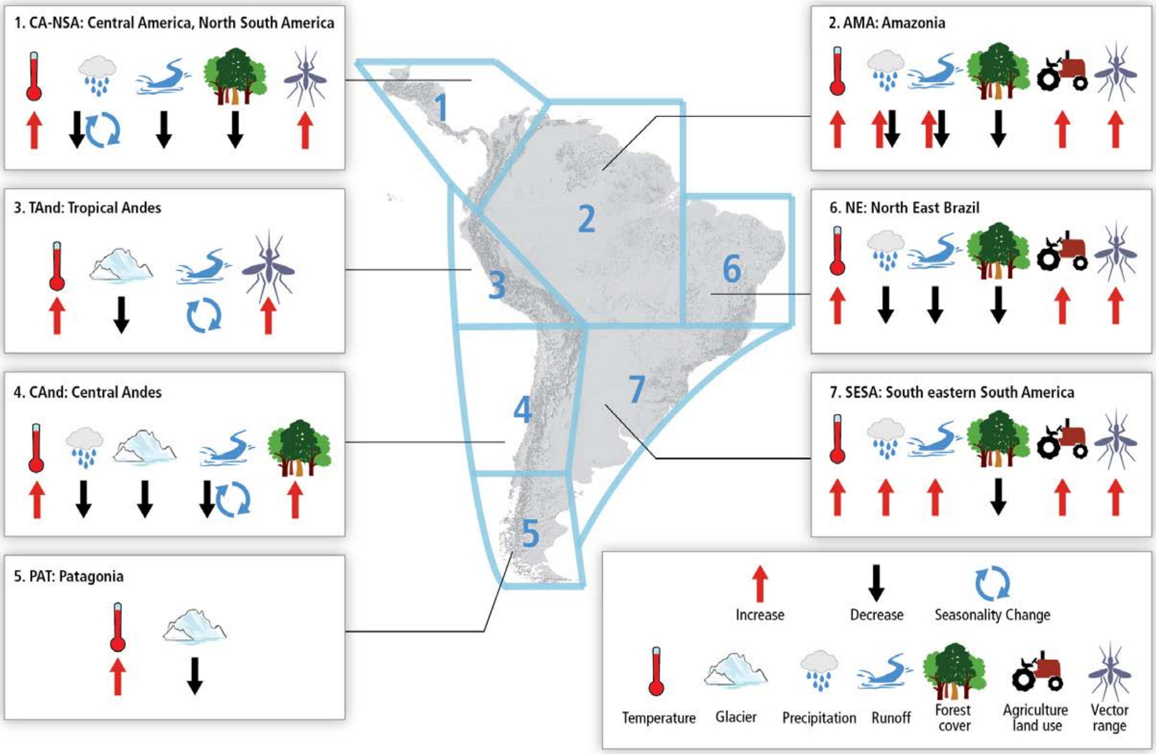


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Figure 27-7: Summary of observed changes in climate and other environmental factors in representative regions of CA and SA. The boundaries of the regions in the map are conceptual (neither geographic nor political precision). Information and references to changes provided are presented in different sections of the chapter.

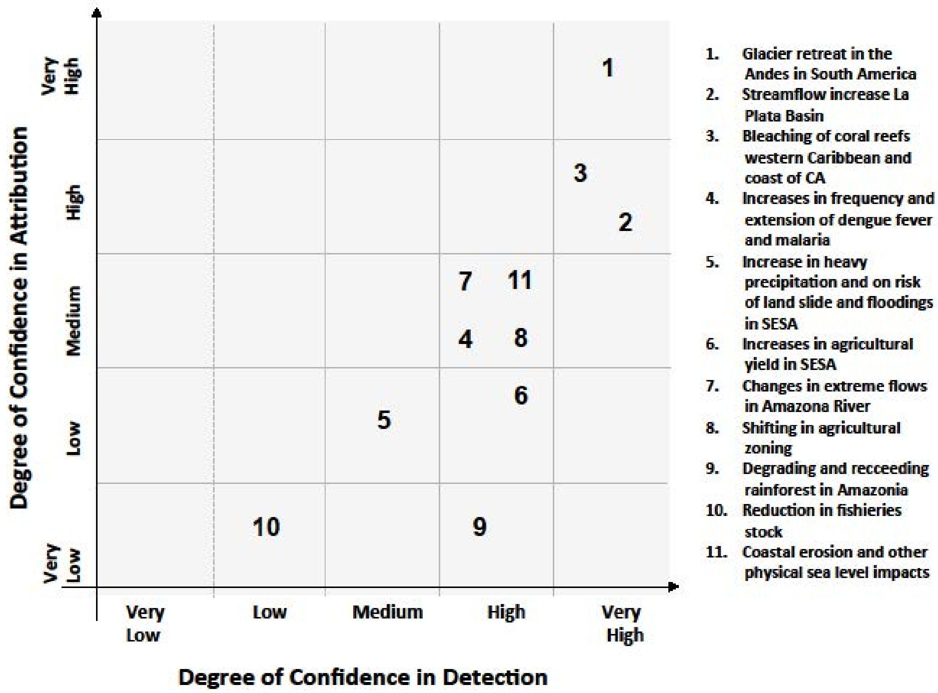

Figure 27-8: Observed impacts of climate variations and attribution of causes in CA and SA.
[Illustration to be redrawn to conform to IPCC publication specifications.]

Chapter 28. Polar Regions

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Contents

Executive Summary

Additional and stronger scientific evidence has accumulated since the AR4 that reinforces key findings made in the Fourth Assessment Report (AR4).

The impacts of climate change, and the adaptations to it, exhibit strong spatial heterogeneity in the Polar Regions because of the high diversity of social systems, bio-physical regions and associated drivers of change (*high confidence*). [28.2.2] For example, the tree line has moved northward and upward in many, but not all, Arctic areas (*high confidence*) and significant increases in tall shrubs and grasses have been observed in many places (*very high confidence*). [28.2.3.2]

Some marine species will shift their ranges in response to changing ocean and sea ice conditions in the Polar Regions (*medium confidence*)**.** The response rate and the spatial extent of the shifts will differ by species based on their vulnerability to change and their life history. [28.2.2; 28.3.2] Loss of sea ice in summer and increased ocean temperature is expected to enhance secondary pelagic production in some but not all regions of the Arctic Ocean with associated changes in the energy pathways within the marine ecosystem (*medium confidence*). These changes are expected to alter the species composition and carrying capacity with associated impacts on marine fish and shellfish populations (*medium confidence*). [28.2.2.1] Also, changes in sea ice and the physical environment to the west of the Antarctic Peninsula are altering phytoplankton stocks and productivity, and krill (*high confidence*). [28.2.2.2]

Climate change is impacting terrestrial and freshwater ecosystems in some areas of Antarctica and the Arctic. This is due to ecological effects resulting from reductions in the duration and extent of ice and snow cover and enhanced permafrost thaw (*very high confidence*), and through changes in the precipitation-evaporation balance (*medium confidence*). [28.2]

The primary concern for polar bears over the foreseeable future is the recent and projected loss of annual ice over continental shelves, decreased ice duration, and decreased ice thickness (*high confidence*). Of the two subpopulations where data are adequate for assessing abundance effects, it is *very likely* that the recorded population declines are caused by reductions in sea ice extent. [28.2.2.1.2; 28.3.2.2.2]

Rising temperatures, leading to the further thawing of permafrost and changing precipitation patterns have the potential to affect infrastructure and related services in the Arctic (*high confidence*). Particular concerns are associated with the damage of residential buildings due to thawing permafrost, including, Arctic cities; small, rural settlements; and storage facilities for hazardous materials. [28.2.4; 28.2.4.2; 28.2.5]

In addition, there is new scientific evidence that has emerged since the AR4.

The physical, biological and socio-economic impacts of climate change in the Arctic have to be seen in the context of often interconnected factors that include not only environmental changes caused by drivers other than climate change but also demography, culture and economic development. Climate change has compounded some of the existing vulnerabilities caused by these other factors (*high confidence*). [28.2.4; 28.2.5; 28.4] For example, food security for many indigenous and rural residents in the Arctic is being impacted by climate change and in combination with globalization and resource development projected to increase significantly in the future (*high confidence*). [28.2.4]

The rapid rate at which climate is changing in the Polar Regions will impact natural and social systems (*high confidence)* **and may exceed the rate at which some of their components can successfully adapt** (*low to medium confidence*). [28.2.4; 28.4] The decline of Arctic sea-ice in summer is occurring at a rate that exceeds most model projections (*high confidence*) and evidence of similarly rapid rates of change is emerging in some regions of Antarctica. [IPCC WGI Chapter 14] In the future, trends in Polar Regions of populations of marine mammals, fish and birds will be a complex response to multiple stressors and indirect effects (*high confidence*). [28.3.2] Already, accelerated rates of change in permafrost thaw, loss of coastal sea ice, sea level rise and increased weather intensity are forcing relocation of some indigenous communities in Alaska (high confidence). [28.2.4.2; 28.2.5; 28.3.4]

Shifts in the timing and magnitude of seasonal biomass production could disrupt matched phenologies in the food webs, leading to decreased survival of dependent species (*medium confidence*). If the timing of primary and secondary production is no longer matched to the timing of spawning or egg release, survival could be impacted with cascading implications to higher trophic levels. This impact would be exacerbated if shifts in timing occur rapidly (*medium confidence*). [28.2.2; 28.3.2] Climate change will increase the vulnerability of terrestrial ecosystems to invasions by non-indigenous species, the majority likely to arrive through direct human assistance (*high confidence*).

Ocean acidification has the potential to inhibit embryo development and shell formation of some zooplankton and krill in the Polar Regions with potentially far-reaching consequences to food webs in these regions (*medium confidence*). Embryos of Antarctic krill have been shown to be vulnerable to increased concentrations of CO_2 in the water (*high confidence*). As well, there is increasing evidence that pelagic mollusks (pteropods) are vulnerable to ocean acidification (*medium confidence*). [28.2.2; 28.3.2]

There is increased evidence that climate change will have large effects on Arctic communities, especially where narrowly based economies leave a smaller range of adaptive choices. [28.2.6.1; 28.4] Some commercial activities will become more profitable while others will face decline. Increased economic opportunities are expected with increased navigability in the Arctic Ocean and the expansion of some land- and freshwater-based transportation networks. [28.2.6.1.3; 28.3.4.3] The informal, subsistence-based economy will be impacted (*high confidence*). There *is high confidence* that changing sea-ice conditions will result in more difficult access for hunting marine mammals. [28.2.6.1.6] Although Arctic residents have a history of adapting to change, the complex inter-linkages between societal, economic, and political factors and climatic stresses represent unprecedented challenges for northern communities, particularly as the rate of change will be faster than the social systems can adapt (*high confidence*). [28.4; 28.4.1; 28.2.5]

Impacts on the health and well-being of Arctic residents from climate change are significant and projected to increase – especially for many indigenous peoples (*high confidence*). [28.2.4] These are expected to vary among the diverse settlements, which range from small, remote predominantly indigenous communities to large cities and industrial settlements (*high confidence*), especially those located in highly vulnerable locations along ocean and river shorelines. [28.2.4]

28.1. Introduction

Several recent climate impact assessments on Polar Regions have been undertaken, including the synthesis report on Snow, Water, Ice and Permafrost in the Arctic (AMAP, 2011), the State of the Arctic Coast 2010 (2011) reports, the Antarctic Climate and the Environment (Turner *et al.*, 2009, 2013), Arctic Resilience Interim Report 2013 (2013), and the findings of the International Polar Year (IPY) (Krupnick *et al*., 2011). These reports draw a consistent pattern of climate-driven environmental, societal and economic changes in the Polar Regions in recent decades. In this chapter, we use the scientific literature, including these reports, to consolidate the assessment of the impacts of climate change on Polar Regions from 2007, advance new scientific evidence of impacts and identify key gaps in knowledge on current and future impacts.

Previous IPCC reports define the Arctic as the area within the Arctic Circle (66ºN), and the Antarctic as the continent with surrounding Southern Ocean south of the polar front, which is generally close to 58ºS (IPCC, 2007). For the purpose of this report we use the conventional IPCC definitions as a basis, while incorporating a degree of flexibility when describing the Polar Regions in relation to particular subjects.

[INSERT FIGURE 28-1 HERE
Figure 28-1: Location maps of the north and south polar regions. Credit: P. Fretwell, British Antarctic Survey.]

Changes in the physical and chemical environments of the Polar Regions are detailed in IPCC WG-1 report. The Arctic has been warming since the 1980s at approximately twice the global rate demonstrating the strongest temperature changes (~ 1 °C per decade) in winter and spring, and smallest in autumn. Sea ice declined at an average rate of 13% per decade; the Arctic Ocean is projected to become nearly ice-free in summer within this century. The duration of snow cover extent and snow depth are decreasing in North-America while increasing in Eurasia. Since late 1970s permafrost temperatures have increased between 0.5 to 2 °C. In the Southern Hemisphere, the strongest rates of atmospheric warming are occurring in the western Antarctic Peninsula (WAP, between 0.2 and 0.3 °C per decade) and the islands of the Scotia Arc, where there have also been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration. Warming, although less than WAP, has also occurred in the continental margins near to Bellingshausen Sea, Prydz Bay and the Ross Sea, with areas of cooling in between. Land regions have experienced glacial recession and changes in the ice and permafrost habitats in the coastal margins. The Southern Ocean continues to warm, with increased freshening at the surface due to precipitation leading to increased stratification. In both Polar Regions, surface waters will become seasonally corrosive to aragonite within decades, with some regions being affected sooner than others (Box CC-OA, WGI AR5 Chapter 6). Observations and models indicate that the carbon cycle of the Arctic and Southern Oceans will be impacted by climate change and increased CO_2.

28.2. Observed Changes and Vulnerability under Multiple Stressors

28.2.1. Hydrology and Freshwater Ecosystems

28.2.1.1. Arctic

Arctic rivers and lakes continue to show pronounced changes to their hydrology and ecology. Previously noted increases in Eurasian Arctic river flow (1936-1999; Peterson *et al.*, 2002) could not, for a similar period (1951-2000), be attributed with certainty to precipitation changes (Milliman *et al.*, 2008) but has been, including more recent extreme increases (2007), to enhanced poleward atmospheric moisture transport (Zhang *et al.*, 2013). By contrast, decreased flow in high-latitude Canadian rivers (1964-2000; average -10%) does match that for precipitation (Déry and Wood, 2005). Recent data (1977-2007) for 19 circumpolar rivers also indicates an area-weighted average increase of +9.8% (–17.1 to 47.0%; Overeem and Syvitski, 2010) accompanied by shifts in flow timing, with May snowmelt increasing (avg. 66%) but flow in the subsequent month of peak discharge decreasing (~7%). Across the Russian Arctic, dates of spring maximum discharge have also become earlier, particularly in the most recent [1960-2001] period analyzed (average -5d; range for 4 regions +0.2 to -7.1 d), but no consistent trend exists for magnitude (average -1%; range +21 to -24%; Shiklomanov *et al.*, 2007). Earlier timing was most pronounced in eastern, colder continental climates where increases in air temperature have been identified as the dominant control (Tan *et al.*, 2011).

Increases have also occurred in winter low flows for many Eurasian and North American rivers (primarily late 20th century; Smith *et al.*, 2007; St. Jacques and Sauchyn, 2009*;* Walvoord and Striegl, 2007; Ye *et al.*, 2009), the key exceptions being decreases in eastern North America and unchanged flow in small basins of eastern Eurasia (Rennermalm *et al.*, 2010). Most of such studies suggest permafrost thaw (WGI, Ch.4) has increased winter flow, while others suggest increases in net winter precipitation minus evapotranspiration (Landerer *et al.*, 2010; Rawlins *et al.*, 2009a, b). Insufficient precipitation stations preclude deciphering the relative importance of these factors (WGI, Ch. 2.5.1).

The surface-water temperatures of large water bodies has warmed (1985-2009; Schneider and Hook, 2010), particularly for mid- and high latitudes of the northern hemisphere with spatial patterns generally matching those for air temperature. Where water bodies warmed more rapidly than air temperature, decreasing ice cover was suggested as enhancing radiative warming. Paleolimnological evidence indicates that highest primary productivity was associated with warm, ice-free summer conditions and the lowest with periods of perennial ice (Melles *et al.*, 2007). Increasing water temperatures affect planktonic and benthic biomass and lead to changes in species composition (Christoffersen *et al.* 2008; Heino *et al.* 2009, Jansson *et al.* 2010). Reduced ice cover with higher air temperatures and evaporation are responsible for the late 20th c – early 21st c desiccation of some Arctic ponds (Smol and Douglas, 2007).

Changes have occurred in the size and number of permafrost lakes over the last half-century (Hinkel *et al.*, 2007; Marsh *et al.*, 2009), but their patterns and rates of change are not consistent because of differing thawing states, variations in warming and effects of human activities (Hinket *et al.* 2007; Prowse and Brown, 2010a). Thawing permafrost affects the biogeochemistry of water entering lakes and rivers (Frey and McClelland, 2009; Kokelj et al., 2009) and their ecological structure and function (Lantz and Kokelj, 2008; Mesquita *et al.*, 2010; Thompson *et al.*, 2008), such as enhancing eutrophication by a shift from pelagic to benthic-dominated production (Thompson *et al.*, 2012).

The aquatic ecosystem health and biodiversity of northern deltas is dependent on combined changes in the elevation of spring river ice-jam floods and sea level (Lesack and marsh, 2007, 2010). Diminishing ice shelves (last half-century) have also caused a decline in the number of freshwater epishelf lakes that develop behind them (Veillette *et al.*, 2008; Vincent *et al.*, 2009). While such biophysical dependencies have been established, temporal trends in such river-delta and epishelf lake impacts and their linkages to changing climate remain to be quantified precisely.

An interplay of freshwater-marine conditions also affect the timing, growth, run size and distribution of several Arctic freshwater and anadromous fish. Key examples include: the timing of marine exit of Yukon River Chinook salmon (*Oncorhynchus tshawytscha;* 1961-2009) varied with air and sea temperatures and sea ice cover (Mundy and Evenson, 2011); the growth of young-of-year Arctic cisco (*Coregonus autumnalis;* 1978 – 2004) varied in response to lagged sea-ice concentration and Mackenzie River discharge, also indicating that decreased sea-ice concentration and increased river discharge enhanced marine primary production leading to more favorable foraging conditions (Von Biela *et al.* (2011); and factors that influence the water level and freshening of rivers, as well as the strength, duration and directions of prevailing coastal winds, affect survival of anadromous fishes during coastal migration and their subsequent run size (Fechhelm *et al.*, 2007).

28.2.1.2. Antarctic

Biota of Antarctic freshwater systems (lakes, ponds, short streams and seasonally wetted areas) are dominated by benthic microbial communities of cyanobacteria and green algae in a simple food web. Mosses occur in some continental lakes with higher plants absent. Planktonic ecosystems are typically depauperate and include small algae, bacteria and colourless flagellates, with few metazoans and no fish (Quesada and Velázquez, 2012). Recent compilations of single-year datasets have reinforced previous conclusions on the changing freshwater habitats in Antarctica (Verleyen *et al.*, 2012). In regions where the climate has warmed the physical impacts on aquatic ecosystems include loss of ice and perennial snow cover, increasing periods of seasonal open water, increased water column temperatures and changes in water column stratification. In some areas a negative water balance has occured due to increased temperature and changes in wind strength driving enhanced evaporation and sublimation and leading to increased salinity in lakes in recent decades (Hodgson *et al.*, 2006a). In other areas, especially glacial forelands, increased temperatures have led to greater volumes of seasonal meltwater in streams and lakes together with increased nutrient fluxes (*high confidence*). In both cases the balance between precipitation and evaporation can have detectable effects on lake ecosystems (*medium confidence*) through changes in water body volume and lake chemistry (Lyons *et al.*, 2006; Quesada *et al.*, 2006). Non-dilute lakes with a low lake depth to surface area ratio are most susceptible to inter-annual and inter-decadal variability in the water balance, as measured by changes in specific conductance (*high confidence*) (Verleyen *et al.*, 2012). Warming in the northwestern Antarctic Peninsula region has resulted in permafrost degradation in the last c. 50 yr impacting surface geomorphology and hydrology (Bockheim *et al.*, 2013) with the potential to increase soil biomass.

28.2.2. Oceanography and Marine Ecosystems

28.2.2.1. Arctic

28.2.2.1.1. Marine plankton, fish, and other invertebrates

Working Group I documents the expected physical and chemical changes that will occur in Arctic marine ecosystems (WGI AR5 Chapters 4, 6, and 11). In addition to climate change, naturally occurring interannual, decadal, and multi-decadal variations in climate will influence the Arctic Ocean and its neighboring high latitude seas (WGII Chapter 5). In recent years (2007-2012) ocean conditions in the Bering Sea have been cold (Stabeno *et al.*, 2012a), while the Barents Sea has been warm (Lind and Ingvaldsen, 2012).

In this section we build on previous reviews of observed species responses to climate (Wassman *et al*. 2011) to summarize the current evidence of the impact of physical and chemical changes in marine systems on the phenology, spatial distribution and production of Arctic marine species. For each type of response, the implications for phytoplankton, zooplankton, fish and shellfish are discussed. The implications of these changes on marine ecosystem structure and function will be the result of the synergistic effects of all three types of biological responses.

Phenological response

The timing of spring phytoplankton blooms is a function of seasonal light, hydrographic conditions, and the timing of sea ice breakup (Wassman, 2011). In addition to the open water phytoplankton bloom, potentially large ice algal blooms can form under the sea ice (Arrigo, 2012). During the period 1997-2009, a trend towards earlier phytoplankton blooms was detected in approximately 11% of the area of the Arctic Ocean (Kahru *et al.*, 2011). This advanced timing of annual phytoplankton blooms coincided with decreased sea ice concentration in early summer. Brown and Arrigo (2013) studied the timing and intensity of spring blooms in the Bering Sea from 1997-2010 and found that in northern regions, sea ice consistently retreated in late spring and was associated with ice-edge blooms, whereas, in the southern regions the timing of sea ice retreat varied, with ice-edge blooms associated with late ice retreat, and open water blooms associated with early ice retreat. Given the short time series and limited studies, there is *medium confidence* that climate variability and change has altered the timing and the duration of phytoplankton production.

The life cycles of calanoid copepods in the Arctic Ocean and Barents Sea are timed to utilize ice algal and phytoplankton blooms (Falk-Petersen *et al*. 2009; Søreide *et al.*, 2010; Darnis *et al.* 2012). Based on a synthesis of existing data, Hunt *et al.* (2011) hypothesized that in the southeastern Bering Sea, ocean conditions and the timing of sea ice retreat influences the species composition of dominant zooplankton, with lipid rich copepods being more abundant in cold years.

There is ample evidence that the timing of spawning and hatching of some fish and shellfish is aligned to match larval emergence with seasonal increases availability of prey (Gjosaeter *et al.*, 2009; Vikebø *et al*., 2010; Bouchard and Fortier, 2011; Drinkwater *et al*., 2011). These regional phenological adjustments to local conditions occurred over many generations (Ormseth and Norcross, 2009; Geffen *et al.*, 2011; Kristiansen *et al.*, 2011). There is *medium* to *high confidence* that climate induced disruptions in this synchrony can result in increased larval or juvenile mortality or changes in the condition factor of fish and shellfish species in the Arctic marine ecosystems.

Observed spatial shifts

Spatial heterogeneity in primary production has been observed (Lee *et al.*, 2010; Grebmeier, 2012). Simulation modeling studies show that spatial differences in the abundance of four species of copepod can be explained by regional differences in the duration of the growing season and temperature (Ji *et al*., 2012). Retrospective studies based on surveys from 1952-2005 in the Barents Sea revealed that changes in the species composition, abundance and distribution of euphausiids were related to climate-related changes in oceanographic conditions (Zhukova *et al.*, 2009).

Retrospective analysis of observed shifts in the spatial distribution of fish and shellfish species along latitudinal and depth gradients showed observed spatial shifts were consistent with expected responses of species to climate change (Simpson *et al.*, 2011; Poloczanska *et al*. 2013; Box CC-MB, Chapter 30). Retrospective studies from the Bering Sea, Barents Sea, and the northeast Atlantic Ocean and Icelandic waters, showed that fish shift their spatial distribution in response to climate variability (i.e. interannual, decadal or multi-decadal changes in ocean temperature; Mueter and Litzow, 2008; Sundby and Nakken, 2008; Hátún *et al.*, 2009; Valdimarsson *et al.*, 2012; Kotwicki and Lauth, 2013). There are limits to the movement potential of some species. Vulnerability assessments indicate that the movement of some sub-arctic fish and shellfish species into the Arctic Ocean may be impeded by the presence of water temperatures on the shelves that fall below their thermal tolerances (Hunt *et al.*, 2013; Hollowed *et al.*, 2013). Coupled bio-physical models have reproduced the observed spatial dynamics of some the species in the Bering and Barents Seas, and are being used to explain the role of climate variability and change on the distribution and abundance of some species (Huse and Ellingsen, 2008; Parada *et al.*, 2010). In summary, there is *medium* to *high confidence* based on observations and modeling that some fish and shellfish have shifted their distribution in response to climate impacts on the spatial distribution and volume of suitable habitat.

Observed variations in production

Seasonal patterns in light, sea ice cover, freshwater input, stratification and nutrient exchange act in concert to produce temporal cycles of ice algal and phytoplankton production in Arctic marine ecosystems (Wassmann, 2011; Perrette *et al.*, 2011; Tremblay *et al*., 2012). Satellite observations and model estimates for the period 1988–2007 showed that phytoplankton productivity increased in the Arctic Ocean in response to a downward trend in the extent of summer sea ice (Zhang *et al.*, 2010). Satellite data provided evidence of a 20% increase in annual net primary production in the Arctic Ocean between 1998 and 2009 in response to extended ice free periods (Arrigo and van Dijken, 2011). Regional trends in primary production will differ in response to the amount of open water area in summer (Arrigo and van Dijken, 2011). Other studies showed gross primary production increased with increasing air temperature in the Arctic Basin and Eurasian shelves (Slagstad *et al.*, 2011). A recent 5 year study (2004-2008) in the Canadian Basin showed that smaller phytoplankton densities were higher than larger phytoplankton densities in years when sea surface temperatures were warmer, the water column was more stratified, and nutrients were more depleted during the Arctic summer (Li *et al.*, 2009; Morán *et al.*, 2010). Additional observations will help to resolve observed differences between in-situ and satellite derived estimates of primary production (Matrai *et al.*, 2013). In conclusion, based on recent observations and modeling, there is *medium to high confidence* that primary production has increased in the Arctic Ocean in response to changes in climate and its impact on the duration and areal extent of ice free periods in summer.

Regional differences in zooplankton production have been observed. During a period of ocean warming (1984-2010), Dalpadado *et al*. (2012) observed an increase in the biomass of lipid rich euphausiids in the Barents Sea and relatively stable levels of biomass and production of *Calanus finmarchicus*. In the Bering Sea, observations over the most recent decade in the southeast Bering Sea showed *C. marshallae* were more abundant in cold years than warm years (Coyle *et al.*, 2011).

There is strong evidence that climate variability impacts the year-class strength of Arctic marine fish and shellfish through its influence on: predation risk; the quality, quantity and availability of prey; and reproductive success (Mueter *et al.*, 2007; Bakun 2010; Drinkwater *et al.*, 2010). Regional differences in the species responses to climate change will be a function of the exposure of the species to changing environmental conditions, the sensitivity of the species to these changes (Beaugrand and Kirby, 2010) and the abilities of species to adapt to changing conditions (Pörtner and Peck, 2010; Donelson *et al.*, 2011). There is *high confidence* that shifts in ocean conditions have impacted the abundance of fish and shellfish in Arctic regions. Observed trends in the abundance of commercial fish and shellfish may also be influenced by historical patterns of exploitation (Vert-pre *et al*., 2013).

28.2.2.1.2. Marine mammals, polar bear, and sea birds

Studies on responses of Arctic and subarctic marine mammals to climate change are limited and vary according to insight into their habitat requirements and trophic relationships (Laidre *et al.*, 2008). Many Arctic and subarctic marine mammals are highly specialized, have long-life spans, and are poorly adapted to rapid environmental change (Moore and Huntington, 2008), and changes may be delayed until significant sea ice loss has occurred (Freitas *et al.*, 2008; Laidre *et al.*, 2008).

Climate change effects on Arctic and subarctic marine mammal species will vary by life history, distribution, and habitat specificity (*high confidence*). Climate change will improve conditions for a few species, have minor negative effects for others, and some will suffer major negative effects (Ragen *et al.*, 2008; Laidre *et al.*, 2008). Climate change resilience will vary and some ice-obligate species should survive in regions with sufficient ice and some may adapt to ice-free conditions (Moore and Huntington, 2008). Less ice-dependent species may be more adaptable but an increase in seasonally migrant species could increase competition (Moore and Huntington, 2008).

Climate change vulnerability was associated with feeding specialization, ice dependence, and ice reliance for prey access and predator avoidance (Laidre *et al.*, 2008). There is *medium agreement* on which species' life histories are most vulnerable. Hooded seals (*Cystophora cristata)* and narwhal (*Monodon monoceros)* were identified as most at risk and ringed seals (*Pusa hispida)* and bearded seals (*Erignathus barbatus)* as least sensitive (Laidre *et al.*, 2008). Kovacs *et al.* (2010) shared concern for hooded seals and narwhal but had concerns for ringed seals and bearded seals. Narwhal may have limited ability to respond to habitat alteration (Williams *et al.* 2011). Species that spend only part of the year in the Arctic (e.g., gray whale (*Eschrichtius robustus*), killer whale (*Orcinus orca*)) may benefit from reduced ice (Moore, 2008; Laidre *et al.*, 2008; Higdon and Ferguson, 2009; Matthews *et al.*, 2011; Ferguson *et al.*, 2012). Killer whale expansion into the Arctic could cause a trophic cascade (Higdon and Ferguson, 2009) although there is *limited evidence* at this time.

There is *limited evidence* although *medium agreement* that generalists and pelagic feeding species may benefit from increased marine productivity from reduced ice while benthic feeding species near continental shelf habitats may do poorly (Bluhm and Gradinger, 2008). There is *limited evidence* but *high agreement* that dietary or habitat specialists will do poorly with reduced ice. Reduction of summer/autumn ice was the primary extrinsic factor affecting Pacific walrus (*Odobenus rosmarus)* with predictions of distribution changes, reduced calf recruitment, and longer-term predictions of high extinction probability (Cooper *et al.*, 2006; MacCracken, 2012). Summer ice retreat may make migration to such habitats energetically unprofitable for ringed seals (Freitas *et al.*, 2008). Ice loss threatens Baltic ringed seals (Kovacs and Lydersen, 2008). In Hudson Bay, earlier spring break-up and changes in snow cover over lairs have reduced ringed seal recruitment (Ferguson *et al.*, 2005). Changes in snowfall over the 21st century were projected to reduce ringed seal habitat for lairs by 70% (Hezel *et al.*, 2012). Similarly, harp seal (*Pagophilus groenlandicus)* breeding habitat was affected by changing ice conditions that could reduce pup survival (Bajzak *et al.*, 2011). While there is *limited evidence*, there are concerns that climate change may cause indirect effects on Arctic marine mammals' health (e.g., pathogen transmission, food web changes, toxic chemical exposure, shipping, and development) (Burek *et al.*, 2008).

Empirical studies provide direct insight into the mechanisms of climate change impact on polar bears (*Ursus maritimus*) but modelling allows predictive capacity (Hunter *et al.*, 2010; Amstrup *et al.*, 2010; Durner *et al.*, 2011; Castro de la Guardia *et al.*, 2013).

Polar bears are highly specialized and use annual ice over the continental shelves as their preferred habitat (Durner *et al.*, 2009; Miller *et al.*, 2012). The recent and projected loss of annual ice over continental shelves, decreased ice duration, decreased ice thickness, and habitat fragmentation is causing reduced food intake, increased energy expenditure, and increased fasting in polar bears (*high confidence*) (Stirling and Parkinson, 2006; Regehr *et al.*, 2007; Durner *et al.*, 2009; Amstrup *et al.*, 2010; Hunter *et al.*, 2010; Derocher *et al.*, 2011; Rode *et al.*, 2012; Sahanatien and Derocher, 2012; Castro de la Guardia *et al.*, 2013).

Subpopulation response varies geographically. Only 2 of the 19 subpopulations, Western Hudson Bay (Regehr *et al.*, 2007) and the Southern Beaufort Sea (Regehr *et al.*, 2010; Rode *et al.*, 2010a) have data series adequate for clear identification of abundance effects related to climate change. Many other subpopulations show characteristics associated with decline but some remain stable. Declining ice is causing lower body condition, reduced individual growth rates, lower fasting endurance, lower reproductive rates, and lower survival (*high confidence*) (Regehr *et al.*, 2007; Regehr *et al.*, 2010; Rode *et al.*, 2010a; Molnar *et al.*, 2011; Rode *et al.*, 2012). Condition is a precursor to demographic change (*very high confidence*) (Regehr *et al.*, 2010; Hunter *et al.*, 2010; Rode *et al.*, 2010a; Robinson *et al.*, 2011). The decline in the subpopulation in Western Hudson Bay by 21% between 1987 and 2004 was related to climate change (*medium confidence*) (Regehr *et al.*, 2007).

Replacement of multiyear ice by annual ice could increase polar bear habitat (*low confidence*) (Derocher *et al.*, 2004). Increasing the distance to multiyear ice and terrestrial refugia at maximal melt may result in drowning, cub mortality, and increased energetic costs (Monnett and Gleason, 2006; Durner *et al.*, 2011; Pagano *et al.*, 2012).

There is *robust evidence* of changes in sea ice conditions changing polar bear distribution including den areas (*high confidence*) (Fischbach *et al.*, 2007; Schliebe *et al.*, 2008; Gleason and Rode, 2009; Towns *et al.*, 2010; Derocher *et al.*, 2011). The number of human-bear interactions are projected to increase with warming (*high confidence*) (Stirling and Parkinson, 2006; Towns *et al.*, 2009).

Use of terrestrial resources by polar bears was suggested as adaptive (Dyck *et al.*, 2007; Dyck and Romberg, 2007; Armstrong *et al.*, 2008; Dyck *et al.*, 2008; Dyck and Kebreab, 2009; Rockwell and Gormezano, 2009; Smith *et al.*, 2010). Polar bears cannot adapt to terrestrial foods (Stirling *et al.*, 2008b; Amstrup *et al.*, 2009; Slater *et al.*, 2010; Rode *et al.*, 2010b), and will *most likely* not be able to adapt to climate change and reduced sea ice extent (*very high confidence*). Changing ice conditions are linked to cannibalism (Amstrup *et al.*, 2006), altered feeding (Cherry *et al.*, 2009), unusual hunting behaviour (Stirling *et al.*, 2008a), and diet change (Iverson *et al.*, 2006; Thiemann *et al.*, 2008) (*medium confidence*).

Upwelling or subsurface convergence areas found in frontal zones and eddies, and the marginal ice zone, are associated with high marine productivity important to Arctic seabirds (e.g. (Irons *et al.*, 2008). Long-term or permanent shifts in convergence areas and the marginal ice-edge zone induced by climate change may cause mismatch between the timing of breeding and the peak in food availability and, thus, potentially have strong negative impacts on seabird populations (Gaston *et al*., 2005; Moline *et al*., 2008; Gaston *et al*., 2009; Gremillet and Boulinier, 2009) (m*edium confidence*).

The contrasting results from the relatively few studies of impacts of climate change on Arctic seabirds, demonstrate that future impacts will be highly variable between species and between populations of the same species (*medium confidence*). Retreating sea ice and increasing SSTs have favored some species and disadvantaged others (Gaston et al. 2005; Byrd *et al*. 2008; Irons *et al*. 2008; Karnovsky *et al*. 2010; Fredriksen et al. 2013). Some species of sea birds respond to a wide range of sea surface temperatures via plasticity of their foraging behaviour, allowing them to maintain their fitness levels (Grémillet *et al*. 2012). Phenological changes and changes in productivity of some breeding colonies have been observed (Byrd *et al*. 2008; Gaston and Woo 2008; Moe *et al*. 2009). Negative trends in population size, observed over the last few decades for several species of widespread Arctic seabirds, may be related to over-harvesting and pollution as well as climate change effects (Gaston, 2011). For those species whose distribution is limited by sea ice and cold water, polar warming could be beneficial (Mehlum 2012).

A major ecosystem shift in the Northern Bering Sea starting in the mid 1990s caused by increased temperatures and reduced sea ice cover had a negative impact on benthic prey for diving birds and these populations have declined in the area (Grebmeier *et al.*, 2006). More recently, the Bering Sea has turned colder again.

28.2.2.2. Antarctica

Productivity and food web dynamics in the Southern Ocean are dominated by the extreme seasonal fluctuations of irradiance and the dynamics of sea ice, along with temperature, carbonate chemistry and vertical mixing (Massom and Stammerjohn, 2010; Boyd *et al.*, 2012; Murphy *et al*., 2012a). Moreover, there is large-scale regional variability in habitats (Grant *et al*., 2006) and their responses to climate change (WGI). Antarctic krill, *Euphausia superba* (hereafter, 'krill') is the dominant consumer, eating diatoms, and, in turn, is the main prey of fish, squid, marine mammals and seabirds. Krill is dominant from the Bellingshausen Sea east through to the Weddell Sea and the Atlantic sector of the Southern Ocean (Rogers *et al.*, 2012). In the East Indian and southwest Pacific sectors of the Southern Ocean, the krill-dominated system lies to the south of the Southern Boundary of the Antarctic Circumpolar Current (Nicol *et al.*, 2000a,b) while to the north copepods and myctophid fish are most important (Rogers *et al.*, 2012). Further west, where the Weddell Sea exerts an influence, krill are found as far north as the Subantarctic Circumpolar Current Front (Jarvis *et al.*, 2010). Where sea ice dominates for most of the year, ice-obligate species (e.g. *Euphausia crystallorophias* and *Peluragramma antarcticum*) are most important (Smith *et al.*, 2007).

Few studies were available in AR4 to document and validate the changes in these systems resulting from climate change. Those studies reported increasing abundance of benthic sponges and their predators, declining populations of krill, Adélie and emperor penguins, and Weddell seals, and a possible increase in salps, noting some regional differences in these trends. The importance of climate processes in generating these changes could not be distinguished from the indirect consequences of the recovery of whale and seal populations from past over-exploitation (Trathan and Reid, 2009; Murphy *et al*., 2012a,b).

28.2.2.2.1. Marine plankton, krill, fish, and other invertebrates

Distributions of phytoplankton and zooplankton have moved south with the frontal systems (Hinz *et al.*, 2012; Mackey *et al.*, 2012), including range expansion into the Southern Ocean from the north by the coccolithophorid, *Emiliania huxleyi* (Cubillos *et al.*, 2007), and the red-tide dinoflagellate *Noctiluca scintillans* (McLeod *et al.*, 2012) (*medium confidence*). There is *insufficient evidence* to determine whether other range shifts are occurring.

Collapsing ice shelves are altering the dynamics of benthic assemblages by exposing areas previously covered by ice shelves, allowing increased primary production and establishment of new assemblages (e.g. collapse of the Larson A/B ice shelves) (Peck *et al.*, 2009; Gutt *et al.*, 2011) (*medium confidence*). More icebergs are grounding, causing changes in local oceanography and declining productivity that consequently affects productivity of benthic assemblages (Thrush and Cummings 2011) (*low confidence)*. Iceberg scour on shallow banks is also increasing, disrupting resident benthic assemblages (Barnes and Souster 2011; Gutt *et al.*, 2011) (*medium confidence*).

Primary production is changing regionally in response to changes in sea ice, glacial melt and oceanographic features (Arrigo *et al.*, 2008; Boyd *et al.*, 2012) (*medium confidence*). Off the west Antarctic Peninsula, phytoplankton stocks and productivity have decreased north of 63°S, but increased south of 63°S (Montes-Hugo *et al.*, 2009) (WGII Chapter 6) (*high confidence*). This study (based on time-series of satellite-derived and measured chlorophyll concentrations) also indicated a change from diatom-dominated assemblages to ones dominated by smaller phytoplankton (Montes-Hugo *et al.*, 2009). The reduced productivity in the north may be tempered by increased inputs of iron through changes to ocean processes in the region (Dinniman *et al.*, 2012) (*low confidence*).

Since the 1980s, Antarctic krill densities have declined in the Scotia Sea (Atkinson *et al*., 2004), in parallel with regional declines in the extent and duration of winter sea ice (Flores *et al.*, 2012). Uncertainty remains over changes in the krill population because this decline was observed using net samples and is not reflected in acoustic abundance time series (Nicol and Brierley 2010); the observed changes in krill density may have been partly a result of changes in distribution (Murphy *et al*. 2007). Nevertheless, given its dependence on sea ice (Nicol *et al.*, 2008) the krill population may already have changed and will be subject to further alterations (*high confidence*).

The response of krill populations is probably a complex response to multiple stressors. Decreases in recruitment of post-larval krill across the Scotia Sea have been linked to declines in sea-ice extent in the Antarctic Peninsula region (Wiedenmann *et al.,* 2009) (*medium confidence*) but these declines may have been offset by increased growth arising from increased water temperature in that area (Wiedenmann *et al.*, 2008). However, near South Georgia krill productivity may have declined as a result of the increased metabolic costs of increasing temperatures (Hill *et al.,* 2013) (*low confidence*). The combined effects of changing sea ice, temperature and food have not been investigated.

28.2.2.2.2. Marine mammals and sea birds

In general, many Southern Ocean seals and seabirds exhibit strong relationships to a variety of climate indices, and many of these relationships are negative to warmer conditions (Trathan *et al.*, 2007; Barbraud *et al.*, 2012; Forcada *et al.*, 2012) (*low confidence*). Regional variations in climate change impacts on habitats and food will result in a mix of direct and indirect effects on these species. For example, Adélie penguin colonies are declining in recent decades throughout the Antarctic Peninsula while the reduction in chinstrap penguins is more regional (Lynch *et al.,* 2012) and related to reductions in krill availability (Lima and Estay, 2013). In contrast gentoo penguins are increasing in that region and expanding south (Lynch *et al.*, 2012) (*high confidence*). This may be explained by the reduced sea ice habitats and krill availability in the north resulting in a southward shift of krill predators, particularly those dependent on sea ice (Forcada *et al.,* 2012) and the replacement of these predators in the north by species that do not depend on sea ice, such as gentoo penguins and elephant seals (Costa *et al.*, 2010; Trivelpiece *et al.*, 2011; Ducklow *et al.,* 2012; Murphy *et al.,* 2013) (*low confidence*). A contrasting situation is in the Ross Sea where Adélie penguin populations have increased (Smith *et al.*, 2012). The mechanisms driving these changes are currently under review and may be more than simply sea ice (Lynch *et al.*, 2012; Melbourne-Thomas et al., 2013). For example, too much or too little sea ice may have negative effects on the demography of Adélie and emperor penguins (see Barbraud *et al.,* 2012 for review). Also, increased snow precipitation which accumulates in breeding colonies can decrease survival of chicks of Adélie penguins when accompanied by reduced food supply (Chapman *et al.,* 2011).

Changes elsewhere are less well known. Some emperor penguin colonies have decreased in recent decades (Barbraud *et al.,* 2008; Jenouvrier *et al.,* 2009) (*low confidence*) and one breeding site has been recorded as having been vacated (Trathan *et al.,* 2011). However, there is *insufficient evidence* to make a global assessment of their current trend. In the subantarctic of the Indian sector, reductions in seal and seabird populations may indicate a region-wide shift to a system with lower productivity (Weimerskirch *et al.,* 2003; Jenouvrier *et al.,* 2005a, b) (*low confidence*) but commercial fishing activities may also play a role.

Where frontal systems are shifting south, productive foraging areas also move to higher latitudes. In the Indian sector, this is thought to be causing declines in king penguin colonies on subantarctic islands (Péron *et al.,* 2010) (*low confidence*), while the shift in wind patterns may be causing changes to the demography of albatross (Weimerskirch *et al.,* 2012) (*low confidence*).

As identified in the last assessment, some species' populations may suffer as a result of fisheries while others are recoverying from past over-exploitation, either of which may confound interpretation of the response of these species and their food webs to climate change. The recovery of Antarctic fur seals on some subantarctic islands has been well documented and their populations may now be competing with krill-eating macaroni penguins (Trathan *et al.,* 2012). More recently, there has been confirmation that populations of some Antarctic whales are recovering, such as humpbacks (Nicol *et al.*, 2008; Zerbini *et al.*, 2010), suggesting that food is currently not limiting. In contrast, a number of albatross and petrel populations are declining as a result of incidental mortality in longline fisheries in southern and temperate waters where these birds forage (Croxall *et al.*, 2012).

28.2.3. Terrestrial Ecosystems

28.2.3.1. Arctic

Arctic terrestrial ecosystems have undergone dramatic changes throughout the late Pleistocene and Holocene (last 130 000 years) mainly driven by natural climate change. Significant altitudinal and latitudinal advances and retreats in tree line have been common, animal species have gone extinct, and animal populations have fluctuated significantly throughout this period e.g. (Lorenzen *et al.*, 2011; Salonen *et al.*, 2011; Mamet and Kershaw, 2012).

28.2.3.1.1. Phenology

Phenological responses attributable to warming are apparent in most Arctic terrestrial ecosystems (*medium confidence*). They vary from earlier onset and later end of season in western Arctic Russia (Zeng *et al.*, 2013), to little overall trend in plant phenology in the Swedish sub Arctic (Callaghan *et al.*, 2010), to dramatic earlier onset of phenophases in Greenland (Høye *et al*., 2007; Post *et al.*, 2009a; Callaghan *et al.*, 2011a) (Figure 28-2).

[INSERT FIGURE 28-2 HERE
Figure 28-2: Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initiation dates (birds) in high-Arctic Greenland. Red dots are statistically significant, blue dots are not. Source: Høye *et al.*, 2007.]

28.2.3.1.2. Vegetation

The latest assessment of changes in NDVI (Normalized Difference Vegetation Index, a proxy for plant productivity) from satellite observations between 1982 and 2012 shows that about a third of the Pan-Arctic has substantially greened, <4% browned and > 57% did not change significantly (Xu et al., 2013) (Figure 28-3). The greatest increases reported in recent years were in the North American high Arctic, along the Beaufort Sea and the east European Arctic (Zhang *et al.*, 2008; Pouliot *et al.*, 2009; Bhatt *et al.*, 2010; Forbes *et al.*, 2010; Walker *et al.*, 2011; Epstein *et al.*, 2012; Macias-Fauria *et al.*, 2012; Xu *et al.*, 2013).

[INSERT FIGURE 28-3 HERE
Figure 28-3: Significant changes ($p< 0.01$) in photosynthetically active period NDVI between 1982 and 2012. Source: Xu et al., 2013.]

The positive trends in NDVI are associated with increases in the summer warmth index (sum of the monthly-mean temperatures above freezing expressed as ^{o}C per month) that have increased on average by 5^{o}C per month for the Arctic as a whole (Xu *et al.*, 2013). However, the even greater 10 to 12^{o}C per month increase for the land adjacent to the Chukchi and Bering Seas (Figure 28-3) was associated with decreases in NDVI. On the Yamal Peninsula in Russia the pattern of NDVI is partly due to surface disturbance, such as landslide activity (Walker *et al.*, 2009). Small rodent cycles reduce NDVI in sub Arctic Sweden, by decreasing biomass and changing plant species composition (Olofsson *et al.*, 2012). The changing NDVI signal should therefore generally be interpreted with care.

In common with treeline trees and herbs, the abundance and biomass of deciduous shrubs and graminoids (grasses and grass-like plants) have increased substantially in certain parts of the Arctic tundra in recent years, but remained stable or decreased in others (*very high confidence*). Attribution for the increases and decreases in deciduous shrubs and graminoids is heterogeneous with drivers varying among different regions (*very likely*), including Arctic warming, differences in herbivory, industrial development, legacies from past land use, and changes in moisture (Post and Pedersen 2008; Olofsson *et al.*, 2009; Forbes *et al.*, 2009 and 2010; Kitti *et al.*, 2009; Kumpula *et al.*, 2011 and 2012; Myers-Smith *et al.*, 2011; Elmendorf *et al.*, 2012b;Callaghan *et al.*, 2011b and 2013: Gamon *et al.*, 2013).

Shrubs have generally expanded their ranges and/or growth over the last 20 years (Danby and Hik, 2007; Hudson and Henry, 2009; Forbes *et al.*, 2010; Hallinger *et al.*, 2010; Rundqvist *et al.*, 2011; Hedenås *et al.*, 2011; Hill and Henry, 2011; Myers-Smith *et al.*, 2011a,b; Callaghan *et al.*, 2011b; Elmendorf *et al.*, 2012a,b; Macias-Fauria *et al.*, 2012), and have varied from dramatic, i.e. 200% area increase in study plots (Rundqvist *et al.*, 2011) in sub arctic Sweden to early invasion of a fell field community on west Greenland by low shrubs (Callaghan *et al.*, 2011a).

A synthesis (61 sites: (Elmendorf *et al.*, 2012a) of experimental warming studies of up to 20 years duration in tundra sites worldwide, showed, overall, increased growth of deciduous shrubs and graminoids, decreased cover of mosses and lichens, and decreased species diversity and evenness. Elmendorf et al., (2012a) point out that the groups that increased most in abundance under simulated warming were graminoids in cold regions and primarily shrubs in warm regions of the tundra. However, strong heterogeneity in responses to the experimental warming suggested that other factors could moderate the effects of climate warming significantly like herbivory, differences in soil nutrients and pH, precipitation, winter temperatures and snow cover, and species composition and density.

Snow bed habitats have decreased in sub arctic Sweden (Björk and Molau, 2007; Hedenås *et al.*, 2011). In other plant communities, changes have been less dramatic, ranging from small increases in species richness in the south west Yukon of the Canadian sub Arctic (Danby *et al.*, 2011), through subtle changes in plant community composition in west and southeast Greenland (Daniëls and De Molenaar, 2011; Callaghan *et al.*, 2011a) to 70 year stability of a plant community on Svalbard (Prach *et al.*, 2010).

The responses to Arctic warming of lichen and bryophyte (mosses) diversity have been heterogenous, varying from consistent negative effects to significant increases in recent years (Hudson and Henry, 2009; Tømmervik *et al.*, 2009; Tømmervik *et al.*, 2012). Forbes and Kumpula (2009) recorded long-term and widespread lichen degradation in northern Finland attributed more to trampling of dry lichens by reindeer in summer than winter consumption as forage.

Palaeorecords of vegetation change indicate that the northern tree line should extend upwards and northwards during current climate warming (Callaghan *et al.*, 2005) because tree line is related to summer warmth (e.g. Harsch *et al.*, 2009). Although the tree line has moved northwards and upwards in many Arctic areas, it has not shown a general circumpolar expansion in recent decades (*high confidence*).

Model projections that suggest a displacement of between 11 and 50% of tundra by forest by 2100 (see references in Callaghan *et al.*, 2005) and shifts upslope by 2 to 6 m per year (Moen *et al.*, 2004) and northwards by 7.4–20 km per year (Kaplan and New, 2006) might be overestimating rate of tree line advance by a factor of up to 2000 (Van Bogaert *et al.*, 2011). The fastest upslope shifts of tree lines recorded during 20th century warming are 1 to 2 m per year (Shiyatov *et al.*, 2007; Kullman and Öberg, 2009) whereas the fastest so-far recorded northward-migrating tree line replaces tundra by taiga at a rate of 3–10 m per year (Kharuk *et al.*, 2006). In some areas, the location of the tree line has not changed or has changed very slowly (Payette, 2007; MacDonald *et al.*, 2008a). A global study by Harsch *et al.* (2009) showed that only 52% of 166 global tree line sites studied had advanced over the past 100 years. In many cases the tree line has even retreated (Cherosov *et al.*, 2010). At the small scale, the tree line has shown increase, decrease and stability in neighboring locations (Van Bogaert *et al.*, 2011; Lloyd *et al.*, 2011).

Evidence for densification of the forest at the sub Arctic tree line is robust and consistent within Fennoscandia (Tømmervik *et al.*, 2009; Rundqvist *et al.*, 2011; Hedenås *et al.*, 2011) and Canada (Danby and Hik, 2007). Dendroecological studies indicate enhanced conifer recruitment during the twentieth century in the northern Siberian taiga (Briffa *et al.*, 2008). Some of the changes are dramatic, such as an increase in area of mountain birch in study plots in northern Sweden by 600% between 1977/8 and 2009/10 (Rundqvist *et al.*, 2011) and a doubling of tree biomass in Finnmarksvidda in northern Norway since 1957 (Tømmervik *et al.*, 2009). However, model projections of displacement of deciduous forest by evergreen forest (Wolf *et al.*, 2008; Wramneby *et al.*, 2010) have not so far been validated.

Where the mountain birch tree line has increased in elevation and shrub (e.g. willow, dwarf birch) abundance has increased, the response can be an interaction between climate warming, herbivory pressure and earlier land use

(Olofsson *et al.*, 2009; Hofgaard *et al.*, 2010; Van Bogaert *et al.*, 2011). In Fennoscandia and Greenland, heavy grazing by large herbivores may significantly check deciduous low erect shrub (e.g. dwarf shrub and willow) growth (Post *et al.*, 2008; Kitti *et al.*, 2009; Olofsson *et al.*, 2009).

Less moisture from snow and more rain now favors broadleaf trees over conifers and mosses in some areas (Juday, 2009) while moisture deficits are reducing the growth of some northern forests (Goetz *et al.*, 2005; Verbyla, 2008; Yarie, 2008) and making them more susceptible to insect pest outbreaks (see references in (Callaghan *et al.*, 2011c). Death of trees through drought stress or insect pest activity will increase the probability of fire that will have positive feedbacks (increase warming) on the climate (Mack *et al.*, 2011).

28.2.3.1.3. Changes in animal populations

The documented collapse or dampening of population cycles of voles and lemmings over the last 20-30 years in parts of Fennoscandia and Greenland (Schmidt *et al.*, 2012), can be attributed with *high confidence* to climate change (Ims *et al.*, 2007; Gilg *et al.*, 2009; Ims *et al.*, 2011; Kausrud *et al.*, 2009). A shortening of the snow season and more thaw and/or rain events during the winter will influence on the subnivean space which provide thermal insulation, access to food, and protection from predators (Berg *et al.*, 2008; Johansson *et al.*, 2011; Kausrud et al., 2009). However, the causes of the changes in the lemming and vole cycles are still being debated as factors other than climate change may also be of importance (Brommer *et al.*, 2010; Krebs, 2011).

Climate-mediated range expansion both in altitude and latitude of insect pests, and increased survival due to higher winter temperatures, has been documented for bark beetles in North America (Robertson *et al.*, 2009) and for geometrid moths in Fennoscandia (Jepsen *et al.*, 2008; Callaghan *et al.*, 2010; Jepsen *et al.*, 2011), causing more extensive forest damage than before. Outbreaks of insect pests like geometrid moths can even reduce the strengths of CO_2 sinks in some areas (Heliasz *et al.*, 2011).

The decline in wild reindeer and caribou (both *Rangifer tarandus*) populations in some regions of about 30 percent over the last 10-15 years has been linked both to climate warming and anthropogenic landscape changes (Post et al., 2009a; Vors and Boyce 2009; Russell and Gunn 2010). Even though most of the Arctic has warmed, the decline in the populations has not been uniform. Some of the North American large, wild herds have for example declined by 75-90 percent, while other wild herds and semi-domestic herds in Fennoscandia and Russia have been stable or even increased (Gunn *et al.*, 2009; Vors and Boyce, 2009; Joly *et al.*, 2011; Forbes *et al.*, 2009; Forbes 2010; Kumpula *et al.*, 2012).

The expected and partially observed increased primary productivity of Arctic tundra may potentially increase the supply of food for Arctic ungulates. However, the overall quality of forage may decline during warming, for example if the nitrogen content of key fodder species for ungulates were to drop during warming (Turunen *et al.*, 2009; Heggberget *et al.*, 2010), while lichen biomass, an important winter fodder for reindeer, is decreasing over parts of the Arctic region. Herbivory also changes the vegetation itself in concert with the warming, further complicating the prediction of vegetation changes and their impacts on ungulate populations (van Der Wal *et al.*, 2007; Turunen *et al.*, 2009).

More frequent rain-on-snow icing events and thicker snow-packs caused by warmer winters and increased precipitation may restrict access to vegetation and may have profound negative influences on the population dynamics of Arctic ungulates (Berg *et al.*, 2008; Forchhammer *et al.*, 2008; Miller and Barry, 2009; Stien *et al.*, 2010; Hansen *et al.*, 2011; Stien *et al.*, 2012). Such events have caused heavy mortality in some semi-domestic reindeer herds and musk oxen in recent years (Grenfell and Putkonen, 2008; Forbes, 2009; Bartsch *et al.*, 2010), and have also been shown to synchronize the dynamics of a resident vertebrate community (small mammals, reindeer and Arctic fox) in Svalbard (Hansen *et al.*, 2013). In contrast, Tyler *et al.* (2008) and Tyler (2010) suggested that generally warmer winters enhance the abundance of reindeer populations.

It has been suggested that warming-induced trophic mismatches between forage availability and quality and timing of calving have a role in the decline of circumpolar reindeer and caribou populations (Post and Forchhammer, 2008; Post *et al.*, 2009a,b), although such trophic mismatch has been disputed (Griffith *et al.*, 2010).

Adjustment via phenotypic plasticity instead of adaptation by natural selection is expected to dominate vertebrate responses to rapid Arctic climate change, and many such adjustments have already been documented (Gilg *et al.*, 2012).

28.2.3.1.4. Long-term trends and event-driven changes

Long-term climate change impacts on vegetation and animal populations are accelerated when tipping points are triggered by events such as extreme weather, fire, insect pest and disease outbreaks. The impacts of winter thaw events on ecosystems are now well-documented e.g. (Bokhorst *et al.*, 2011) but studies of the severe impacts of tundra fires on vegetation and biospheric feedbacks are recent (Mack *et al.*, 2011). Results from experimental winter thaws were validated by a natural event in northern Norway and Sweden in 2007 that reduced NDVI by almost 30% over at least 1400 km^2 (Bokhorst *et al.*, 2009). Studies on relationships between climate change and plant disease are rare but Olofsson *et al.*, (2011) showed that increased snow accumulation led to a higher incidence of fungal growth on sub Arctic vegetation.

28.2.3.2. Antarctica

Antarctic terrestrial ecosystems occur in 15 biologically-distinct areas (Terauds *et al.*, 2012) with those in the maritime and sub-Antarctic islands experiencing the warmest temperatures, reduced extreme seasonality and greatest biodiversity (Convey, 2006). In the cooler conditions on the continent, species must be capable of exploiting the short periods where temperature and moisture availability are above physiological and biochemical thresholds. In many areas there is no visible vegetation, with life being limited, at the extreme, to endolithic (within rock) communities of algae, cyanobacteria, fungi, bacteria and lichens (Convey, 2006).

Few robust studies are available of biological responses to observed climatic changes in natural Antarctic terrestrial ecosystems. The rapid population expansion and local-scale colonisation by two native flowering plants (*Deschampsia antarctica* and *Colobanthus quitensis*) in maritime Antarctica (Parnikoza *et al.*, 2009) remains the only published repeat long-term monitoring study of any terrestrial vegetation or location in Antarctica. Radiocarbon dating of moss peat deposits has shown that growth rates and microbial productivity have risen rapidly on the Antarctic Peninsula since the 1960s, consistent with temperature changes, and are unprecedented in the last 150 years (Royles *et al*., 2013). In east Antarctica moss growth rates over the last 50 yrs have been linked to changes in wind speed and temperature and their influence on water availability (Clarke *et al.*, 2012). A contributing factor is that air temperatures have increased past the critical temperature at which successful sexual reproduction (seed set) can now take place, changing the dominant mode of reproduction, and increasing the potential distance for dispersal (Convey, 2011) (*low confidence*). Similar changes in the local distribution and development of typical cryptogamic vegetation of this region have been reported (Convey, 2011), including the rapid colonisation of ice free ground made available through glacial retreat and reduction in extent of previously permanent snow cover (Olech and Chwedorzewska, 2011). As these vegetation changes create new habitat, there are concurrent changes in the local distribution and abundance of the invertebrate fauna that then colonise them (*low confidence*).

28.2.4. Health and Well-Being of Arctic Residents

The warming Arctic and major changes in the cryosphere are significantly impacting the health and well-being of Arctic residents and projected to increase – especially, for many indigenous peoples. While impacts are expected to vary among the diverse settlements that range from small, remote predominantly indigenous to large cities and industrial settlements, this section focuses more on health impacts of climate change on indigenous, isolated, and rural populations because they are especially vulnerable to climate change due to a strong dependence on the environment for food, culture and way of life; their political and economic marginalization; existing social, health, poverty disparities; as well as their frequent close proximity to exposed locations along ocean, lake or river shorelines (Ford and Furgal, 2009; Galloway-McLean, 2010; Larsen *et al.*, 2010; Cochran *et al.*, 2013).

28.2.4.1. Direct Impacts of a Changing Climate on the Health of Arctic Residents

Direct impacts of climate changes on the health of Arctic residents include extreme weather events, rapidly changing weather conditions, and increasingly unsafe hunting conditions (physical/mental injuries, death, disease), temperature-related stress (limits of human survival in thermal environment, cold injuries, cold-related diseases), and UV-B radiation (immunosuppression, skin cancer, non-Hodgkin's lymphoma, cataracts) (Revich, 2008; AMAP, 2009 ; IPCC, 2012). Intense precipitation events and rapid snowmelt are expected to impact the magnitude and frequency of slumping and active layer detachment resulting in rock falls, debris flow, and avalanches (Kokelj *et al.*, 2009; Ford *et al.*, 2010). Other impacts from weather, extreme events, and natural disasters are the possibility of increasingly unpredictable, long duration and/or rapid onset of extreme weather events, storms, inundation by large storm surges, which, in turn, may create risks to safe travel or subsistence activities, loss of access to critical supplies and services to rural or isolated communities (e.g. food, fuel, telecommunications), and risk of being trapped outside one's own community (Laidre *et al.*, 2008; Parkinson, 2009; Brubaker *et al.*, 2011b). Changing river and sea ice conditions affect the safety of travel for indigenous populations especially, and inhibit access to critical hunting, herding and fishing areas (Andrachuk and Pearce, 2010; Derksen *et al.*, 2012; Huntington and Watson, 2012).

Cold exposure has been shown to increase the frequency of certain injuries (e.g. hypothermia, frostbite) or accidents, and diseases (respiratory, circulatory, cardiovascular, musculoskeletal skin) (Revich and Shaposhmikov, 2010). Studies in Northern Russia have indicated an association between low temperatures and social stress and cases of cardiomyopathy (Revich and Shaposhnikov, 2010). It is expected that winter warming in the Arctic will reduce winter mortality rates, primarily through a reduction in respiratory and cardiovascular deaths (Shaposhnikov *et al.*, 2010). Researchers project that a reduction in cold-related injuries may occur, assuming that the standard for protection against the cold is not reduced (including individual behavior-related factors) (Nayha, 2005). Conversely, studies are showing respiratory and cardio stress associated with extreme warm summer days and that rising temperatures are accompanied by increased air pollution and mortality, especially in Russian cities with large pollution sources (Revich, 2008; Revich and Shaposhnikov, 2012).

28.2.4.2. Indirect Impacts of Climate Change on the Health of Arctic Residents

Indirect effects of climate change on the health of Arctic residents include a complex set of impacts such as changes in animal and plant populations (species responses, infectious diseases), changes in the physical environment (ice and snow, permafrost), diet (food yields, availability of country food), the built environment (sanitation infrastructure, water supply system, waste systems, building structures), drinking water access, contaminants (local, long-range transported), and coastal issues (harmful algal blooms, erosion) (Maynard and Conway, 2007; Brubaker *et al.*, 2011a; Parkinson and Evengard, 2009; Chapter 11).

In addition to the climate change impacts and processes, are the complicated impacts from contaminants such as POPs (persistent organic pollutants), radioactivity, and heavy metals (e.g., mercury) which create additional and/or synergistic impacts on the overall health and well-being of all Arctic communities (Armitage *et al*., 2011; UNEP/AMAP, 2011; Teran *et al*., 2012). Ambient temperature variability and temperature gradients directly affect the volatilization, remobilization, and transport pathways of mercury and POPs in the atmosphere, ocean currents, sea ice and rivers. Transport pathways, intercompartmental distribution, bioaccumulation and transformation of environmental contaminants such as persistent organic pollutants (POPs), mercury (Hg) and radionuclides in the Arctic may consequently be affected by climate change (AMAP 2011;UNEP/AMAP 2011; Ma *et al.*, 2011; Teng *et al.*, 2012) (*high confidence*). Ma *et al.* (2011) and Hung *et al*. (2010) demonstrated that POPs are already being remobilized into the air from sinks in the Arctic region as a result of decreasing sea ice and increasing temperatures.

Contaminants and human health in the Arctic are tightly linked to the climate and Arctic ecosystems by factors such as contaminant cycling and climate (increased transport to and from the Arctic), and the related increased risks of transmission to residents through subsistence life ways (Maynard, 2006; AMAP, 2010; Armitage *et al*., 2011; UNEP/AMAP 2011; Teran *et al*., 2012). The consumption of traditional foods by indigenous peoples places these populations at the top of the Arctic food chain and through biomagnification, therefore, they may receive some of the highest exposures in the world to certain contaminants (Armitage *et al.*, 2011; UNEP/AMAP, 2011). Contaminants such as POPs are known for their adverse neurological and medical effects on humans, particularly, the developing fetus, children, women of reproductive age and the elderly, thus it is important to include contaminants as a significant part of any climate impact assessment (UNEP/AMAP, 2011).

Radioactivity in the Arctic is also a concern because there are many potential and existing radionuclide sources in some parts of the Arctic and contamination can remain for long periods of time in soils and some vegetation, creating potentially high exposures for people (AMAP, 2010). Climate changes can mobilize radionuclides throughout the Arctic environment, and also potentially impact infrastructure associated with nuclear activities by changes in permafrost, precipitation, erosion, and extreme weather events (AMAP, 2010).

Warming temperatures are enabling increased overwintering survival and distribution of new insects that sting and bite as well as many bird, animal, and insect species that can serve as disease vectors and, in turn, causing an increase in human exposure to new and emerging infectious diseases (Parkinson *et al.*, 2008; Epstein and Ferber, 2011). Examples of new and emerging diseases are tick-borne encephalitis (brain infection) in Russia and Canada (Ogden *et al.*, 2010; Tokarevich *et al.*, 2011) and Sweden (Lindgren and Gustafson, 2001), *Giardia* spp. and *Cryptosporidium* spp. infection of ringed seals (*Phoca hispida*) and bowhead whales (*Balaena mysticetus*) in the Arctic Ocean (Hughes-Hanks *et al.*, 2005). It is also expected that temperature increases will increase the incidence of zoonotic diseases as relocations of animal populations occur (Revich et al., 2012; Hueffler *et al.*, 2013).

Harmful algal blooms (HABs), whose biotoxins can be a serious health hazard to humans or animals (paralysis, death), are increasing globally and expected to increase in the Arctic, and HABS are influenced directly by climate change related factors such as temperature, winds, currents, nutrients and runoff (Portier *et al.*, 2010; Epstein and Ferber, 2011; Walsh *et al.*, 2011; Chapters 6; 11). Increasing ocean temperatures have caused an outbreak of a cholera-like disease, Vibrio parahaemolyticusin, in Alaskan oysters (McLaughlin *et al.*, 2005). In addition, warmer temperatures raise the possibility of anthrax exposure in Siberia from permafrost thawing of historic cattle burial grounds (Revich and Podolnaya, 2011).

The impacts of climate change on food security and basic nutrition are critical to human health because subsistence foods from the local environment provide Arctic residents, especially, indigenous peoples, with unique cultural and economic benefits necessary to well-being and contribute a significant proportion of daily requirements of nutrition, vitamins and essential elements to the diet (Ford and Berrang-Ford, 2009; Ford, 2009). However, climate change is already an important threat due to the decrease in predictability of weather patterns, low water levels and streams, timing of snow, ice extent and stability, impacting the opportunities for successful hunting, gathering, fishing and access to food sources and increasing the probability of accidents (Ford and Furgal, 2009; Ford et al., 2010). Populations of marine and land mammals, fish and water fowl are also being reduced or displaced, thus, reducing the traditional food supply (Gearheard *et al.*, 2006; West and Hovelsrud, 2010; Lynn *et al.*, 2013).

Traditional food preservation methods such as drying of fish and meat, fermentation, and ice cellar storage are being compromised by warming temperatures, thus further reducing food available to the community (Brubaker *et al.*, 2011b). For example, food contamination caused by thawing of permafrost "ice cellars" is occurring and increasingly wet conditions make it harder to dry food for storage (Hovelsrud *et al.*, 2011). Indigenous people increasingly have to abandon their semi-nomadic lifestyles, limiting their overall flexibility to access traditional foods from more distant locations (www.arctichealthyukon.ca). These reductions in the availability of traditional foods plus general globalization pressures are forcing indigenous communities to increasingly depend upon expensive, non-traditional and often less healthy western foods, increasing the rates of modern diseases associated with processed food and its packaging, such as cardiovascular diseases, diabetes, dental cavities, and obesity (Armitage *et al.*, 2011; Berrang-Ford *et al.*, 2011; Brubaker *et al.*, 2011b).

Climate change is beginning to threaten community and public health infrastructure, often in communities with no central water supply and treatment sources. This is especially serious in low-lying coastal Arctic communities (e.g., Shishmaref, Alaska, USA; Tuktoyaktuk, Northwest Territories, Canada) through increased river and coastal flooding and erosion, increased drought and thawing of permafrost, resulting in loss of reservoirs, damage to landfill sites, or sewage contamination (GAO, 2009; Bronen, 2011). Salt-water intrusion and bacterial contamination may also be threatening community water supplies (Parkinson *et al.*, 2008; Virginia and Yalowitz, 2012). Quantities of water available for drinking, basic hygiene and cooking are becoming limited due to damaged infrastructure, drought, and changes in hydrology (Virginia and Yalowitz, 2012). Disease incidence caused by contact with human waste may increase when flooding and damaged infrastructure spreads sewage in villages with no municipal water supply. This can result in higher rates of hospitalization for pneumonia, influenza, skin infections, and respiratory viral infections (Parkinson and Evengard, 2009; Virginia and Yalowitz, 2012). Compounding these impacts in rural areas as well as cities are respiratory and other illnesses caused by airborne pollutants (e.g., contaminants, microbes, dust, mold, pollen, smoke) (Revich, 2008; Rylander and Schilling, 2011; Revich and Shaposhnikov, 2012).

It is now well-documented that the many climate-related impacts on Arctic communities are causing significant psychological and mental distress and anxiety among residents (Portier *et al.*, 2010; Coyle and Susteren, 2012; AR5 Chapter 11; Levintova, 2010). For example, changes in the physical environment (e.g., through thawing permafrost and erosion) which may lead to forced or voluntary relocation of residents out of their villages or loss of traditional subsistence species are causing mental health impacts among indigenous and other vulnerable, isolated populations (Curtis *et al.*, 2005; Albrecht *et al.*, 2007; Coyle and Susteren, 2012; Maldonado et al, 2013). Special concern has been expressed by many communities about the unusually high and increasing numbers of suicides in the Arctic especially among indigenous youth, and efforts are under way to try to develop a thorough assessment as well as establish effective intervention efforts (Albrecht *et al.*, 2007; Portier *et al.*, 2010; USARC, 2010).

28.2.5. Indigenous Peoples and Traditional Knowledge

Indigenous populations in the Arctic – the original Native inhabitants of the region – are considered especially vulnerable to climate change, due to their close relationship with the environment and its natural resources for physical, social, and cultural well-being (Nuttall *et al.*, 2005; Parkinson, 2009; Cochran *et al.*, 2013). Arctic indigenous peoples are estimated to number between 400,000 and 1.3 million (Bogoyavlensky and Siggner, 2004; Galloway-McLean, 2010). According to the 2010 census data, there are 68,3 thousand indigenous people living in the Russian Arctic. These Arctic residents depend heavily on the region's terrestrial, marine and freshwater renewable resources, including fish, mammals, birds, and plants; however, the ability of indigenous peoples to maintain traditional livelihoods such as hunting, harvesting, and herding is increasingly being threatened by the unprecedented rate of climate change (Nakashima *et al.*, 2012; Cochran *et al.*, 2013). In habitats across the Arctic, climate changes are affecting these livelihoods through decreased sea ice thickness and extent, less predictable weather, severe storms, sea level rise, changing seasonal melt/freeze-up of rivers and lakes, changes in snow type and timing, increasing shrub growth, permafrost thaw, and storm-related erosion which, in turn, are causing such severe loss of land in some regions that a number of Alaskan coastal villages are having to relocate entire communities (Oskal, 2008; Mahoney *et al.*, 2009; Forbes and Stammler, 2009; Bartsch *et al.*, 2010; Weatherhead *et al.*, 2010; Brubaker *et al.*, 2011b; Bronen, 2011; Bongo *et al.*, 2012; Eira *et al.*, 2012; McNeeley, 2012; Huntington and Watson, 2012; Maldonado *et al.*, 2013). In addressing these climate impacts, indigenous communities must at the same time consider multiple other stressors such as resource development (oil and gas, mining), pollution, changes in land use policies, changing forms of governance, and the prevalence in many indigenous communities of poverty, marginalization, and resulting health disparities (Abryutina, 2009; Reinert et al., 2009; Magga et al., 2011; Nakashima *et al.*, 2012 Vuojala-Magga *et al.*, 2011).

Traditional knowledge is the historical knowledge of indigenous peoples accumulated over many generations and it is increasingly emerging as an important knowledge base for more comprehensively addressing the impacts of environmental and other changes as well as development of appropriate adaptation strategies for indigenous communities (IPCC AR4; IPCC AR5, chp 15; Oskal, 2008; Reinert *et al.*, 2008; Wildcat, 2009; Nakashima *et al.*, 2012; Magga *et al.*, 2011; Vuojala-Magga *et al.*, 2011; Vogesser et al, 2013) For example, Saami reindeer herders have specialized knowledge of dynamic snow conditions, which mediate access to forage on autumn, winter and spring reindeer rangelands (Roturier and Roue, 2009; Eira *et al.*, 2012; Vikhamar-Schuler *et al.*, 2013) and traditional governance systems for relating to natural environments (Sara, 2013). Increasingly, traditional knowledge is being combined with western scientific knowledge to develop more sustainable adaptation strategies for all communities in the changing climate.

For example, at Clyde River, Nunavut, Canada, Inuit experts and scientists both note that wind speed has increased in recent years and that wind direction changes more often over shorter periods (within a day) than it did during the past few decades (Gearheard *et al.*, 2010; Overland et al., 2012). In Norway, Sámi reindeer herders and scientists are both observing direct and indirect impacts to reindeer husbandry such as changes in snow and ice cover, forage availability and timing of river freeze-thaw patterns from increasing temperatures. (Eira *et al.*,2012). On the Yamal Peninsula in western Siberia, detailed Nenets observations and recollections of iced-over autumn and winter pastures due to rain-on-snow events have proven suitable for calibrating the satellite-based microwave sensor SeaWinds (Bartsch *et al.*, 2010) and NASA's AMSR-E sensor (Bongo *et al.*, 2012).

28.2.6. Economic Sectors

28.2.6.1. Arctic

28.2.6.1.1. Agriculture and forestry

Climate change presents benefits and costs for forestry and agriculture (Aaheim *et al.*, 2009; Hovelsrud *et al.*, 2011). In Iceland for example tree limits are found at higher altitudes than before, and productivity of many plants has increased (Björnsson *et al.*, 2011). Grain production in Iceland, has increased in the last two decades, and work on soil conservation and forestry has benefited from warming (Sigurdsson *et al.*, 2007; Björnsson *et al.*, 2011), but also the number of new insect pests on trees and shrubs has increased in the past 20 years. A strong relationship between rate of new insect pest colonisation and outbrake intensity in forests exists with changes in annual temperature during the past century (Halldórsson *et al.*, 2013). Climate change impacts on species change and fire frequency have potential impact on commercial forest harvesting activity. Vulnerability of forestry to changes that affect road conditions and thus accessibility during thawing periods has been found in Sweden (Keskitalo, 2008). A case study on Greenland found challenges for plant diseases in potatoes and grass fields, with pathogens and pests present in agricultural cropping systems, e.g. black scurf (Rhizoctonia) and common scab (Streptomyces scabies) (Neergaard *et al.*, 2009).

28.2.6.1.2. Open and freshwater fisheries

Current commercial fisheries are sharply divided between regions of high-yield and value commercial fisheries in the southern Bering Sea, Baffin Bay, the east and west Greenland Seas, the Iceland Shelf Sea, the deep Norwegian/Greenland Sea, and the Barents Seas and subsistence fisheries in the coastal regions of the Arctic Ocean. The relative absence of commercial fishing activity in the Arctic Ocean results from a combination of fisheries policy, the abundance of the resource, the lack of infrastructure for capturing and processing fish, and the difficulties in accessing fishing grounds especially during winter. In most regions, fisheries management strategies have been developed to build sustainable fisheries and rebuild overfished stocks (Froese and Proelß, 2010; Livingston *et al.*, 2011). Recently observed changes in the spatial distribution and abundance of mackerel (*Scomber scombrus*) has challenged existing international agreements for shared resources in the North Atlantic (Arnason, 2012; Astthorsson *et al.*, 2012). Although loss of sea ice in summer is allowing greater access to fisheries resources in the Arctic Ocean, some nations have prohibited commercial fishing within their EEZ until there is sufficient understanding of stock status to ensure that proposed fisheries would be managed sustainably (Wilson and Ormseth, 2009; Stram and Evans, 2009).

Several Arctic coastal sea-run fishes are targeted for subsistence and commercial use in the Arctic. Commercial transactions from fishing are typically for local markets, however, the socioeconomic and cultural importance of these fishes to Indigenous Peoples far outweighs their monetary value. Reist *et al.* (2006) and Fechhelm *et al.* (2007)

found that climate related factors that influenced the water level and freshening of rivers were related to run size of arctic cisco (*Coregonus autumnalis*). Similarly, a recent study based on Chinook salmon (*Oncorhynchus tshawytscha*) run timing for the period (1961-2009) showed that success in the fishery was dependent on the timing of the marine exit, which was tightly coupled to environmental conditions that were linked to climate (Mundy and Evenson, 2011).

28.2.6.1.3. Marine transportation

Observations and climate models indicate that in the period between 1979-1988 and 1998-2007 the number of days with ice free conditions (less than 15% ice concentration) increased by 22 days along the Northern Sea Route (NSR) in the Russian Arctic, and by 19 days in the Northwest Passage (NWP) in the Canadian Arctic, while the average duration of the navigation season in the period 1980-1999 was 45 and 35 days, respectively (Mokhow and Khon, 2008). Increased shipping associated with the opening of the NSR will lead to increased resource extraction on land and in the sea, and with two-way commodity flows between the Atlantic and Pacific. The future status of marine, terrestrial and freshwater biota may be negatively affected due to substantial coastal infrastructure to facilitate offshore developments (Meschtyb *et al.*, 2010). Also, the frequency of marine transportation along the NSR is at its highest during the most productive and vulnerable season for fish and marine mammals, which is the late spring/summer, when these resources can be found throughout the NSR area (Østreng, 2006).

28.2.6.1.4. Infrastructure

Much of the physical infrastructure in the Arctic rely on and are adapted to local sea-ice conditions, permafrost, and snow (Huntington *et al.*, 2007; Sundby and Nakken, 2008; West and Hovelsrud, 2010; Forbes, 2011; Sherman *et al.*, 2009). Damage from ice action and flooding to installations such as bridges, pipelines, drilling platforms, and hydropower poses major economic costs and risks, which are more closely linked to the design of the structure than with thawing permafrost. Current engineering practices are designed to help minimize the impacts (Prowse *et al.*, 2009). Much of the infrastructure has been built with weather conditions in mind, but remains vulnerable and inadequate to respond to environmental emergencies, natural disasters, and non-environmental accidents (NRTEE, 2009). Northern safety, security, and environmental integrity are much dependent upon transportation infrastructure. Ice as a provisioning system provides a transportation corridor and a platform for a range of activities and access to food sources in the Arctic (Eicken *et al.*, 2009).

In Northern Canada climate warming presents an additional challenge for northern development and infrastructure design. While the impacts of climate change become increasingly significant over the longer time scales, in the short term of greater significance will be the impacts associated with ground disturbance and construction (Smith and Risebrough, 2010).

Climate change impacts have increased the demand for improved communication infrastructure and related services and community infrastructure for the safety and confidence in drinking water (NRTEE, 2009). The access, treatment and distribution of drinking water is generally dependent upon a stable platform of permafrost for pond or lake retention. Several communities have reported the need for more frequent water-quality testing both municipal systems and untreated water sources to ensure its suitability for drinking (Furgal, 2008).

28.2.6.1.5. Resource exploration

The Arctic has large reserves of minerals (Lindholt, 2006; Peters *et al.*, 2011; Harsem *et al.*, 2011) and potentially large reserves of undiscovered sources of raw minerals, and oil and gas. Predicted new access to offshore energy resources is hypothesized to be a significant share of the global supply of oil and gas (Gautier *et al.*, 2009; Berkman *et al.*, 2010).The socio-economic impacts of oil and gas exploration activity may be positive or negative (Duhaime *et al.*, 2004; Huntington *et al.*, 2007; Forbes, 2008; Kumpula *et al.*, 2011; Forbes *et al.*, 2009; Harsem *et al.*, 2011).

Climatic warming is accelerating access to northern lands for development (Forbes *et al.*, 2009). Yamal in Western Siberia has approximately 90 % of Russia's gas reserves, but at the same time represents the largest area of reindeer herding in the world (Jernsletten and Klokov, 2002; Stammler, 2005; Forbes and Kumpula, 2009). Development activities to obtain these resources would shrink the grazing lands, and have been characterized as one of the major human activities in the Arctic contributing to loss of "available room for adaptation" for reindeer husbandry (Oskal, 2008; Forbes *et al.*, 2009; Nuttall *et al.*, 2005). Sharp increases in future oil and gas and other resource development in the Russian North and other Arctic regions is anticipated - along with associated infrastructure, pollution, and other by products of development – which will reduce the availability of pasturelands for reindeer and indigenous communities (Derome and Lukina, 2011; Degteva and Nellermann, 2013).

28.2.6.1.6. Informal, subsistence-based economy

Hunting, gathering, herding, and fishing for subsistence, as well as commercial fishing, all play an important role in the mixed cash-subsistence economies (Nuttall *et al.*, 2005; Poppel and Kruse, 2009; Larsen and Huskey, 2010; Crate *et al.*, 2010). In the early 1990s – initially in western Canada, and later elsewhere - indigenous communities started reporting climate change impacts (Berkes and Armitage, 2010). According to some herders, whalers and walrus hunters non-predictable conditions resulting from more frequent occurrence of unusual weather events are the main effect of recent warming (Forbes and Stammler, 2009; Ignatowski and Rosales, 2013; Forbes *et al.*, 2009).

The Inuit and Saami have expressed strong concern about the effects of climate warming on their livelihoods (Forbes and Stammler, 2009; Magga *et al.*, 2011). For the Inuit, the issues revolve around sea ice conditions, such as later freeze-up in autumn, earlier melt-out and faster sea ice retreat in spring, and thinner, less predictable ice in general (Krupnik and Jolly, 2002; Cochran *et al.*, 2013). Diminished sea ice translates into more difficult access for hunting marine mammals, and greater risk for the long-term viability of subsistence species such as polar bear populations (Laidre *et al.*, 2008). Most Inuit communities depend to some extent on marine mammals for nutritional and cultural reasons, and many benefit economically from polar bear and narwhal hunting. A reduction in these resources represents a potentially significant economic loss (Hovelsrud *et al.*, 2008). Among Fennoscandian Saami, the economic viability of reindeer herding is threatened by competition with other land users coupled with strict agricultural norms (Forbes, 2006; Magga *et al.*, 2011). Reindeer herders are concerned that more extreme weather may exacerbate this situation (Oskal, 2008).

Climate change is affecting reindeer herding communities through greater variability in snow melt/freeze, ice, weather, winds, temperatures and precipitation, which, in turn are affecting snow quality and quantity – the most critical environmental variables for reindeer sustainability (Magga *et al.*, 2011; Eira *et al.*, 2012). Increasing temperature variations in wintertime, with temperatures rising above freezing with rain, followed by refreezing ("rain-on-snow" conditions), are becoming more frequent, forming ice layers in the snow which then block the animals' access to their forage and subsequent starvation (Maynard *et al.*, 2011; Eira *et al.*, 2012; Bongo *et al.*, 2012).

28.2.6.2. Antarctica and the Southern Ocean

Economic activities in the Antarctic have been limited to fishing and tourism (IPCC WG2, 2007). Ship-based tourism is a significant industry in Antarctica but does not involve permanent shore-based infrastructure. Over recent decades, the number of tourists landing in Antarctica has risen from 7322 in 1996/1997 to 32,637 in 2007/2008 (IAATO, 2012). Visits generally coincide with the times when wildlife are breeding and are often restricted because of the presence of fast ice, sea ice or icebergs. They are expected to continue to increase, with an increasing chance of terrestrial alien species being introduced from tourism and other vectors as ice-free areas increase from climate change (Chown *et al.*, 2012). Scientific activity by a number of nations is also taking place and has the potential to impact upon local ecologies. Mineral resource activity is prohibited south of 60°S under the Protocol on Environmental Protection to the Antarctic Treaty.

Fisheries in Antarctica, primarily through fisheries for Antarctic krill, could amount to approximately 6% of existing global marine capture fisheries (Nicol *et al.*, 2011). The pattern of the krill fishery has been affected by changes in the sea ice extent around the Antarctic Peninsula where the fishery has been taking advantage of the ice-free conditions and taking more of its catch during winter in that region (*high confidence*) (Kawaguchi *et al.*, 2009). Ecosystem-based management of krill fisheries by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) is yet to include procedures to account for climate change impacts, although the need to do so has been identified (Trathan and Agnew, 2010; Constable, 2011).

28.3. Key Projected Impacts and Vulnerabilities

28.3.1. Hydrology and Freshwater Ecosystems

28.3.1.1. Arctic

Accompanying projected increases in high-latitude river flow (WGI Ch.12.4.5.4. and WGII Ch. 3.4.5.) are earlier spring runoff (Dankers and Middelkoop, 2008; Hay and McCabe, 2010; Pohl *et al.*, 2007), greater spring snowmelt (Adam *et al.*, 2009) and increases in spring sediment fluxes (Lewis and Lamoureux, 2010). Enhanced permafrost thaw (WGI Ch. 12.4.6.2) will continue to affect the dynamics of thermokarst lakes and related ecological effects (Section 28.2.1.1). Thawing permafrost and changes in the hydrological regime of the Arctic rivers, particularly those traversing regions affected by industrial developments, will increase the contaminant flow (Nikanorov *et al.*, 2007). Loss of glacier ice masses will alter runoff hydrographs, sediment loads, water chemistry, thermal regimes, and related channel stability, habitat and biodiversity (Milner et al., 2009; Moore et al. 2009).

Although snow, freshwater ice and permafrost affect the morphology of arctic alluvial channels, their future combined effects remain unclear (McNamara and Kane, 2009). For small permafrost streams, however, longer projected periods of flowing water will modify nutrient and organic matter processing (Greenwald *et al.*, 2008; Zarnetske *et al.*, 2008) but long-term negative impacts of increased sediment load on biological productivity could outweigh any positive effects from increased nutrient loading (Bowden *et al.*, 2008).

Changes to river-ice flooding are also projected to occur due to changes in i) hydraulic gradients for near-coastal locations because of sea-level rise, ii) streamwise air-temperature gradients, and iii) the timing and magnitude of spring snowmelt (Prowse et al. 2011). Synergistic/antagonistic effects among these factors, however, require detailed site-specific analyses for accurate projections of future conditions (Beltaos and Prowse, 2009). Reduced (increased) ice-jam flooding will have positive (negative) benefits for river-side northern communities/infrastructure but could also alter delta-riparian (Lesack and Marsh, 2010) and coastal-marine (Emmerton *et al.*, 2008) ecosystems. The quality of river water entering the marine environment will also be affected by the reduction or loss of stamukhi lakes that process river inputs (Dumas *et al.*, 2006; Galand *et al.*, 2008).

Future changes to lake-ice regimes will include: delayed freeze-up, advanced break-up, thinner ice and changes in cover composition (especially white ice in areas of enhanced winter precipitation), increased water temperature, and earlier and longer-lasting summer stratification (Dibike et al. 2011), all of which will affect a range of aquatic processes, including secondary productivity (Prowse and Brown, 2010b; Borgstrøm and Museth, 2005; Prowse *et al.*, 2007). Patterns of species richness and diversity are also projected to change with alterations to ice duration - increased open-water periods favouring the development of new trophic levels, colonization of new aquatic species assemblages (Vincent *et al.*, 2009), greater atmosphere-water gas exchange and a decrease in winter kill of resident fish with cascading effects on lower trophic levels (Balayla *et al.*, 2010). The loss of ice, however, can also decrease key habitat availability and quality (Vincent *et al.*, 2008).

Geochemical responses of Arctic lakes will also be altered. As observed for thermokarst lakes, the loss of ice cover and associated warming can greatly increase methane production (Laurion *et al.*, 2010; Metje and Frenzel, 2007). Because temperature sensitivity has a stronger control over methane production than oxidation (Duc *et al.*, 2010), elevated water temperatures will enhance methanogenesis, causing increased methane release from sediments. The net balance of these two processes operating under a broad range of future changing environmental factors, however, remains to be quantified (Laurion *et al.*, 2010; Walter *et al.*, 2007a, b; 2008).

As well as methane, increased water temperatures are projected to lead to reduced organic carbon (OC) burial. Projections, based on a range of six climate warming scenarios (Solomon *et al.*, 2007), indicates that there will be a 4-27% decrease (0.9-6.4 TgC yr-1) in OC burial across lakes of the northern boreal zone by the end of the 21st Century as compared to rates for the approximately last half-century (Gudasz *et al.*, 2010). Although these estimates assume that future organic carbon delivery will be similar to present-day conditions, even with enhanced supply from thawing permafrost, higher water temperatures will increase organic carbon mineralization and thereby lower burial efficiency. The amount of burial also depends on lake depth and mixing regimes. For non-thermally stratified shallow lakes, there will be a greater opportunity for water-sediment mixing and hence, greater carbon recycling back into the water column. By contrast, for lakes that become increasingly thermally stratified, carbon sinking below the thermocline will tend not to return to the surface until an increasing later fall turnover, thereby decreasing the probability of sediment-stored carbon being returned to the water column (Flanagan *et al.*, 2006).

Changes in ice cover, thermal regimes and stratification patterns will also affect the fate of contaminants in northern lakes. Higher water temperatures can enhance the methylation of mercury and modify food-web and energy pathways, such as through enhanced algal scavenging (a major foodweb entry pathway for mercury) resulting in increased mercury bio-availability to higher trophic levels (Carrie *et al.*, 2010; Outridge *et al.*, 2007).

28.3.1.2. Antarctica

This assessment reinforces conclusions of AR4. Increased temperatures will impact aquatic ecosystems in Antarctica (*high confidence*) but the exact nature of these impacts will vary regionally. The most vulnerable freshwater systems are in the northern Antarctic Peninsula and maritime Antarctic islands, where a small increase in temperature can have widespread ecosystem impacts because the average temperature is within a few degrees of the melting point (Quesada and Velázquez 2012) (*high confidence*). Potential impacts are expected to range from immediate catastrophic impacts such as loss of bounding ice masses causing drainage of freshwater and epishelf lakes (Smith *et al.*, 2006; Hodgson, 2011), to more gradual impacts on changes in the amount and duration of catchment ice and snow cover, accelerated glacier melting, declining volumes of precipitation falling as snow, permafrost, active layer and hydrological changes, such as water retention times (e.g. Vieira *et al.*, 2010, Quesada and Velázquez 2012, Bockheim *et al.*, 2013) (*medium confidence*).

Changes in the thickness and duration of seasonal ice cover, longer melt seasons and larger volumes of water flowing into the lakes are expected in the future (Lyons *et al.*, 2006) (*medium confidence*) but the ecological effects will vary between lakes, depending on their depth to surface area ratio, with *insufficient evidence* to fully assess future changes in these systems. Longer ice free seasons may cause physical conditions to be more favorable for primary production (Hodgson and Smol 2008) but very high irradiances experienced during summer in some systems can substantially inhibit algal blooms under ice free conditions (Tanabe *et al.*, 2007), which would favor the growth of benthic cyanobacteria species (Hodgson *et al.*, 2005). In other lakes, increases in meltwater supply may increase suspended solids and reduce light penetration and may offset the increases in the underwater light regime predicted as a result of extended ice free periods (Quesada *et al.*, 2006).

Under a warming climate an increase in microbial biomass is likely because of the increased water supply from glacial melt and warmer temperatures, and could result in further development of soils and elevated nutrient and dissolved organic carbon delivery to lakes (Velázquez *et al.*, 2013). This organic supply will promote growth and reproduction in the benthos and plankton and imbalances in population dynamics (Quesada and Velázquez, 2013). Nutrient enrichment of some freshwater habitats in the vicinity of fur seal colonies will increase because of expanding fur seal populations (Quayle *et al*. 2013) (*high confidence*).

Away from glacial forelands, increasing aridity will occur in the long-term in some areas of the continent (Hodgson *et al.*, 2006b) and on subantarctic islands (Smith Jr *et al.*, 2012) (*medium confidence*). Closed basin lakes can dry up completely causing local extinctions or retreat into cryptic or resistant life-cycle stages, as experienced in Arctic lakes (Smol and Douglas, 2007b). Other effects include dessication of moss banks due to increased evaporation and sublimation rates (Wasley *et al.*, 2006) (*medium confidence*). Studies have also shown that warming of once cold freshwater habitats in Antarctica will allow the sub- and maritime Antarctic species to re-invade and establish self-maintaining populations on the Antarctic continent, particularly where human vectors are involved (Barnes *et al.*, 2006, Hodgson *et al.*, 2006b) (*medium confidence*). For other organisms with lower dispersal capabilities there is increasing evidence of endemism, particularly in microbial groups (Vyverman *et al.*, 2010), with a possibility that surface Antarctic lakes contain endemic species that are relicts of Gondwana (cf. Convey and Stevens 2007) and that would become extinct should they be lost from these lakes as a result of climate change..

28.3.2. Oceanography and Marine Ecosystems

28.3.2.1. Ocean Acidification in the Arctic and Antarctic

Ocean acidificaiton on polar marine food webs can have considerable implications (*medium certainty*). For example, if some regions in the Arctic become understaturated with respect to aragonite (the primary structural component of the shells of some marine calcifiers such as mollusks and urchins) the growth and survial of these organisms will be impacted (WG I, Chapter 6 Figure 6.28; Chierici and Fransson, 2009; Fabry *et al.*, 2009; Yamamoto-Kawai *et al.*, 2009). In laboratory experiments, Arctic pteropods (*Limacina helicina*, a small planktonic mollusk) held under conditions consistent with projected ocean warming and acidification in the Arctic Ocean in early spring were able to extend their shells in corosive waters but dissolution marks were observed (Comeau *et al.*, 2010; Comeau *et al.*, 2012). Additional studies are needed to scale up regional impacts to assess the population level impact of ocean acidification on *Limacina helicina* and other vulnerable species (Orr *et al.*, 2009). At the current time there is insufficient data to fully assess the ecosystem consequences of acidification on pteropods because it is unclear whether other species, with a similar nutritive value, will replace pteropods.

In the Southern Ocean, foraminifera have thinner shells than in the Holocene and there is evidence for shell thickness to be related to atmospheric CO_2, supporting the hypothesis that ocean acidification will affect this abundant protozoan in this region (Moy *et al.*, 2009). Similarly, shells are thinner from sediment traps in aragonite under-saturated water (below the aragonite saturation horizon - ASH) compared to those captured above the ASH in Subantarctic waters, but there is no time series of data related to change in the ASH (Roberts *et al.*, 2011). Shell dissolution has been observed in surface waters in the Atlantic sector as a result of both upwelling and atmosperhic changes in CO_2 (Bednarsek *et al.*, 2012) (*medium confidence*). Other impacts of acidification on Southern Ocean organisms are currently uncertain, but short term negative impacts need to be considered together with an organism’s capacity to adapt in the longer term (Watson *et al.*, 2012).

Only a few studies have been conducted on commercially exploited polar species on ocean acidification. Antarctic krill embryonic development (Kawaguchi *et al.*, 2011) and post-larval krill metabolic physiology (Saba *et al.*, 2012) may be impeded by elevated CO_2 concentrations, which may negatively impact the reproductive success of krill more generally under emission scenarios used in CMIP5 (Kawaguchi *et al.*, 2013) (*medium confidence*). Long et al. (2013) examined the effects of acidification on red king crab (*Paralithodes camtschaticus*) and found animals exposed to reduced pH exhibited increased hatch duration, decreased egg yolk, increased larval size, and decreased larval survival. In contrast, Hurst *et al.*, (2012) conducted laboratory experiments at levels of elevated CO_2 predicted to be present in the Gulf of Alaska and Bering Sea in the next century and found that juvenile walleye pollock exhibited a general resiliency of growth energetics to the direct effects of CO_2 changes.

28.3.2.2. Arctic

28.3.2.2.1. Marine plankton, fish, and other invertebrates

Phenological response

Projected changes in the timing, spatial distribution and intensity of spring blooms may result in mis-matches with the timing of the emergence of Arctic grazers (Søreide *et al.*, 2010). Based on past experience, some species will adapt to local conditions by shifting key life cycle events (hatch-date, maturity schedule and reproductive timing) or diet to accommodate differences in the regional timing and availability of prey and environmental conditions (Ormseth and Norcross, 2007; Sundby and Nakken, 2008; Vikebø *et al*., 2010, Darnis *et al.*,2012). For example, loss of sea ice cover in spring is expected to change fish behavior in ice bound areas (Mundy and Evenson, *2011*). It is uncertain whether endemic animals will be able to alter key phenologies fast enough to keep pace with the projected rates of change in the Arctic Ocean.

Projected spatial shifts

Simulation studies revealed that a 2 week longer growing season and a 2 degree C increase in temperature would not be sufficient to allow expatriate species (*Calanus finmarchicus* or *C. marshallae*) to invade the Arctic Ocean (Ji *et al.,* 2012). Ellingsen *et al.,* (2008) projected future zooplankton distribution and abundance in the Barents Sea for the period 1995-2059 using a regional climate model which was forced with climate model output based on the IPCC-SRES B2 scenario. They projected that by 2059, Atlantic origin zooplankton will increase and Arctic origin zooplankton will decrease in the Barents Sea.

The literature is mixed with respect to the potential for future movement of fish and shellfish into the Arctic Ocean. Modeling studies project that marine fish stocks potentially will shift their distributions into the Arctic Ocean resulting in an increase in biodiversity in the region (Cheung *et al.,* 2009; Cheung *et al.,* 2011; Box CC-MB). However, other studies show the persistence of cold sea water temperatures on the shelf regions of the Arctic Ocean and Northern Bering Sea will restrict or retard the movement of several sub-arctic fish and shellfish species into the Arctic Ocean (Sigler *et al.,* 2011; Stabeno *et al.,* 2012b; Hunt *et al.,* 2013). In waters off the coasts of Europe there is a potential for increased fish production because of the combined effects of intrusion of Atlantic water over the relatively broader shelf regions and advective corridors for larval drift and range expansion of spawners. Huse and Ellingsen (2008) forced a spatially explicit coupled bio-physical model for the Barents Sea with future climate scenarios to project the implications of climate change on the spawning distribution of capelin (*Mallotus villosus*). Projections show that the spawning distribution of capelin will shift to the east and new spawning grounds will be colonized. A key factor governing this expansion will be the availability of pelagic prey. In the Bering Sea, there is evidence that planktivorous species like walleye pollock (*Theragra chalcogramma*) in the eastern Bering Sea will shift their distribution in response to shifts in ocean temperature (Kotwicki and Lauth, 2013). In summary, the spatial distribution of fish and shellfish in the Barents and Bering Seas will shift in response to climate change (*high confidence*)

Projected impacts on production

In the deep basins of the Arctic Ocean the number of ice free days in summer are expected to result longer productive seasons (Slagstad *et al.,* 2011, *high confidence*). Ellingsen *et al.* (2008) projected that annual primary production would increase by 2059 in the Barents Sea. Tremblay *et al.* (2012) hypothesized that longer ice free periods in summer in the Arctic Ocean could provide for more opportunities for episodic nutrient pulses that would enhance secondary production through the growing season. However, in the Arctic Ocean, these changes in primary production may be offset later in the year by increased zooplankton grazing (Olli *et al.,* 2007) or nutrient depletion due to stronger stratification and shifts in the mixed layer depth (Tremblay *et al.,* 2012; Wassmann, 2011). Therefore, there is *medium confidence* that annual phytoplankton production will increase the central Arctic Ocean.

In the few cases where future abundance of fish has been projected using climate change scenarios, species exhibited different trends related to their vulnerability. Forward extrapolation of observed responses suggests that increased summer sea surface temperatures in the Bering Sea and Barents Sea will cause a decrease in the abundance of energy rich copepods and euphausiids (Coyle *et al.*, 2011; Slagstad *et al.*, 2011). This change in prey quality is expected to lower survival of walleye pollock in the eastern Bering Sea by 2050 (Mueter *et al.*, 2011). Climate enhanced stock projection models showed time trends in cross-shelf transport of juvenile northern rock sole (*Lepidopsetta polyxystra*) to nursery areas will not be substantially altered by climate change (Wilderbuer *et al.*, 2012).

28.3.2.2.2. Marine mammals, polar bear, and seabirds

The effects of the projected reduction is sea ice extent in this century (Wang and Overland, 2011) on Arctic marine mammals and sea birds will vary spatially and temporally (Laidre *et al.*, 2008). Many ice-associated marine mammals and sea birds will be affected by ice loss with altered species distributions, migration patterns, behaviour, interspecific interactions, demography, population changes, and vulnerability to extinction but there is limited evidence of changes for most species (*high confidence*).

The polar bear population of the Southern Beaufort Sea is projected to decline by 99% by 2100 with a probability estimated at 0.80-0.94 under A1B (Hunter *et al.*, 2010). The Northern Beaufort Sea population is stable although decline is predicted with warming (Stirling *et al.*, 2011). Projected extirpation of approximately two-thirds of the world’s polar bears was predicted for mid-century under A1B (Amstrup *et al.*, 2008). Aspects of this study were criticized (Armstrong *et al.*, 2008) but refuted (Amstrup *et al.*, 2009). The two-thirds decline is consistent with other studies and has robust evidence with *medium agreement*. Projected extinction of polar bears is *unlikely*. There is *very high confidence* of subpopulation extirpation.

Several factors other than climate influence sea bird population dynamics (Regular *et al.*, 2010), and projections of changes with a continued Arctic warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA, 2005). At present, the resolution of AOGCMs are not detailed enough to project spatial changes in mesoscale oceanographic features like frontal zones and eddies of importance to Arctic sea birds.

It is likely that the high Arctic seabird species partly or completely dependent on the sympagic ecosystem or the cold Arctic waters close to the ice-edge will be negatively impacted if the projected changes in these physical parameters occur (medium *confidence*). A general increase in SSTs, retreat of the ice cover, and earlier break up of fast ice may improve the environmental conditions and food abundance for sea bird species that have their range in the southern part of the Arctic or south of the Arctic (medium *confidence*). A poleward expansion of the range of these species is expected during a continued warming (*medium confidence*).

Several factors other than climate influence sea bird population dynamics (Regular *et al.*, 2010), and projections of changes with a continued Arctic warming are therefore highly uncertain. Pattern of change will be non-uniform and highly complex (ACIA 2005). At present, the resolution of AOGCMs are not detailed enough to project spatial changes in mesoscale oceanographic features like frontal zones and eddies of importance to Arctic sea birds.

28.3.2.3. Antarctica and the Southern Ocean

Continued rising temperatures in the Southern Ocean will result in increased metabolic costs in many ectothermic pelagic species, southward movement of temperate species and contraction of the range of polar species (*medium confidence*). Southward movement of ocean fronts and associated biota that are prey of subantarctic island-based predators, will result in energetic inefficiencies for some of those predators (Péron *et al.*, 2012; Weimerskirch *et al.*, 2012) (*low confidence*).

For Antarctic krill, *insufficient evidence* is available to predict what will happen to the circumpolar productivity of krill because of regional variability of the effects of climate change on the different factors (positive and negative) that affect krill, directly and indirectly. For example, increased metabolic and growth rates from warming may be countered by a reduced food supply and the effects of ocean acidification (28.2.2.2, 28.3.2.1). Also, areas that are already warm may result in slower growth with further warming, such as could happen in the northern Scotia Arc (Wiedenmann *et al.,* 2008; Hill *et al.,* 2013). Models of recruitment and population dynamics indicate that the biomass of krill will decline if surface warming continues, but preliminary projections incorporating a range of factors are uncertain (*low confidence*) (Murphy *et al.,* 2007, 2012b). Physiological and behavioural responses might also ameliorate impacts. For example, krill are now known to exploit the full depth of the ocean, which could provide escapes from further warming (Schmidt *et al.,* 2011) as well as refuge from air-breathing predators.

The strong dependence of species in more southern regions (e.g. southern west Antarctic Peninsula, WAP, and Ross Sea region) on sea-ice means that changes in sea-ice distribution will cause spatial shifts in the structure of ice-obligate food webs (Murphy *et al.,* 2012b) (*low confidence*). Projections show that the loss of summer sea ice from the west Antarctic Peninsula is expected to result in ice-dependent seals declining and being replaced by other seal species that are not dependent on sea ice (Siniff *et al.,* 2008, Costa *et al.,* 2010) (*low confidence*). There is *insufficient evidence* to determine whether there will be a mismatch in phenologies of different species as a result of changes in the winter sea ice season (timing and winter extent), such as might occur if the timing of sea ice melt was not at a time of optimal growing conditions for phytoplankton (Trathan and Agnew, 2010).

Reductions in krill abundance in the marine food webs around the South Atlantic islands may result in a shift in their structure towards a more fish-centred ecosystem as observed in the Indian Sector (Trathan, et al., 2007; Shreeve *et al.,* 2009; Waluda *et al.,* 2010; Trathan *et al.,* 2012; Murphy *et al.,* 2012a; Murphy *et al.,* 2012b) (*low confidence*). Also, salps have been postulated to be competitors with krill for phytoplankton around the Antarctic Peninsula when oceanic conditions displace shelf and near-shelf waters during times of low sea ice (Ducklow *et al.,* 2012). In the absence of krill, longer food chains have lower trophic efficiency (Murphy *et al.,* 2012; Muprhy *et al.,* 2013) and the long-term implications of this for higher trophic levels are unknown.

Coastal environments will be impacted by the dynamics of fast ice, ice shelves and glacier tongues. These factors will positively affect local primary production and food web dynamics (Peck *et al.,* 2009) but negatively affect benthic communities (Barnes and Souster, 2011) (*low confidence*). Projections of the response of emperor penguins and Southern Ocean seabirds based on AR4 model outputs for sea ice and temperature in east Antarctica indicate that general declines in these populations are to be expected if sea ice habitats decline in the future (Barbraud *et al.,* 2011; Jenouvrier *et al.,* 2012) (*low confidence*). However, these responses are also expected to be regionally specific because of the regional differences in expectations of change in the ice habitats (*high confidence*). Additional studies at other sites are needed to improve confidence levels of predictions.

28.3.3. Terrestrial Environment and Related Ecosystems

28.3.3.1. Arctic

The boreal forest is generally projected by models to move northward under a warming climate, that will displace between 11% and 50% of the tundra within 100 years (Callaghan *et al.,* 2005; Wolf *et al.,* 2008; Tchebakova *et al.,* 2009; Wramneby *et al.,* 2010 in a pattern similar to that which occurred during the early Holocene climatic warming (*high confidence*). Pearson *et al.* (2013) projected that at least half of vegetated Arctic areas will shift to a different physiognomic class, and woody cover will increase by as much as 52%, in line with what has been occurring in northwest Eurasia (Macias-Fauria et al. 2012).

Dynamic vegetation models applied to Europe and the Barents Region project a general increase in net annual primary production by climate warming and CO_2 fertilization (Wolf *et al.,* 2008; Wramneby *et al.,* 2010; Anisimov *et al.,* 2011). Boreal needle-leaved evergreen coniferous forest replaces tundra and expands into the mountain areas of Fennoscandia, but this advance may be delayed or prevented in regions already occupied by clonal deciduous shrubs whose *in situ* growth has increased significantly in recent decades (Macias-Fauria et al. 2012).

In contrast to these expected results, shrubs, currently expanding in area in many Arctic locations, were modelled to decrease in extent over the next 100 years after an initial increase (Wolf *et al.,* 2008). Also counter-intuitively, tundra areas increased in the projections. This was a result of changes at the highest latitudes that opened land for colonisation at a rate exceeding displacement of tundra by shrubs in the south.

Several studies have calculated the magnitude of the effects of vegetation change in the Arctic on negative feedbacks of CO_2 sequestration and increased evapo-transpiration and the positive feedback of decreased albedo (Swann *et al.,*2010; Wramneby *et al.,* 2010; Wolf et al., 2010; Pearson *et al.,* 2013). It is *likely* that vegetation changes will result in an overall positive feedback on the climate.

Recent changes and results of climate change simulation experiments in the field have shown that there are considerable uncertainties in the projected rates of change e.g. (Van Bogaert *et al.* 2010). Furthermore, the models do not yet include vertebrate and invertebrate herbivory, extreme events such as tundra fire and extreme winter warming damage or changes in land use that either reduce the rate of vegetation change or open up niches for rapid change. Projections suggest increases in the ranges of the autumn and winter moths that have outbreaks in populations resulting in the defoliation of birch forest (Jepsen *et al.,* 2008 and 2011), and a general increase in the "background" (non-outbreak) invertebrate herbivores (Wolf *et al.,* 2008).

Animal terrestrial biodiversity is generally projected to increase in the Arctic during warming by immigration of new species from the south, vegetation changes, and indirectly by introduction of invasive species caused by increased human activities and increased survival of such species (*high confidence*) (Post *et al.,* 2009; Gilg *et al.,* 2012; CAFF 2013). Many native Arctic species will *most likely* be increasingly threatened during this century.

28.3.3.2. Antarctica

Projected effects of climate change on Antarctic terrestrial species are limited to knowledge of their ecophysiological tolerances to changes in air temperature, wind speed, precipitation (rain and snowfall), permafrost thaw and exposure of new habitat through glacial/ice retreat. The climate is expected to become more tolerable to a number of species, leading to increases in biomass and extent of existing ecological communities.

The frequency with which new potential colonising plant and animal species arrive in Antarctica (particularly the Antarctic Peninsula region) from lower latitudes, and the subsequent probability of their successful establishment will increase with regional climate warming and associated environmental changes (Chown *et al.,* 2012) (*high confidence*). Human-assisted transfers of biota may be more important by two orders of magnitude than natural introductions (Frenot *et al.,* 2005) as the transfer is faster and avoids extreme environments such as altitude or oceans (Barnes *et al.,* 2006). The potential for anthropogenic introduction of non-indigenous species to Antarctic terrestrial areas, which could have devastating consequences to the local biodiversity, will increase (Convey *et al.,* 2009; Convey, 2011, Hughes and Convey, 2010; Braun *et al.,* 2012) (*high confidence*). At present, established non-indigenous species in the sub- and maritime Antarctic are very restricted in their distributions (Frenot *et al.,* 2005). Climate change could result in a greater rate of spread of invasive species through colonisation of areas exposed by glacial retreat, as has occurred at South Georgia (Cook *et al.,* 2010) and in the maritime Antarctic (Olech and Chwedorzewska 2011). Biosecurity measures may be needed to help control dispersal of established non-indigenous species to new locations, particularly given the expected increase in human activities in terrestrial areas (Hughes and Convey, 2010; Convey *et al.,* 2011). An important gap in understanding is the degree to which climate change may facilitate some established but localised alien species to become invasive and widespread (Frenot *et al.,* 2005; Convey 2010; Hughes and Convey 2010; Cowan *et al.,* 2011), which has been shown for the sub-Antarctic (Chown *et al.,* 2012).

Overall, the likely impacts of existing and new non-indigenous species on the native terrestrial ecosystems of Antarctica and the sub-Antarctic islands, along with the continued increased presence of Antarctic fur seals are likely to have far greater importance over the timescale under consideration than are those attributable to climate change itself (Turner *et al.,* 2009; Convey and Lebouvier, 2009; Convey, 2010).

28.3.4. Economic Sectors

Projections of economic costs of climate change impacts for different economic sectors in the Arctic are limited, but current assessments suggest that there will be both benefits and costs (Forbes, 2011; AMAP, 2011). Non-Arctic actors are likely to receive most of the benefits from increased shipping and commercial development of renewable and non-renewable resources, while indigenous peoples and local Arctic communities will have a harder time maintaining their way of life (Hovelsrud *et al.,* 2011).

Contributing to the complexity of measuring the future economic effects of climate change is the uncertainty in future predictions and the rapid speed of change, which are linked with the uncertainty of the technological and ecological effects of such change (NorAcia, 2010). Communities within the same eco-zone may experience different effects from identical climate-related events because of marked local variations in site, situation, culture and economy (Clark *et al.,* 2008).

Economic cost estimates have been made for the case of the Alaskan economy, for example, which suggest that a heavy reliance on climate-sensitive businesses such as tourism, forestry, and fisheries, renders the economy vulnerable to climate change, and that Alaska Native peoples, reliant on the biodiversity of the Alaskan ecosystem, are being affected disproportionately (Epstein and Ferber, 2011). Some Alaskan villages such as Shishmaref, Kivalina, and Newtok have already lost critical infrastructure and services and are becoming unlivable due to storm damage and coastal erosion but the high costs and limitations of government mechanisms are significant barriers to the actual relocation of these communities (Bronen, 2011; Cochran *et al.*, 2013; Maldonado *et al.*, 2013).

28.3.4.1. Fisheries

Climate change will impact the spatial distribution and catch of some open ocean fisheries in the Barents and Bering Seas (*high certainty*). The future of commercial fisheries in Arctic Ocean is uncertain. There is strong evidence and considerable data showing links between climate driven shifts in ocean conditions and shifts in the spatial distribution and abundance of commercial species in the Bering and Barents Seas (Section 28.3.2.2.1). In limited cases, coupled bio-physical models or climate enhanced stock projection models have been used to predict future commercial yield or shifts in fishing locations. However, these predictions are uncertain (Huse and Ellingsen, 2008; Ianelli *et al.,* 2011; Wilderbuer *et al.* 2012). Cheung *et al.* (2011) used projections from an earth system model to estimate shifts in bio-climatic windows that included climate change effects on biogeochemistry (oxygen and acidity) and primary production to project future catch potential of 120 demersal fish and invertebrates. Results from their model suggested that the catch potential will increase in the Barents and Greenland Seas and regions > 70^o north latitude (Cheung *et al.,* 2011). In contrast, vulnerability analysis suggests that only a few species are expected to be abundant enough to support viable fisheries in the Arctic Ocean (Hollowed *et al.*, 2013). Potential fisheries for snow crab on shelf areas of the Arctic Ocean may be limited by the associated impacts of ocean acidification. If fisheries develop in the Arctic Ocean, adoption of sustainable strategies for management will be a high priority (Molenaar, 2009). The moratorium on fishing in the U.S. portion of the Chukchi and Beaufort Seas would prevent fishing until sufficient data become available to manage the stock sustainably (Wilson and Ormseth, 2009).

Predicting of how harvesters will respond to changing economic, institutional and environmental conditions under climate change is difficult. Current techniques, track fishers choices based on revenues and costs associated with targeting a species in a given time and area with a particular gear given projected changes in the abundance and spatial distribution of target species (Haynie and Pfeiffer, 2012). However, estimates of future revenues and costs will depend, in part, on future demand for fish, global fish markets and trends in aquaculture practices (Merino *et al.,* 2012; Rice and Garcia, 2011).

28.3.4.2. Forestry and Farming

Climate change is likely to have positive impacts for agriculture, including extended growing season (Grønlund, 2009; Falloon and Betts, 2009; Tholstrup and Rasmussen, 2009), although variations across regions are expected (Hovelsrud *et al.*, 2011), and the importance of impacts to the Arctic economy will likely remain minor (Eskeland and Flottorp, 2006). Potential positive effects of climatic warming for forestry include decreased risk of snow damage. Kilpelainen *et al.* (2010) estimate a 50% decrease in snow damage in Finland towards the end of the century. A warmer climate is likely to impact access conditions and plant diseases for forestry and farming. Grønlund (2009) found in the case of Northern Norway – where about half of the arable land area is covered by forest and 40% by marshland – that the potential harnessing of arable land for farming will be at the cost of forestry production, or dried-up marshlands, which may contribute to more greenhouse emissions. Larger field areas may contribute to land erosion through rainfall and predicted unstable winters, and may increase conditions for plant diseases and fungal infections (Grønlund, 2009). If the winter season continues to shorten due to climate change (Xu *et al.*, 2013), accessibility to logging sites will be negatively affected. Accessibility is higher when frozen ground makes transportation possible in sensitive locations or areas that lack road. If weather changes occur when logging has taken place, sanding of roads may be necessary which carries significant economic costs. Impact on carrying capacity of ground or road accessibility will thus affect forestry economically. Challenges may include limited storage space for wood (Keskitalo, 2008).

28.3.4.3. Infrastructure, Transportation, and Terrestrial Resources

Rising temperatures and changing precipitation patterns have the potential to affect all infrastructure types and related services, as much of the infrastructure in the North is dependent upon the cryosphere to, for example, provide stable surfaces for buildings and pipelines, contain waste, stabilize shorelines and provide access to remote communities in the winter (Furgal and Prowse, 2008; Huntington *et al.*, 2007; Sherman *et al.*, 2009; Sundby and Nakken, 2008; West and Hovelsrud, 2010; Forbes, 2011). In the long term marine and freshwater transportation will need to shift its reliance from ice routes to open-water or land-based transportation systems. Of appropriate community adaptations to the predicted changes relocation is one option to deal with persistent flooding and bank erosion (Furgal, 2008; NRTEE, 2009). Changing sea-ice (multiyear) conditions are suspected i.e. to have a regulating impact on marine shipping and coastal infrastructure through possible hazards on them (Eicken *et. al.*, 2009).

By adapting transportation models to integrate monthly climate model (CCSM3) predictions of air temperature, combined with datasets on land cover, topography, hydrography, built infrastructure, and locations of human settlements, estimates have been made of changes to inland accessibility for northern landscapes northward of 40ºN by mid-21st Century (Stephenson *et al.*, 2011). Milder air temperatures and/or increased snowfall reduce the possibilities for constructing inland winter-road networks, including ice roads, with the major seasonal reductions in road potential (based on a 2000 kg vehicle) being in the winter shoulder-season months of November and April. The average decline (compared to a baseline of 2000-2014) for eight circumpolar countries was projected to be -14%, varying from -11 to -82%. In absolute terms, Canada and Russia (both at -13%) account for the majority of declining winter-road potential with ~$1x10^6$ km^2 being lost (See Table 28.1). The winter road season has decreased since the 1970s on the Alaska´s North Slope, from as much as 200 to 100 days in some areas (Hinzman, *et al.*, 2005).

Climate change is expected to lead to a nearly ice free Arctic Ocean in late summer and increased navigability of Arctic marine waters. New possibilities for shipping routes and extended use of existing routes may result from increased melting of sea ice (Paxian *et al.*, 2010; Corbett *et al.*, 2010; Khon *et al.*, 2010; Peters *et al.*, 2011; Stephenson *et al.*, 2011).

Projections made by Stephenson *et al.* (2011) suggest that all five Arctic littoral states will gain increased maritime access to their current exclusive economic zones, especially Greenland (+28% relative to baseline), Canada (+19%), Russia (+16%) and United States (+15%). In contrast, Iceland, Norway, Sweden, and Finland display little or no increase in maritime accessibility,(Table 28.1) (Stephenson *et al.*, 2011).

GCMs generally underestimate the duration of the ice-free period in the Arctic Ocean and simulate slower changes than those observed in the past decades (Stroeve *et al.*, 2007). Mokhow and Khon (2008) used a sub-set of climate models that better than other GCMs reproduce the observed sea ice dynamics to project the duration of the navigation season along the NSR and through the NWP under the moderate SRES-A1B emission scenario. According to their results, by the end of the 21st century the NSR may be open for navigation 4.5±1.3 months per year, while the NWP may be open 2-4 months per year (Figure 28-4). The models did not predict any significant changes of the ice conditions in the NWP until the early 2030s.

[INSERT FIGURE 28-4 HERE
Figure 28-4: Projected duration of the navigation period (days) over the Northwest Passage and Northern Sea Route. Source: Mokhow and Khon, 2008.]

[INSERT TABLE 28-1 HERE
Table 28-1: Annually averaged changes in inland and maritime transportation accessibility by mid-century (2045–2059) versus baseline (2000–2014). Source: Stephenson et al., 2011.]

An increase in the length of the summer shipping season, with sea-ice duration expected to be 10 days shorter by 2020 and 20-30 days shorter by 2080, is likely to be the most obvious impact of changing climate on Arctic marine transportation (Prowse *et al.*, 2009). Reduction in sea ice and increased marine traffic could offer opportunities for economic diversification in new service sectors supporting marine shipping. Loss of sea ice may open up waterways and opportunities for increased cruise traffic (e.g. Glomsrød and Aslaksen, 2009), and add to an already rapid increase in cruise tourism (Stewart *et al.*, 2010; Stewart *et al.*, 2007; Howell *et al.*, 2007). Climate change has increased the prevalence of cruise tourism throughout Greenland, Norway, Alaska and Canada because of decreasing sea ice extent.

Projected declines in sea-ice covers leading to development of integrated land and marine transportation networks in Northern Canada may stimulate further mine exploration and development (Prowse *et al.*, 2009). These possibilities however also come with challenges including their predicted contribution to the largest change in contaminant movement into or within the Arctic, as well as their significant negative impacts on the traditional ways of life of northern residents (Furgal and Prowse, 2008). Added shipping and economic activity will increase the amount of black carbon and reinforce warming trends in the region (Lack and Corbett, 2012), leading to additional economic activity.

Longer shipping season and improved access to ports may lead to increased petroleum activities, although possible increased wave activity and coastal erosion may increase costs related to infrastructure and technology. Peters *et al*. (2011) find by using a bottom-up shipping model and a detailed global energy market model to construct emission inventories of Arctic shipping and petroleum activities in 2030 and 2050 – and based on estimated sea-ice extent – that there will be rapid growth in transit shipping; oil and gas production will be moving into locations requiring more ship transport; and this will lead to rapid growth in emissions from oil and gas transport by ship.

The Arctic contains vast resources of oil, which is hard to replace as transportation fuel, and vast resources of gas, a more climate benign fuel than coal. Petroleum resources are unevenly distributed among Arctic regions and states. Arctic resources will play a growing role in the world economy, but increased accessibility is expected to create challenges for extraction, transport, engineering, search-and-rescue needs and responses to accidents (Hovelsrud *et al.*, 2011), and climatic change presents the oil and gas industry with challenges in terms of planning and predictions (Harsem *et al.*, 2011). Increased emissions due to rapid growth in Arctic Ocean transportation of oil and gas are projected (Peters *et al.*, 2011). Due to high costs and difficult access conditions the impact on future oil and gas production in the Arctic remains unclear (Peters *et al.*, 2011; Lindholdt and Glomsrød, 2012).

28.4. Human Adaptation

There is general agreement that both indigenous and non-indigenous people in the Arctic have a history of adapting to natural variability in the climate and natural resource base, as well as recent socio-economic, cultural and technological changes (Forbes and Stammler, 2009; Wenzel, 2009; West and Hovelsrud, 2010; Ford and Pearce, 2010; Bolton *et al.*, 2011Cochran et al., 2013). Climate change exacerbates the existing stresses faced by Arctic communities (Rybråten and Hovelsrud, 2010; Crate and Nuttall, 2009) and is only one of many important factors influencing adaptation (Berrang-Ford *et al.*, 2011). Climate adaptation needs to be seen in the context of these inter-connected and mutually reinforcing factors (Tyler *et al.*, 2007; Hovelsrud and Smit, 2010). The challenges faced today by communities in the Arctic are complex and interlinked and are testing their traditional adaptive capacity.

Climatic and other large-scale changes have potentially large effects on Arctic communities, in particular where simple economies leave a narrower range of adaptive choices (Anisimov and Vaughan, 2007; Ford and Furgal, 2009; Andrachuk and Pearce, 2010; Ford *et al.*, 2010; Forbes, 2011; Berkes *et al.*, 2003). There is considerable evidence that changing weather patterns, declining sea-ice and river as well as lake ice, thawing permafrost, and plant and animal species' abundance and composition have consequences for communities in the Arctic (see 28.2.4, 28.2.5.2 and 28.3.4). Sea-ice is particularly important for coastal communities which rely upon it for transportation between communities and hunting areas (Krupnik et al., 2010). Changes in the duration and condition of sea ice and the consequent changes to country food availability significantly impact the wellbeing of communities (Furgal and Seguin, 2006; Ford and Berrang-Ford, 2009; Ford *et al.*, 2010), outdoor tourism (Dawson *et al.*, 2010) and hunting and fishing (Wiig *et al.*, 2008; Brander, 2010).

Adaptation to climate change is taking place at the local and regional levels where impacts are often felt most acutely and the resources most readily available (Oskal, 2008; Hovelsrud and Smit, 2010). Current experiences and projections of future conditions often lead to technological adaptation responses such as flood and water management and snow avalanche protection (West and Hovelsrud, 2010; Hovelsrud and Smit, 2010) rather than policy responses (Hedensted Lund et al., 2012; Rudberg et al., 2012). Climate variability and extreme events are found to be salient drivers of adaptation (Berrang-Ford *et al.*, 2011; Dannevig *et al.*, 2012; Amundsen et al., 2010).

The lack of local scale climate projections, combined with uncertainties in future economic, social and technological developments often act as barriers to adaptation. These barriers, together with other societal determinants such as ethics, cultures, and attitudes towards risk may cause inaction (Adger *et al.*, 2009; West and Hovelsrud, 2010). Resolving divergent values across and within different communities poses a challenge for governance regimes. A determining factor in building adaptive capacity is the flexibility of enabling institutions to develop robust options (Keskitalo *et al.*, 2009; Hovelsrud and Smit 2010; Forbes *et al.*, 2009; Ford and Goldhar, 2012; Whyte, 2013). In the North American and Scandinavian context, adaptive co-management responses have been developed through land claims settlements and/or multi-scale institutional cooperation to foster social learning (Berkes, 2009; Armitage et *al.*, 2008).

Indigenous Peoples

While Arctic indigenous peoples with traditional lifestyles are facing unprecedented impacts to their ways of life from climate change and resource development (oil and gas, mining, forestry, hydropower, tourism, etc.), they are already implementing creative ways of adapting (Cruikshank, 2001; Forbes *et al.*, 2006; Krupnik and Ray, 2007; Salick and Ross, 2009; Green and Raygorodetsky, 2010; Cullen-Unsworth *et al.*, 2011; Alexander *et al.*, 2011; Bongo *et al.*, 2012). Examples of indigenous adaptation strategies have included changing resource bases, shifting land use and/or settlement areas, combining technologies with traditional knowledge, changing timing and location of hunting, gathering, herding, and fishing areas, and improving communications and education (Galloway McLean, 2010; Bongo *et al.*, 2012). Protection of grazing land will be the most important adaptive strategy for reindeer herders under climate change (Forbes *et al.*, 2009; Magga *et al.*, 2011; Kumpula *et al.*, 2012; Degteva and Nellemann, 2013).

The adaptive capacity of Arctic indigenous peoples is largely due to an extensive traditional knowledge and cultural repertoire, and flexible social networks (see Chapter 12, section 12.3) (Williams and Hardison, 2013). The dynamic nature of traditional knowledge is valuable for adapting to current conditions (Kitti *et al.*,. 2006; Tyler *et al.*, 2007; *Eira et al.*, 2012). The sharing of knowledge ensures rapid responses to crises (Ford *et. al.*, 2007). In addition, cultural values such as sharing, patience, persistence, calmness, respect for elders and the environment are important. Some studies suggest that traditional knowledge may not always be sufficient to meet the rapid changes in climate (see also Chapter 12) and it may be perceived to be less reliable because the changing conditions are beyond the current knowledge range (Ingram et al., 2002; Ford et al., 2006; Valdivia et al., 2010; Hovelsrud et al., 2010).

Over the last half-century, the adaptive capacity in some indigenous communities has been challenged by the transition from semi-nomadic hunting groups to permanent settlements (Ford et al., 2010). Forced or voluntary migration as an adaptation response can have deep cultural impacts (Shearer, 2011,2012; Maldonado *et al*., 2013).The establishment of permanent communities, particularly those associated with new industrial development, can also lead to increasing employment opportunities and income diversification for indigenous peoples. The intergenerational transfers of knowledge and skills through school curricula, land camps, and involvement in community-based monitoring programmes may strengthen adaptive capacity (Bolton et al., 2011; Hovelsrud and Smit, 2010; Ford *et. al.*, 2007; Forbes 2007).

Renewable resource harvesting remains a significant component of Arctic livelihoods and with climate change hunting and fishing has become a riskier undertaking and many communities are already adapting (Gearheard *et al.*, 2011; Laidler *et al.*, 2011). Adaptation includes taking more supplies when hunting; constructing permanent shelters on land as refuges from storms; improved communications infrastructure; greater use of global positioning systems (GPS) for navigation; synthetic aperture radar (SAR) to provide estimates of sea-ice conditions (Laidler *et al.*, 2011) and the use of larger or faster vehicles (Ford *et al.*, 2010). Avoiding dangerous terrain can result in longer and time-consuming journeys which can be inconvenient to those with wage-earning employment (Ford *et al.*, 2007).

Reindeer herders have developed a wide range of adaptation strategies in response to changing pasture conditions. These include: moving herds to better pastures (Bartsch *et al.*, 2010); providing supplemental feeding (Helle and Jaakkola, 2008; Forbes and Kumpula, 2009); retaining a few castrated reindeer males to break through heavy ice-crust (Oskal, 2008; Reinert *et al.*, 2008); ensuring an optimal herd size (Forbes *et al.*, 2009; Tyler *et al.*, 2007); and creating multicultural initiatives combining traditional knowledge with scientific (Vuojala-Magga *et al.*, 2011; Bongo *et al.*, 2012). Coastal fishers have adapted to changing climate by targeting different species and diversifying income sources (Hovelsrud *et al.*, 2010).

In some Arctic countries indigenous peoples have successfully negotiated land claims rights and have become key players in addressing climate change (Abele *et al.*, 2009). In some instances this has given rise to tensions over land/water use between traditional livelihoods and new opportunities (e.g. tourism and natural resource development) (Forbes *et al.*, 2006; Hovelsrud and Smit, 2010). Some territorial governments in Northern Canada have promoted adaptation by providing hunter support programs (Ford *et al.*, 2006, 2010).

The health of many indigenous people is being affected by the interaction of changes in the climate with ongoing changes in human, economic and biophysical systems (Donaldson et al., 2010). The distribution of traditional foods between communities and the use of community freezers in the Canadian Arctic has improved food security, an important factor for health (Ford et al., 2010). While wage employment may enhance the possibilities for adaptive capacity, greater involvement in full time jobs can threaten social and cultural cohesion and mental well-being by disrupting the traditional cycle of land-based practices (Berner et al., 2005; Furgal, 2008).

28.5. Research and Data Gaps

There remains a poor knowledge of coupling among, and thresholds within, bio-geophysical and socio-economic processes to fully assess the effects of a changing climate, and to separate them from those due to other environmental stressors:

- Existing integrative models are either lacking or insufficiently validated to project and to assess the cascading effects on, and feedbacks from the systems in the Polar Regions, in particular socio-economic systems.
- There is a need to enhance or establish a coordinated network of long-term representative sites for monitoring and assessment of climate change detection and attribution studies in Polar Regions. Regional differences and confounding variables will need to be considered in designing field and modelling studies. Standardised methods and approaches of biophysical and socio-economic analysis along with coordinated sampling in more regions will be necessary.

There are more specific research gaps, including:

- Many mechanisms of how climate change and ocean acidification may be affecting polar ecosystems have been proposed but few studies of physiological tolerances of species, long term field studies of ecosystem effects and ecosystem modelling studies are available to be able to attribute with high confidence current and future change in these ecosystems to climate change.
- More comprehensive studies including long-term monitoring on the increasing impacts from climate changes on Arctic communities (urban and rural) and their health, well-being, traditional livelihoods and life ways are needed. There is a need to assess more fully vulnerabilities and to develop response capacities at the local and regional level.

Frequently Asked Questions

FAQ 28.1: What will be the net socio-economic impacts of change in the polar regions?
[to remain at the end of the chapter]
Climate change will have costs and benefits for Polar Regions. Climate change, exacerbated by other large-scale changes, can have potentially large effects on Arctic communities, where relatively simple economies leave a narrower range of adaptive choices.

In the Arctic, positive impacts include new possibilities for economic diversification, marine shipping, agricultural production, forestry, and tourism. The Northern Sea Route is predicted to have up to 125 days per year suitable for navigation by 2050, while the heating energy demand in the populated Arctic areas is predicted to decline by 15%. In addition, there could be greater accessibility to offshore mineral and energy resources although challenges related to environmental impacts and traditional livelihoods are possible.

Changing sea ice condition and permafrost thawing may cause damage to bridges, pipelines, drilling platforms, hydropower and other infrastructure. This poses major economic costs and human risks, although these impacts are closely linked to the design of the structure. Furthermore, warmer winter temperatures will shorten the accessibility of ice roads that are critical for communications between settlements and economic development and have implications for increased costs.. Statistically, a long-term mean increase of 2 to 3°C in autumn and spring air temperature produces an approximate 10 to 15 day delay in freeze-up and advance in break-up, respectively.

Particular concerns are associated with projected increase in the frequency and severity of ice-jam floods on Siberian rivers. They may have potentially catastrophic consequences for the villages and cities located in the river plain, as exemplified by the 2001 Lena River flood, which demolished most of the buildings in the city of Lensk.

Changing sea ice conditions will impact indigenous livelihoods, and changes in resources, including marine mammals, could represent a significant economic loss for many local communities. Food security and health and well-being are expected to be impacted negatively.

In the Antarctic, tourism is expected to increase, and risks exist of accidental pollution from maritime accidents, along with an increasing likelihood of the introduction of alien species to terrestrial environments. Fishing for Antarctic krill near to the Antarctic continent is expected to become more common during winter months in areas where there is less winter sea ice.

FAQ 28.2: Why are changes in sea ice so important to the polar regions? *[to remain at the end of the chapter]*
Sea ice is a dominant feature of Polar Oceans. Shifts in the distribution and extent of sea ice during the growing season impacts the duration, magnitude and species composition of primary and secondary production in the Polar Regions. With less sea ice many marine ecosystems will experience more light, which can accelerate the growth of phytoplankton, and shift the balance between the primary production by ice algae and water-borne phytoplankton,

with implications for Arctic food webs. In contrast, sea ice is also an important habitat for juvenile Antarctic krill, providing food and protection from predators. Krill is a basic food source for many species in polar marine ecosystems.

Changes in sea ice will have other impacts, beyond these "bottom-up" consequences for marine foodwebs. Mammals and birds utilize sea ice as haul-outs during foraging trips (seals, walrus, and polar bears in the Arctic and seals and penguins in the Antarctic). Some seals (e.g. Bearded seals in the Arctic and crabeater and leopard seals in the Antarctic) give birth and nurse pups in pack ice. Shifts in the spatial distribution and extent of sea ice will alter the spatial overlap of predators and their prey. According to model projections, within 50-70 years loss of hunting habitats may lead to elimination of polar bears from seasonally ice-covered areas, where two thirds of their world population currently live. The vulnerability of marine species to changes in sea ice will depend on the exposure to change, which will vary by location, as well as the sensitivity of the species to changing environmental conditions and the adaptive capacity of each species. More open waters and longer ice-free period in the northern seas enhance the effect of wave action and coastal erosion with implications for coastal communities and infrastructure.

While the overall sea ice extent in the Southern Ocean has not changed markedly in recent decades, there have been increases in oceanic temperatures and large regional decreases in winter sea ice extent and duration in the western Antarctic Peninsula region of West Antarctica and the islands of the Scotia Arc.

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Table 28-1: Annually averaged changes in inland and maritime transportation accessibility by mid-century (2045–2059) versus baseline (2000–2014).

	Change in winter road-accessible land area (km2) (2,000–kg GVWRvehicle)	**Change in maritime-accessible ocean area (km2) (Type A vessel)—current EEZ**
Canada	-13%	19%
Finland	-41%	0%
Greenland	-11%	28%
Iceland	-82%	<1%
Norway	-51%	2%
Russia	-13%	16%
Sweden	-46%	0%
USA (Alaska)	-29%	5%
High seas	n/a	406%
Total	**-14%**	**23%**

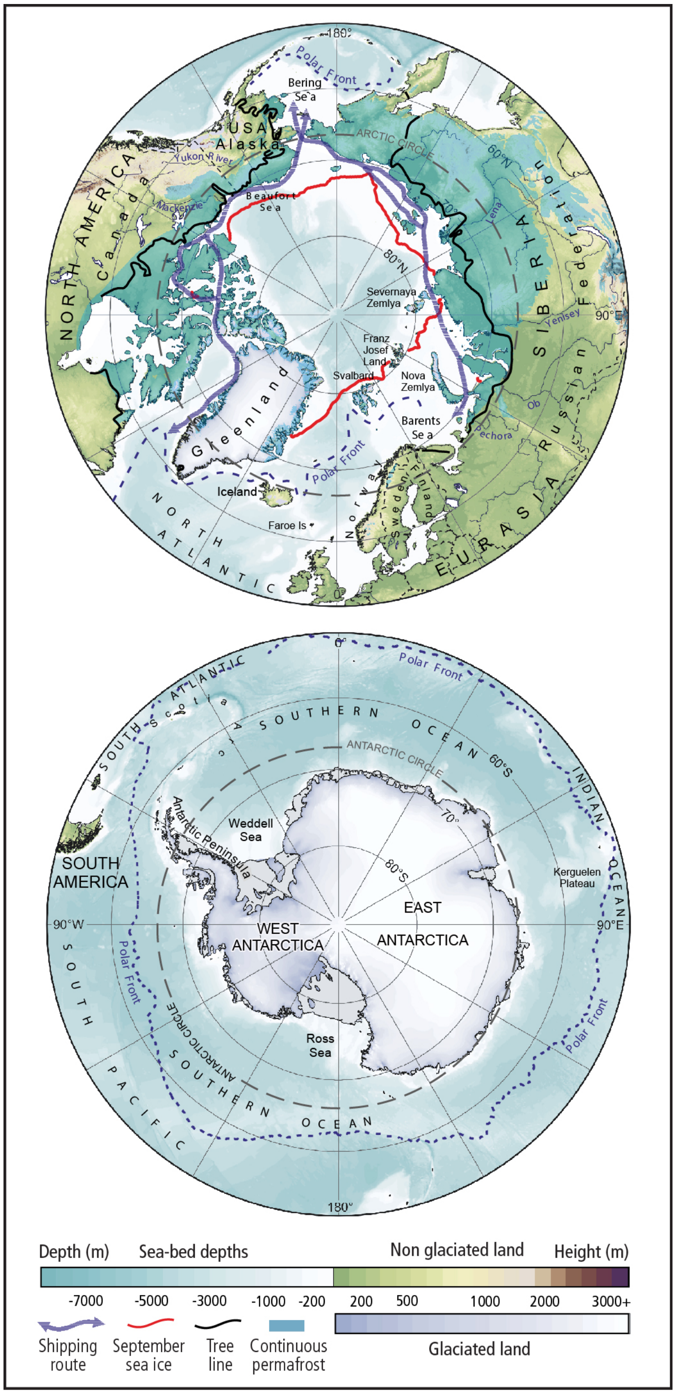

Figure 28-1: Location maps of the north and south polar regions.
Credit: P. Fretwell, British Antarctic Survey.

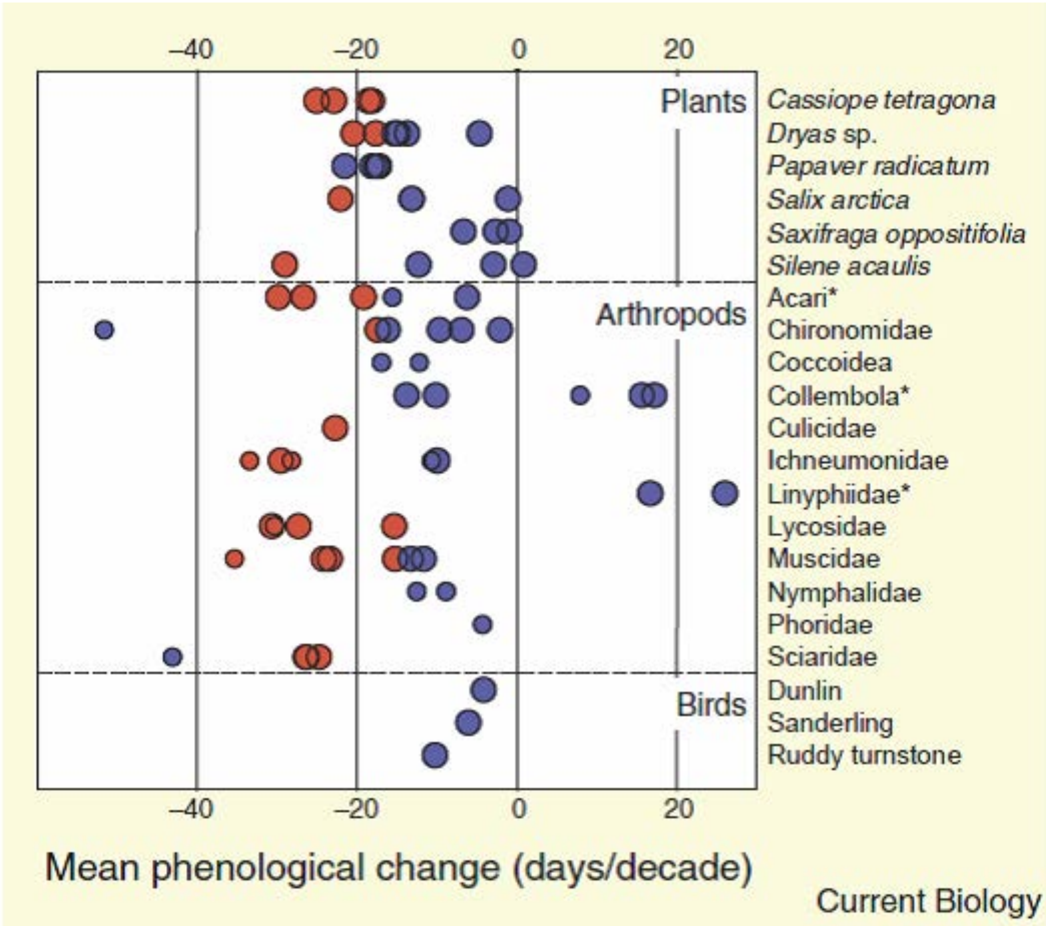

Figure 28-2: Temporal change in onset of flowering (plants), median date of emergence (arthropods) and clutch initiation dates (birds) in high-Arctic Greenland. Red dots are statistically significant, blue dots are not. Source: Høye *et al.*, 2007. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

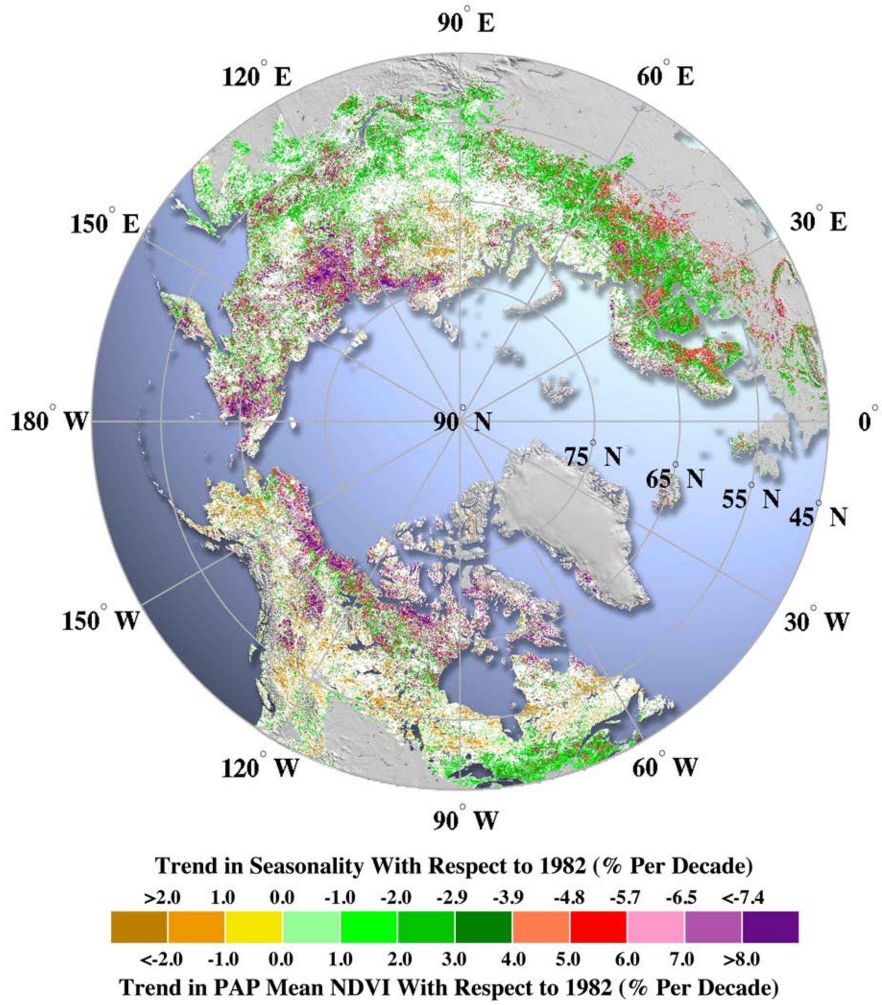

Figure 28-3: Significant changes ($p < 0.01$) in photosynthetically active period NDVI between 1982 and 2012. Source: Xu et al., 2013. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

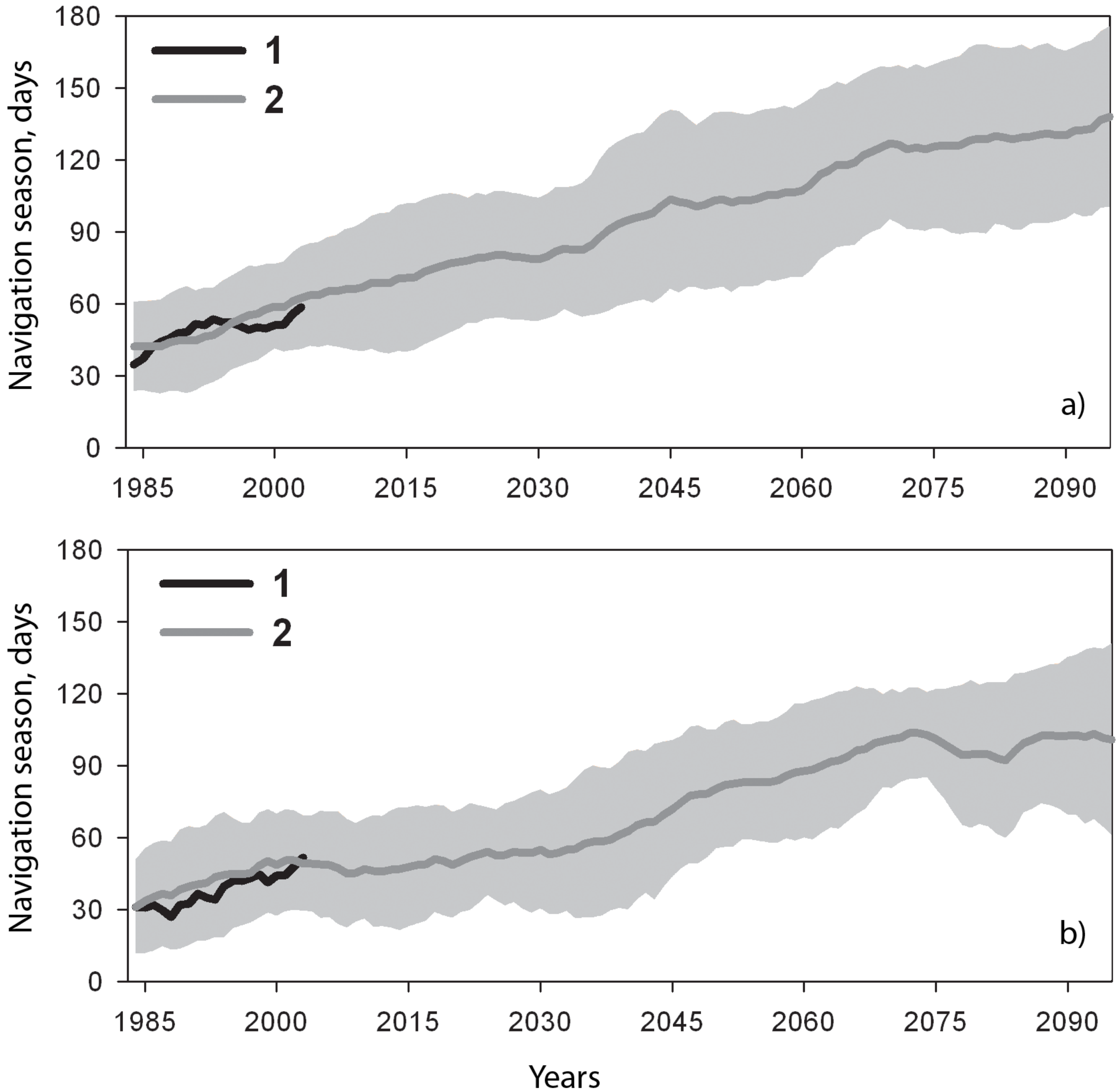

Figure 28-4: Projected duration of the navigation period (days) over the Northwest Passage and Northern Sea Route. Source: Mokhow and Khon, 2008. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

Chapter 29. Small Islands

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Contents

Executive Summary

Current and future climate-related drivers of risk for small islands during the 21st century include sea-level rise, tropical and extra-tropical cyclones, increasing air and sea surface temperatures, and changing rainfall patterns (*high confidence, robust evidence, high agreement*) [WGI 14, Table 29-1]. Current impacts associated with these changes confirm findings reported on small islands from the AR4 and previous IPCC assessments. The future risks associated with these drivers include loss of adaptive capacity [29.6.2.1, 29.6.2.3] and ecosystem services critical to lives and livelihoods in small islands [29.3.1, 29.3.2, 29.3.3].

Sea-level rise poses one of the most widely recognized climate change threats to low-lying coastal areas on islands and atolls (*high confidence, robust evidence and high agreement*) [29.3.1]. It is *virtually certain* that global mean sea-level rise rates are accelerating [WGI 13.2.2.1]. Projected increases to the year 2100 (RCP 4.5: 0.35m to 0.70m, WGI 13.5.1, Table 29-1) superimposed on extreme sea-level events (e.g. swell waves, storm surges, ENSO) present severe sea-flood and erosion risks for low-lying coastal areas and atoll islands (*high confidence*). Likewise, there is *high confidence* that wave over-wash of sea water will degrade fresh ground water resources [29.3.2] and that sea surface temperature rise will result in increased coral bleaching and reef degradation [29.3.1.2]. Given the dependence of island communities on coral reef ecosystems for a range of services including coastal protection, subsistence fisheries and tourism, there is *high confidence* that coral reef ecosystem degradation will negatively impact island communities and livelihoods.

Given the inherent physical characteristics of small islands, the AR5 reconfirms the high level of vulnerability of small islands to multiple stressors, both climate and non-climate (*high confidence, robust evidence, high agreement*). However, the distinction between *observed* and *projected* impacts of climate change is often not clear in the literature on small islands (*high agreement)* [29.3]. There is evidence that this challenge can be partly overcome through improvements in baseline monitoring of island systems and downscaling of climate-model projections, which would heighten confidence in assessing recent and projected impacts [WGI 9.6, 29.3, 29.4, 29.9].

Small islands do not have uniform climate change risk profiles (*high confidence*). Rather their high diversity in both physical and human attributes and their response to climate-related drivers means that climate change impacts, vulnerability and adaptation will be variable from one island region to another and between countries in the same region [Fig 29.1; Table 29.3]. In the past, this diversity in potential response has not always been adequately integrated in adaptation planning.

There is increasing recognition of the risks to small islands from climate-related processes originating well beyond the borders of an individual nation or island. Such trans-boundary processes already have a negative impact on small islands (*high confidence, robust evidence, medium agreement)*. These include: airborne dust from the Sahara and Asia, distant-source ocean swells from mid- high latitudes, invasive plant and animal species and the spread of aquatic pathogens. For island communities the risks associated with existing and future invasive species and human health challenges are projected to increase in a changing climate [29.5.4].

Adaptation to climate change generates larger benefit to small islands when delivered in conjunction with other development activities, such as disaster risk reduction and community based approaches to development *(medium confidence*) [29.6.4]. Addressing the critical social, economic and environmental issues of the day, raising awareness and communicating future risks to local communities [29.6.3] will *likely* increase human and environmental resilience to the longer-term impacts of climate change [29.6.1, 29.6.2.3, Figure 29-5].

Adaptation and mitigation on small islands are not always trade-offs, but can be regarded as complementary components in the response to climate change (*medium confidence).* Examples of adaptation-mitigation inter-linkages in small islands include energy supply and use, tourism infrastructure and activities, and functions and services associated with coastal wetlands. The alignment of these sectors for potential emission reductions together with adaptation, offer co-benefits and opportunities in some small islands [29.7.2, 29.8]. Lessons learned from adaptation and mitigation experiences in one island may offer some guidance to other small island states, though there is *low confidence* in the success of wholesale transfer of adaptation and mitigation options when the local lenses through which they are viewed differ from one island state to the next, given the diverse cultural, socio-economic, ecological and political values [29.6.2, 29.8].

The ability of small islands to undertake adaptation and mitigation programs, and their effectiveness, can be substantially strengthened through appropriate assistance from the international community (*medium confidence*). However, caution is needed to ensure such assistance is not driving the climate change agenda in small islands, as there is a risk that critical challenges confronting island governments and communities may not be addressed . Opportunities for effective adaptation can be found by, for example, empowering communities and optimizing the benefits of local practices that have proven to be efficacious through time, and working synergistically to progress development agendas [29.8, 29.6.2.3, 29.6.3].

29.1. Introduction

It has long been recognized that greenhouse gas emissions from small islands are negligible in relation to global emissions, but that the threats of climate change and sea-level rise to small islands are very real. Indeed, it has been suggested that the very existence of some atoll nations is threatened by rising sea levels associated with global warming. Whilst such scenarios are not applicable to all small island nations, there is no doubt that on the whole the impacts of climate change on small islands will have serious negative effects especially on socio-economic conditions and bio-physical resources – although impacts may be reduced through effective adaptation measures.

The small islands considered in this chapter are principally sovereign states and territories located within the tropics of the southern and western Pacific Ocean, central and western Indian Ocean, the Caribbean Sea, and the eastern Atlantic off the coast of west Africa, as well as in the more temperate Mediterranean Sea.

Although these small islands nations are by no means homogenous politically, socially, or culturally, or in terms of physical size and character or economic development, there has been a tendency to generalise about the potential impacts on small islands and their adaptive capacity. In this chapter we attempt to strike a balance between identifying the differences between small islands as well as recognising that small islands tend to share a number of common characteristics that have distinguished them as a particular group in international affairs. Also in this chapter we reiterate some of the frequently voiced and key concerns relating to climate change impacts, vulnerability and adaptation whilst emphasising a number of additional themes that have emerged in the literature on small islands since the IPCC Fourth Assessment. These include the relationship between climate change policy, activities and development issues; externally generated trans-boundary impacts; and the implications of risk in relation to adaptation and the adaptive capacity of small island nations.

29.2. Major Conclusions from Previous Assessments

Small islands were not given a separate chapter in the IPCC First Assessment (FAR) in1990 though they were discussed in the chapter on 'World Oceans and Coastal Zones' (Tsyban *et al*., 1990). Two points were highlighted. First, that a 30-50 cm sea-level rise projected by 2050 would threaten low islands, and that a 1 m rise by 2100 'would render some island countries uninhabitable' (Tegart *et al*., 1990). Second, the costs of protection works to combat sea-level rise would be extremely high for small island nations. Indeed, as a percentage of GDP the Maldives, Kiribati, Tuvalu, Tokelau, Anguilla, Turks and Caicos, Marshall Islands and Seychelles were ranked among the ten nations with the highest protection costs in relation to GDP (Tsyban *et al*., 1990). Over twenty years later these two points continue to be emphasized. For instance, although small islands represent only a fraction of total global damage projected to occur due to a sea-level rise of 1.0 m by 2100 (SRES A1 scenario) the actual damage costs for the small island states is enormous in relation to the size of their economies with several small island nations being included in the group of ten countries with the highest relative impact projected for 2100 (Anthoff *et al*., 2010).

The Second Assessment (SAR) in 1995 confirmed the vulnerable state of small islands, now included in a specific chapter titled 'Coastal Zones and Small Islands' (Bijlsma *et al*., 1996). However, importantly the SAR recognized that both vulnerability and impacts would be highly variable between small islands and that impacts were 'likely to be greatest where local environments are already under stress as a result of human activities' (Bijlsma *et al*., 1996). The report also summarized results from the application of a common methodology for vulnerability and adaptation analysis that gave new insights into the socio-economic implications of sea-level rise for small islands including: negative impacts on virtually all sectors including tourism, freshwater resources, fisheries and agriculture, human settlements, financial services and human health; protection is likely to be very costly; and, adaptation would involve a series of tradeoffs. It also noted that major constraints to adaptation on small islands included: lack of technology and human resource capacity, serious financial limitations, lack of cultural and social acceptability and uncertain political and legal frameworks. Integrated coastal and island management was seen as a way of overcoming some of these constraints.

The Third Assessment (TAR) in 2001 included a specific chapter on 'Small Island States'. In confirming previously identified concerns of small island states two factors were highlighted, the first relating to sustainability noting that 'with limited resources and low adaptive capacity, these islands face the considerable challenge of meeting the social and economic needs of their populations in a manner that is sustainable' (Nurse *et al*., 2001). And the second, that there were other issues faced by small island states concluding that 'for most small islands the reality of climate change is just one of many serious challenges with which they are confronted' (Nurse *et al*., 2001). Both of these themes are raised again and assessed in the light of recent findings in the present chapter.

Until the Fourth Assessment (AR4) in 2007, sea-level rise had dominated vulnerability and impact studies of small island states. Whilst a broader range of climate change drivers and geographical spread of islands was included in the 'Small Islands' chapter, Mimura *et al.* (2007) prefaced their assessment by noting that the number of 'independent scientific studies on climate change and small islands since the TAR' had been quite limited and in their view 'the volume of literature in refereed international journals relating to small islands and climate change since publication of the TAR is rather less than that between the SAR in 1995 and TAR in 2001' (Mimura *et al*., 2007).

Since AR4 the literature on small islands and climate change has increased substantially. A number of features distinguish the literature we review here from that included in earlier assessments. First, the literature appears more sophisticated and does not shirk from dealing with the complexity of small island vulnerability, impacts and adaptation or the differences between islands and island states. Second, and related to the first, the literature is less one-dimensional, and deals with climate change in a multidimensional manner as just one of several stressors on small island nations. Third, the literature also critiques some aspects of climate change policy, notably in relation to critical present-day development and security needs of small islands [29.3.3.1] as well as the possibility that some proposed adaptation measures may prove to be maladaptive [29.8]. Fourth, many initiatives have been identified in recent times that will reduce vulnerability and enhance resilience of small islands to on-going global change including improving risk knowledge and island resource management while also strengthening socio-economic systems and livelihoods (Hay, 2013).

29.3. Observed Impacts of Climate Change, including Detection and Attribution

The distinction between *observed* impacts of climate change and *projected* impacts is often unclear in the small islands literature and discussions. Publications frequently deal with both aspects of impacts interchangeably, and use observed impacts from, for instance an extreme event, as an analogy to what may happen in the future due to climate change (e.g. Lo-Yat *et al.,* 2011). The key climate and ocean drivers of change that impact small islands include variations in air and ocean temperatures, ocean chemistry, rainfall, wind strength and direction, sea-levels and wave climate and particularly the extremes such as tropical cyclones, drought and distant storm swell events. All have varying impacts, dependent on the magnitude, frequency, temporal and spatial extent of the event, as well as on the bio-physical nature of the island (Figure 29.1) and its social, economic and political setting.

[INSERT FIGURE 29-1 HERE
Figure 29-1: Representative tropical island typologies. From top-left: a young, active volcanic island (with altitudinal zonation) and limited living perimeter reefs (purple zone at outer reef edge), through to an atoll (centre bottom) and raised limestone island (bottom right) dominated by ancient reef deposits (brown + white fleck). Atolls have limited, low-lying land areas but well developed reef/lagoon systems. Islands composed of 'continental rocks' are not included in this figure, but see Table 29-3.]

29.3.1. Observed Impacts on Island Coasts and Marine Biophysical Systems

29.3.1.1. Sea-Level Rise, Inundation, and Shoreline Change on Small Islands

Sea-level rise poses one of the most widely recognized climate change threats to low-lying coastal areas (Church and White 2011; Cazenave and Llovel, 2010; Nicholls and Cazenave, 2010). This is particularly important in small islands where the majority of human communities and infrastructure is located in coastal zones with limited on-island relocation opportunities especially on atoll islands (Woodroffe, 2008) (Figure 29-1). Over much of the 20th Century, global mean sea level rose at a rate between 1.3 to 1.7 mm yr^{-1} and since 1993, at a rate between 2.8 to 3.6 mm yr^{-1} (WGI, Table 13.1) and acceleration is detected in longer records since 1870 (Merrifield *et al.,* 2009; Church and White, 2011; WGI, 13.2.2.1). Rates of sea-level rise are however not uniform across the globe and large regional differences have been detected including in the Indian Ocean and tropical Pacific, where in some parts rates have been significantly higher than the global average (Meyssignac *et al.,* 2012) (refer also to 5.3.2.2). In the tropical western Pacific where a large number of small island communities exist, rates up to four times the global average (approximately 12 mm yr^{-1}) have been reported between 1993 and 2009. These are generally thought to describe short-term variations associated with natural cyclic climate phenomena such as ENSO (El Niño-Southern Oscillation) which has a strong modulating effect on sea level variability with lower/higher-than-average sea level during El Nino/La Nina events of the order of ±20-30 cm (Becker *et al.,* 2012; Cazenave and Remy, 2011). Large interannual variability in sea level has also been demonstrated from the Indian Ocean (e.g. Chagos Archipelago, Dunne *et al.,* 2012) whilst Palanisamy *et al*. (2012) found that over the last 60 years the mean rate of sea-level rise in the Caribbean region was similar to the global average ~ 1.8mm yr^{-1}.

There are few long-term sea-level records available for individual small island locations. Reported sea flooding and inundation is often associated with transient phenomena, such as storm waves and surges, deep ocean swell and predicted astronomical tidal cycles (Vassie *et al.,* 2004; Zahibo *et al*., 2007; Komar and Allan, 2008; Haigh *et al*., 2011). For example, high spring tide floods at Fongafale Island, Funafuti Atoll, Tuvalu, have been well publicized and areas of the central portion of Fongafale are already below high spring tide level. However, rates of relative sea-level rise at Funafuti between 1950 – 2009 have been approximately three times higher than the global average (Becker *et al.,* 2012) and saline flooding of internal low-lying areas occurs regularly, and is expected to become more frequent and extensive over time (Yamano *et al.,* 2007).

Documented cases of coastal inundation and erosion often cite additional circumstances such as vertical subsidence, engineering works, development activities or beach mining as the causal process. Four examples can be cited. First, on the Torres Islands, Vanuatu communities have been displaced due to increasing inundation of low-lying settlement areas due to a combination of tectonic subsidence and sea-level rise (Ballu *et al.,* 2011). Second, on Anjouan Island, Comores in the Indian Ocean, Sinane *et al*. (2010) found beach aggregate mining was a major contributing factor influencing rapid beach erosion. Third, the intrinsic exposure of rapidly expanding settlements and agriculture in the low-lying flood prone Rewa Delta, Fiji is shown by Lata and Nunn (2012) to place populations in increasingly severe conditions of vulnerability to flooding and marine inundation. Fourth, Hoeke *et al*. (2013) describe a 2008 widespread inundation event that displaced some 63,000 people in Papua New Guinea and Solomon Islands alone. That event was primarily caused by remotely generated swell waves, and the severity of flooding was greatly increased by anomalously high regional sea levels linked with ENSO and on-going sea-level rise. Such examples serve to highlight that extreme events superimposed on a rising sea-level baseline are the main drivers that threaten the habitability of low-lying islands as sea levels continue to rise.

Since the AR4 a number of empirical studies have documented historical changes in island shorelines. Historical shoreline position change over 20 – 60 years on 27 central Pacific atoll islands showed that total land area remained relatively stable in 43 per cent of islands, whilst another 43 per cent had increased in area, and the rest showed a net reduction in land area (Webb and Kench, 2010). Dynamic responses were also found in a four year study of 17 relatively pristine islands on two other central Pacific atolls in Kiribati by Rankey (2011) who concluded that sea-level rise was not likely to be the main influencing factor in these shoreline changes. Similarly in French Polynesia Yates *et al*. (2013) showed mixed shoreline change patterns over the last 40 – 50 years with examples of both erosion and accretion in the 47 atoll islands assessed. Sea-level rise did not appear to be the primary control on shoreline processes on these islands. On uninhabited Raine Island on the Great Barrier Reef, Dawson and Smithers (2010) also found that shoreline processes were dynamic but that island area and volume increased 6 per cent and 4 per cent respectively between 1967 and 2007. Overall, these studies of observed shoreline change on reef islands conclude that for rates of change experienced over recent decades normal seasonal erosion and accretion processes appear to predominate over any long-term morphological trend or signal at this time. Ford's (2013) investigation of Wotje Atoll, Marshall Islands also found shoreline variability between 1945 and 2010 but that overall accretion had been more prevalent than erosion up until 2004. From 2004 to the present 17 out of 18 islands became net erosive, potentially corresponding to the high sea levels in the region over the last 10 years. On the high tropical islands of Kauai and Maui, Hawaii, Romine and Fletcher (2013) found shoreline change was highly variable over the last century but that recently chronic erosion predominated with over 70% of beaches now being erosive. Finally, it is important to note the majority of these studies warn that: (1) past changes cannot be simply extrapolated to determine future shoreline responses; and (2) rising sea level will incrementally increase the rate and extent of erosion in the future.

In many locations changing patterns of human settlement and direct impacts on shoreline processes present immediate erosion challenges in populated islands and coastal zones (Yamano *et al*., 2007; Storey and Hunter, 2010; Novelo-Casanova and Suarez, 2010) and mask attribution to sea-level rise. A study of Majuro atoll (Marshall Islands) found that erosion was widespread but attribution to sea-level rise was obscured by pervasive anthropogenic impacts to the coastal system (Ford, 2012) (see also 5.4.4). Similarly a study of three islands in the Rosario Archipelago (Colombia) reported shoreline retreat over a 50-55 year period and found Grande, Rosario, and Tesoro Islands had lost 6.7, 8.2 and 48.7 per cent of their land area respectively. Erosion was largely attributed to poor management on densely settled Grande Island, whilst sea-level rise and persistent northeast winds enhanced erosion on uninhabited Rosario and Tesoro (Restrepo *et al.,* 2012). Likewise, Cambers (2009) reported average beach erosion rates of 0.5 m yr^{-1} in eight Caribbean islands from 1985-2000. Whilst the study could not quantify the extent of attribution it noted that greater erosion rates were positively correlated with the number of hurricane events. Alternately, Etienne and Terry (2012) found a Category 4 tropical cyclone that passed within 30 km of Taveuni Island (Fiji) nourished shorelines with fresh coralline sediments despite localized storm damage. Whilst these studies contribute to improved understanding of island shoreline processes and change since AR4, the warning of increased vulnerability of small island shores and low-lying areas to inundation and erosion in response to sea-level rise and other potential climate change stressors is not diminished.

29.3.1.2. Coastal Ecosystem Change on Small Islands: Coral Reefs and Coastal Wetlands

Coral reefs are an important resource in small tropical islands and wellbeing of many island communities is linked to their on-going function and productivity. Reefs play a significant role in supplying sediment to island shores and in dissipating wave energy thus reducing the potential foreshore erosion. They also provide habitat for a host of marine species upon which many island communities are dependent for subsistence foods as well as underpinning beach and reef-based tourism and economic activity (Bell *et al.,* 2011; Perch-Nielsen, 2010). The documented sensitivity of coral reef ecosystems to climate change is summarised elsewhere (see Chap 5, Box CC-CR).

Increased coral bleaching and reduced reef calcification rates due to thermal stress and increasing CO_2 concentration are expected to affect the functioning and viability of living reef systems (Hoegh-Guldberg *et al.,* 2007; Eakin *et al.,* 2009). Some studies already implicate thermal stress in reduced coral calcification rates (Tanzil *et al*., 2009) and regional declines in calcification of corals that form reef framework (De'ath *et al*., 2009; Cantin *et al*., 2010). Unprecedented bleaching events have been recorded in the remote Phoenix Islands (Kiribati) with nearly 100 per cent coral mortality in the lagoon and 62 per cent mortality on the outer leeward slopes of the otherwise pristine reefs of Kanton Atoll during 2002 / 2003 (Alling *et al*., 2007). Similar patterns of mortality were observed in four other atolls in the Phoenix group and temperature-induced coral bleaching was also recorded in isolated Palmyra Atoll during the 2009 ENSO event (Williams *et al*., 2010). In 2005 extensive bleaching was recorded at 22 sites around Rodrigues Island in the western Indian Ocean with up to 75 per cent of the dominant species affected in some areas (Hardman *et al.,* 2007). Studies of the severe 1998 El Niño bleaching event in the tropical Indian Ocean showed reefs in the Maldives, Seychelles and Chagos Islands were among the most impacted (Cinner *et al.,* 2012; Tkachenko, 2012). In 2005 a reef survey around Barbados following a Caribbean regional bleaching event revealed the most severe bleaching ever recorded with approximately 70 per cent of corals impacted (Oxenford *et al.,* 2008). Globally, the incidence and implications of temperature-related coral bleaching in small islands is well documented and combined with the effects of increasing ocean acidification these stressors could threaten the function and persistence of island coral reef ecosystems (see Chap 5, Box CC-OA).

Island coral reefs have limited defences against thermal stress and acidification. However studies such as Cinner *et al*. (2012) and Tkachenko (2012) highlight that whilst recovery from bleaching is variable, some reefs show greater resilience than others. There is also some evidence to show that coral reef resilience is enhanced in the absence of other environmental stresses such as declining water quality. In Belize chronologies of growth rates in massive corals *(Montastraea faveolata)* over the past 75–150 years suggest that the bleaching event in 1998 was unprecedented and its severity appeared to stem from reduced thermal tolerance related to human coastal development (Carilli *et al*., 2010). Likewise a study over a 40 year period (1960s – 2008) in the Grand Recif of Tulear, Madagascar concluded that severe degradation of the reef was mostly ascribed to direct anthropogenic disturbance, despite an average 1 ^{0}C increase in temperature over this period (Harris *et al*., 2010). Coral recovery following the 2004 bleaching event in the central Pacific atolls of Tarawa and Abaiang (Kiribati) was also noted to be improved in the absence of direct human impacts (Donner *et al.*, 2010) and isolation of bleached reefs was shown by Gilmour *et al*. (2013) to be less inhibiting to reef recovery than direct human disturbance.

The loss of coral reef habitat has detrimental implications for coastal fisheries (Pratchett *et al.,* 2009) in small islands where reef-based subsistence and tourism activities are often critical to the wellbeing and economies of islands (Bell *et al.,* 2011). In Kimbe Bay, Papua New Guinea 65 per cent of coastal fish are dependent on living reefs at some stage in their life cycle and that following degradation of the reef fish abundance declined (Jones *et al.,* 2004). Even where coral reef recovery has followed bleaching, reef associated species composition may not recover to its original state (Pratchett *et al.*, 2009; Donner *et al.*, 2010). Sea Surface Temperature (SST) anomaly events can be associated with a lag in the larval supply of coral reef fishes, as reported by Lo-Yat *et al.* (2011) between 1996 and 2000 at Rangiroa Atoll, French Polynesia. Higher temperatures have also been implicated in negatively affecting the spawning of adult reef species (Munday *et al*., 2009; Donelson *et al*., 2010).

Like coral reefs, mangroves and sea grass environments provide a range of ecosystem goods and services (Polidoro *et al*., 2010; Waycott *et al*., 2009) and both habitats play a significant role in the wellbeing of small island communities. Mangroves in particular serve a host of commercial and subsistence uses as well as providing natural coastal protection from erosion and storm events (Ellison, 2009; Krauss *et al.*, 2010; Waycott *et al.*, 2011).

Sea-level rise is reported as the most significant climate change threat to the survival of mangroves (Waycott *et al.*, 2011). Loss of the seaward edge of mangroves at Hungry Bay, Bermuda has been reported by Ellison (1993) who attributes this process to sea-level rise and the inability of mangroves to tolerate increased water depth at the seaward margin. Elsewhere in the Caribbean and tropical Pacific observations vary in regards to the potential for sedimentation rates in mangroves forests to keep pace with sea-level rise (McKee *et al.*, 2007; Krauss *et al.*, 2003). In Kosrae and Pohnpei Islands (Federated States of Micronesia), Krauss *et al.* (2010) found significant variability in mangrove average soil elevation changes due to deposition from an accretion deficit of 4.95 mm y^{-1} to an accretion surplus of 3.28 mm y^{-1} relative to the estimated rate of sea-level rise. Such surpluses are generally reported from high islands where additional sediments can be delivered from terrestrial runoff. However, Rankey (2011) described natural seaward migration (up to 40m) of some mangrove areas between 1969 and 2009 in atolls in Kiribati suggesting sediment accretion can also occur in sediment rich reefal areas and in the absence of terrigenous inputs.

The response of seagrass to climate change is also complex, regionally variable and manifest in quite different ways. A study of seven species of sea grasses from tropical Green Island, Australia highlighted the variability in response to heat and light stress (Campbell *et al*., 2006). Light reduction may be a limiting factor to sea grass growth due to increased water depth and sedimentation (Ralph *et al.*, 2007). Ogston and Field (2010) observed that a 20 cm rise in sea-level may double suspended sediment loads and turbidity in shallow waters on fringing reefs of Molokai, Hawaiian Islands, with negative implications to photosynthetic species such as seagrass. Otherwise, temperature stress is most commonly reported as the main expected climate change impact on seagrass (e.g. Campbell *et al.*, 2006; Waycott *et al.*, 2011). Literature on seagrass diebacks in small islands is scarce but research in the Balearic Islands (Western Mediterranean) has shown that over a six-year study, seagrass shoot mortality and recruitment rates were negatively influenced by higher temperature (Marbá and Duarte, 2010). (See also Chapter 5.4.2.3 for further discussion of impacts on mangrove and sea grass communities).

29.3.2. Observed Impacts on Terrestrial Systems: Island Biodiversity and Water Resources

Climate change impacts on terrestrial biodiversity on islands, frequently interacting with several other drivers (Blackburn *et al*., 2004; Didham *et al*., 2005), fall into three general categories namely: (a) ecosystem and species horizontal shifts and range decline; (b) altitudinal species range shifts and decline mainly due to temperature increase on high islands; and (c) exotic and pest species range increase and invasions mainly due to temperature increase in high latitude islands. Due to the limited area and isolated nature of most islands, these effects are generally magnified compared to continental areas and may cause species loss especially in tropical islands with high numbers of endemic species. For example, in two low-lying islands in the Bahamas, Greaver and Sternberg (2010) found that during periods of reduced rainfall the shallow freshwater lens subsides and contracts landward and ocean water infiltrates further inland negatively impacting on coastal strand vegetation. Sea-level rise has also been observed to threaten the long-term persistence of freshwater-dependent ecosystems within low-lying islands in the Florida Keys (Goodman *et al*., 2012). On Sugarloaf Key, Ross *et al*. (2009) found pine forest area declined from 88 to 30 h from 1935 to 1991 due to increasing salinisation and rising ground water, with vegetation transitioning to more saline tolerant species such as mangroves.

Whilst there are many studies that report observations associated with temperature increases in mid- and high-latitude islands, such as the Falkland Islands and Marion Islands in the south Atlantic and south Indian ocean respectively (Bokhorst *et al*., 2007, 2008; Le Roux *et al*., 2005) and Svalbard in the Arctic (Webb *et al*., 1998) there are few equivalent studies in tropical small islands. A recent study of the tropical Mauritius kestrel indicate changing rainfall conditions in Mauritius over the last 50 years have resulted in this species having reduced reproductive success due to a mismatch between the timing of breeding and peak food abundance (Senapathi *et al*., 2011).

Increasing global temperatures may also lead to altitudinal species range shifts and contractions within high islands with an upward creep of the tree line and associated fauna (Benning *et al*., 2002; Krushelnycky *et al*., 2013). A study in the Hawaiian Islands which assessed data from 21 stations over 85 years showed a rapid rise in surface temperatures over the last 30 years with stronger warming in mountain areas (CCSP, 2008). Comparative vegetation distribution and composition studies in sub-Antarctic Marion Island, found an altitudinal shift of 3.4 m yr^{-1} for plant species (Parolo and Rossi, 2008). Comparable effects also occur in the tropics such as in Hawaii Volcano National Park where comparison of sample plots over a 40 year period from 1966-67 to 2008 show fire-adapted grasses expanded upward along a warming tropical elevation gradient (Angelo and Daehler, 2013). Reduction in the numbers and sizes of endemic populations caused by such habitat constriction and changes in species composition in mountain systems may result in the demise and possibly extinction of endemic species (Chen *et al*., 2009; Pauli *et al*., 2007; Sekercioglu *et al.*, 2008; Krushelnycky *et al.*, 2013). Altitudinal temperature change has also been reported to influence the distribution for disease vectors such as mosquitoes potentially threatening biota unaccustomed to such vectors (Freed *et al*., 2005; Atkinson and LaPointe, 2009).

Freshwater supply in small island environments has always presented challenges and has been an issue raised in all previous IPCC reports. On high volcanic and granitic islands small and steep river catchments respond rapidly to rainfall events and watersheds generally have restricted storage capacity. On porous limestone and low atoll islands surface runoff is minimal and water rapidly passes through the substrate into the groundwater lens. Rainwater harvesting is also an important contribution to freshwater access and alternatives like desalination have had mixed success in small island settings due to operational costs (White and Falkland, 2010).

Rapidly growing demand, land use change, urbanisation and tourism are already placing significant strain on the limited freshwater reserves in small island environments (Cashman *et al*., 2010; Emmanuel and Spence, 2009; White and Falkland, 2010). In the Caribbean, where there is considerable variation in the types of freshwater supplies utilised, concern over the status of freshwater availability has been expressed for at least the past 30 years (Cashman *et al*., 2010). There have also been economic and management failures in the water sector not only in the Caribbean (Mycoo, 2007) but also in small islands in the Indian (Payet and Agricole, 2006) and Pacific oceans (Moglia *et al.*, 2008a, 2008b; White *et al.*, 2007).

These issues also occur on a background of decreasing rainfall and increasing temperature. Rainfall records averaged over the Caribbean region for 100 years (1900-2000) show a consistent 0.18 mm yr^{-1} reduction in rainfall, a trend that is projected to continue (Jury and Winter, 2010). In contrast, analysis of rainfall data over the past 100 years from the Seychelles has shown substantial variability related to ENSO. Nevertheless an increase in average rainfall from 1959 to 1997 and an increase in temperature of ~ 0.25 ^{o}C per decade have occurred (Payet and Agricole, 2006). Long-term reduction in streamflow (median reduction of 22 – 23%) has been detected in the Hawaiian Islands over the period 1913 – 2008, resulting in reduced freshwater availability for both human use and ecological processes (Bassiouni and Oki 2013). Detection of long-term statistical change in precipitation is an important prerequisite towards a better understanding the impacts of climate change in small island hydrology and water resources.

There is a paucity of empirical evidence linking saline (sea-water) intrusion into fresh groundwater reserves due simply to incremental sea-level rise at this time (e.g. Rozell and Wong, 2010). However this dynamic must be the subject of improved research given the importance of groundwater aquifers in small island environments. White and Falkland’s (2010) review of existing small island studies indicates that a sea-level increase of up to 1 m would have negligible salinity impacts on atoll island groundwater lenses so long as there is adequate vertical accommodation space, island shores remain intact, rainfall patterns do not change and direct human impacts are managed. However, wave overtopping and washover can be expected to become more frequent with sea-level rise and this has been shown to impact freshwater lenses dramatically. On Pukapuka Atoll, Cook Islands storm surge over-wash occurred in 2005. This caused the freshwater lenses to become immediately brackish and took 11 months to recover to conductivity levels appropriate for human use (Terry and Falkland, 2010). The ability of the freshwater lens to float upwards within the substrate of an island in step with incremental sea-level rise also means that in low-lying and central areas of many atoll islands the lens may pond at the surface. This phenomenon already occurs in central areas of Fongafale Island, Tuvalu, and during extreme high 'king' tides large areas of the inner part of the island become inundated with brackish waters (Yamano *et al*., 2007; Locke, 2009).

29.3.3. Observed Impacts on Human Systems in Small Islands

29.3.3.1. Observed Impacts on Island Settlements and Tourism

Whilst traditional settlements on high islands in the Pacific were often located inland, the move to coastal locations was encouraged by colonial and religious authorities and more recently through the development of tourism (Barnett and Campbell, 2010). Now the majority of settlement, infrastructure and development are located on lowlands along the coastal fringe of small islands. In the case of atoll islands, all development and settlement is essentially coastal. It follows that populations, infrastructure, agricultural areas and fresh groundwater supplies are all vulnerable to extreme tides, wave and surge events and sea-level rise (Walsh *et al*., 2012). Population drift from outer islands or from inland, together with rapid population growth in main centres and lack of accommodation space drives growing populations into ever more vulnerable locations (Connell, 2012). Additionally, without adequate resources and planning, engineering solutions such as shoreline reclamation also place communities and infrastructure in positions of increased risk (Duvat, 2013; Yamano *et al*., 2007).

Many of the environmental issues raised by the media relating to Tuvalu, the Marshall Islands and Maldives are primarily relevant to the major population centre and its surrounds, which are Funafuti, Majuro and Male respectively. As an example Storey and Hunter (2010) indicate the 'Kiribati' problem does not refer to the whole of Kiribati but rather to the southern part of Tarawa atoll where pre-existing issues of severe overcrowding, proliferation of informal housing and unplanned settlement, inadequate water supply, poor sanitation and solid waste disposal, pollution and conflict over land ownership are of concern. They argue that these problems require immediate resolution if the vulnerability of the South Tarawa community to the 'real and alarming threat' of climate change is to be managed effectively (Storey and Hunter, 2010).

On Majuro atoll, rapid urban development and the abandonment of traditional settlement patterns has resulted in movement from less vulnerable to more vulnerable locations on the island (Spennemann, 1996). Likewise, geophysical studies of Fongafale Island, the capital of Tuvalu, show that engineering works during World War II, and rapid development and population growth since independence, has led to the settlement of inappropriate shoreline and swampland areas, leaving communities in heightened conditions of vulnerability (e.g. Yamano *et al*., 2007). Ascribing direct climate change impacts in such disturbed environments is problematic due to the existing multiple lines of stress on the island's biophysical and social systems. However, it is clear that such pre-existing conditions of vulnerability add to the threat of climate change in such locations. Increased risk can also result from lack of awareness, particularly in communities in rural areas and outer islands ('periphery') of archipelagic countries such as Cook Islands, Fiji, Kiribati and Vanuatu, whose climate change knowledge often contrasts sharply with that of communities in the major centres ('core'). In the core, communities tend to be better informed and have higher levels of awareness about the complex issues associated with climate change than in the periphery (Nunn *et. al.*, 2013).

The issue of 'coastal squeeze' remains a concern for many small islands as there is a constant struggle to manage the requirements for physical development against the need to maintain ecological balance (Fish *et al.*, 2008; Gero *et al*., 2011; Mycoo, 2011). Martinique in the Caribbean exemplifies the point, where physical infrastructure prevents the beach and wetlands from retreating landward as a spontaneous adaptation response to increased rates of coastal erosion (Schleupner, 2008). Moreover, intensive coastal development in the limited coastal zone combined with population growth and tourism has placed great stress on the coast of some islands and has resulted in dense aggregations of infrastructure and people in potentially vulnerable locations.

Tourism is an important weather and climate-sensitive sector on many small islands and has been assessed on several occasions, including in previous IPCC assessments. There is currently no evidence that observed climatic changes in small island destinations or source markets have permanently altered patterns of demand for tourism to small islands, and the complex mix of factors that actually determines destination choices under a changing climate still need to be fully evaluated (Scott *et al.*, 2012a). However, there are cases reported that clearly show severe weather-related events in a destination country (e.g. heavy, persistent rainfall in Martinique: Hubner and Gössling, 2012; Hurricanes in Anguilla: Forster *et al*., 2012) can significantly influence visitors' perception of the desirability of the location as a vacation choice.

Climate can also impact directly on environmental resources that are major tourism attractions in small islands. Widespread resource degradation challenges such as beach erosion and coral bleaching have been found to negatively impact the perception of destination attractiveness in various locations, for example in Martinique (Schleupner, 2008), Barbados and Bonaire (Uyarra *et al*., 2005). Similarly dive tourists are well aware of coral bleaching, particularly the experienced diver segment (Gössling *et al*., 2012a; Klint *et al.*, 2012). Therefore more acute impacts are felt by tourism operators and resorts that cater to these markets. Houston (2002) and Buzinde *et al.* (2010) also indicate that beach erosion may similarly affect accommodation prices in some destinations. Consequently, some countries have begun to invest in a variety of resource restoration initiatives including artificial beach nourishment, coral and mangrove restoration and the establishment of marine parks and protected areas (McClanahan *et al*., 2008; Mycoo and Chadwick, 2012). There is no analysis of how widespread such investments are or their capability to cope effectively with future climate change. The tourism industry and investors are also beginning to consider the climate risk of tourism operations (Scott *et al.,* 2012b) including those associated with the availability of freshwater. Freshwater is limited on many small islands, and changes in its availability or quality during drought events linked to climate change have adverse impacts on tourism operations (UNWTO 2012). Tourism is a seasonally significant water user in many island destinations and in times of drought, concerns over limited supply for residents and other economic activities become heightened (Gössling *et al.*, 2012b). The increasing use of desalination plants is one adaptation to reduce the risk of water scarcity in tourism operations.

29.3.3.2. Observed Impacts on Human Health

Globally, the effects of climate change on human health will be both direct and indirect, and are expected to exacerbate existing health risks, especially in the most vulnerable communities where the burden of disease is already high (refer to Chapter 11.3, 11.5 and 11.6.1, this volume). Many small island states currently suffer from climate-sensitive health problems, including morbidity and mortality from extreme weather events, certain vector- and food- and water-borne diseases (Lozano, 2006; Barnett and Campbell, 2010; Cashman *et al.*,2010; Pulwarty *et al.*, 2010; McMichael and Lindgren, 2011). Extreme weather and climate events such as tropical cyclones, storm surges, flooding, and drought can have both short- and long-term effects on human health, including drowning, injuries, increased disease transmission, and health problems associated with deterioration of water quality and quantity. Most small island nations are in tropical areas with weather conducive to the transmission of diseases such as malaria, dengue, filariasis and schistosomiasis.

The linkages between human health, climate variability and seasonal weather have been demonstrated in several recent studies. The Caribbean has been identified as a 'highly endemic zone for leptospirosis' with Trinidad and Tobago, Barbados and Jamaica representing the highest annual incidence (12, 10 and 7.8 cases per 100,000 population) in the world with only the Seychelles being higher (43.2 per 100,000 population) (Pappas *et al.*, 2008). Studies conducted in Guadeloupe demonstrated a link between El Niño occurrence and leptospirosis incidence with rates increasing to 13 per 100,000 population in El Nino years as opposed to 4.5 cases per 100,000 inhabitants in La Niña and neutral years (Herrmann-Storck *et al.*, 2008). In addition, epidemiological studies conducted in Trinidad reviewed the incidence of leptospirosis during the period 1996-2007 and showed seasonal patterns in the occurrence of confirmed leptospirosis cases, with significantly ($P<0.001$) more cases occurring in the wet season, May to November (193 cases), than during the dry season, December to May (66 cases) (Mohan *et al*., 2009). Recently changes in the epidemiology of leptospirosis have been detected especially in tropical islands with the main factors being climatic and anthropogenic ones (Pappas *et al*., 2008). These factors may be enhanced with increases in ambient temperature and changes in precipitation, vegetation and water availability as a consequence of climate change (Russell, 2009).

In Pacific islands the incidence of diseases such as malaria and dengue fever has been increasing, especially endemic dengue in Samoa, Tonga and Kiribati (Russell, 2009). While studies conducted so far in the Pacific have only established a direct link between malaria, dengue and climate variability, these and other health risks including from cholera, are projected to increase as a consequence of climate change (Russell, 2009; refer also to Chapter 11.2.4 and 11.2.5 this volume, for detailed discussion on the link between climate change and projected increases in the outbreak of dengue and cholera). Dengue incidence is also a major health concern in other small island countries, including Trinidad and Tobago, Singapore, Cape Verde, Comoros and Mauritius (Chadee 2009; Koh *et al.,* 2008; Van Kleef *et al.,* 2010; Teles, 2011). In the specific cases of Trinidad and Tobago and Singapore the outbreaks have been significantly correlated with rainfall and temperature, respectively (Chadee *et al.,* 2007; Koh *et al.,* 2008).

Previous IPCC assessments have consistently shown that human health on islands can be seriously compromised by lack of access to adequate, safe, freshwater and adequate nutrition (Nurse *et al.*, 2001; Mimura *et al.*, 2007). Lovell (2011) notes that in the Pacific many of the anticipated health effects of climate change are expected to be indirect, connected to the increased stress and declining well-being that comes with property damage, loss of economic livelihood and threatened communities. There is also a growing concern in island communities in the Caribbean and Pacific and Indian oceans, that fresh water scarcity, more intense droughts and storms could lead to a deterioration in standards of sanitation and hygiene (Cashman *et al*., 2010; McMichael and Lindgren, 2011). In such circumstances, increased exposure to a range of health risks including communicable (transmissible) diseases would be a distinct possibility.

Ciguatera fish poisoning (CFP) occurs in tropical regions and is the most common non-bacterial food-borne illness associated with consumption of fish. Distribution and abundance of the organisms that produce these toxins, chiefly dinoflagellates of the genus *Gambierdiscus*, are reported to correlate positively with water temperature. Consequently, there is growing concern that increasing temperatures associated with climate change could increase the incidence of CFP in the island regions of the Caribbean (Morrison *et al.*, 2008; Tester *et al.*, 2010), Pacific (Rongo and van Woesik, 2011; Chan *et al.*, 2011), the Mediterranean *(*Aligizaki and Nikolaidis, 2008; refer also to section 29.5.5), and the Canary Islands in the Atlantic (Pérez-Arellano *et al*., 2005). A recent Caribbean study sought to characterise the relationship between sea surface temperatures (SSTs) and CFP incidence and to determine the effects of temperature on the growth rate of organisms responsible for CFP. Results from this work show that in the Lesser Antilles high rates occur in areas that experience the warmest water temperatures and which show the least temperature variability (Tester *et al*., 2010). There are also high rates in the Pacific in Tokelau, Tuvalu, Kiribati, Cook Islands and Vanuatu (Chan *et al*., 2011).

The influence of climatic factors on malaria vector density and parasite development is well established (Béguin *et al.,* 2011; Chaves and Koenraadt, 2010). Previous studies have assessed the potential influence of climate change on malaria, using deterministic or statistical models (Hay *et al.,* 2009; Martens *et al*., 1999; Parham and Michael, 2010; Pascual *et al*., 2006). While the present incidence of malaria on small islands is not reported to be high, favourable environmental and social circumstances for the spread of the disease are present in some island regions and are expected to be enhanced under projected changes in climate in Papua New Guinea, Guyana, Suriname and French Guyana **(**Michon *et al.*, 2007; Rawlins *et al.*, 2008; Figueroa, 2008). In the Caribbean, the occurrence of autochthonous malaria in non-endemic island countries in the last ten years suggests that all of the essential malaria transmission conditions now exist. Rawlins *et al*. (2008) call for enhanced surveillance, recognizing the possible impact of climate change on the spread of the anopheles mosquito vector and malaria transmission.

29.3.3.3. Observed Impacts of Climate Change on Relocation and Migration

Evidence of human migration as a response to climate change is scarce for small islands. While there is general agreement that migration is usually driven by multiple factors (Black et al., 2011), several authors highlight the lack of empirical studies of the effect of climate-related factors, such as sea-level rise, on island migration (Lilleør and Van den Broeck, 2011; Mortreux and Barnett, 2009). Furthermore, there is no evidence of any government policy that allows for climate ‘refugees’ from islands to be accepted into another country (Bedford and Bedford, 2010). This finding contrasts with the early desk-based estimates of migration under climate change such as the work of

Myers (2002). These early studies have been criticised as they fail to acknowledge the reality of climate impacts on islands, the capacity of islands and islanders to adapt, or the actual drivers of migration (Barnett and O'Neill, 2012).

Studies of island migration commonly reveal the complexity of a decision to migrate and rarely identify a single cause. For example, when looking at historical process of migration within the Mediterranean it appears that rising levels of income, coupled with a decreased dependence on subsistence agriculture has left the Mediterranean less vulnerable to all environmental stressors, resulting in a reduced need for mobility to cope with environmental or climatic change (de Haas, 2011). Studies from the Pacific have also shown that culture, lifestyle and a connection to place are more significant drivers of migration than climate (Barnett and Webber, 2010). For example, a Pacific Access Category of migration has been agreed between New Zealand and Tuvalu that permits 75 Tuvaluans to migrate to New Zealand every year (Kravchenko, 2008). Instead of enabling climate driven migration, this agreement is designed to facilitate economic and social migration as part of the Pacific island lifestyle (Shen and Gemenne, 2011). To date there is no unequivocal evidence that reveals migration from islands is being driven by anthropogenic climate change.

There is however some evidence that environmental change has played a role in Pacific Island migration in the past (Nunn, 2007). In the Pacific environmental change has been shown to affect land use and land rights, which in turn have become drivers of migration (Bedford and Bedford, 2010). In a survey of 86 case studies of community relocations in Pacific islands, Campbell *et al*. (2005) found that environmental variability and natural hazards accounted for 37 communities relocating. In the Pacific, where land rights are a source of conflict, climate change could increase levels of stress associated with land rights and impact on migration (Campbell, 2010; Weir and Virani, 2011). While there is not yet a climate fingerprint on migration and resettlement patterns in all small islands, it is clear that there is the potential for human movement as a response to climate change. To better understand the impact of climate change on migration there is an urgent need for robust methods to identify and measure the effects of the drivers of migration on migration and resettlement.

29.3.3.4. Observed Impacts on Island Economies

The economic and environmental vulnerabilities of small islands states are well documented (Briguglio *et al.,* 2009, Bishop, 2012). Such vulnerabilities, which render the states at risk of being harmed by economic and environmental conditions, stem from intrinsic features of these vulnerable states, and are not usually governance induced. However, governance does remain one of the challenges for island countries in the Pacific in the pursuit of sustainable development through economic growth (Prasad, 2008). Economic vulnerability is often the result of a high degree of exposure to economic conditions often outside the control of small island states, exacerbated by dependence on a narrow range of exports and a high degree of dependence on strategic imports, such as food and fuel (Briguglio *et al.,* 2009). This leads to economic volatility, a condition that is harmful for the economy of the islands (Guillaumont, 2010).

There are other economic downsides associated with small size and insularity. Small size leads to high overhead cost per capita, particularly in infrastructural outlays. This is of major relevance to climate change adaptation that often requires upgrades and redesign of island infrastructure. Insularity leads to high cost of transport per unit, associated with purchases of raw materials and industrial supplies in small quantities, and sales of local produced products to distant markets. These disadvantages are associated with the inability of small islands to reap the benefits of economies of scale resulting in a high cost of doing business in small islands (Winters and Martins, 2004).

High costs are also associated with the small size of island states when impacted by extreme events such as hurricanes and droughts. On small islands such events often disrupt most of the territory, especially on single-island states, and have a very large negative impact on the state’s GDP, in comparison with larger and more populous states where individual events generally only affect a small proportion of the country and have a small impact on its GDP (Anthoff *et al.*, 2010). Moreover, the dependence of many small islands on a limited number of economic sectors such as tourism, fisheries and agricultural crops, all of which are climate-sensitive, means that on the one hand climate change adaptation is integral to social stability and economic vitality but that government adaptation efforts are constrained because of the high cost on the other.

29.3.4. Detection and Attribution of Observed Impacts of Climate Change on Small Islands

While exceptional vulnerability of many small islands to future climate change is widely accepted, the foregoing analysis indicates that the scientific literature on observed impacts is quite limited. Detection of past and recent climate change impacts is challenging due to the presence of other anthropogenic drivers, especially in the constrained environments of small islands. Attribution is further challenged by the strong influence of natural climate variability compared to gradual incremental change of climate drivers. Notwithstanding these limitations a summary of the relationship between detection and attribution to climate change of several of the phenomena described in the above sections has been prepared. Figure 29-2 reflects the degree of confidence in the linkage between observed changes in several components of the coastal, terrestrial and human systems of small islands and the drivers of climate change.

[INSERT FIGURE 29-2 HERE
Figure 29-2: A comparison of the degree of confidence in the detection of observed impacts of climate change on tropical small islands with the degree of confidence in attribution to climate change drivers at this time. For example, the blue symbol No. 2 (Coastal Systems), indicates there is *very high confidence* in both the detection of 'sea-level rise consistent with global means' and its attribution to climate change drivers; whereas the red symbol No. 17 (Human Systems) indicates whilst detection of 'casualties and damage during extreme events' is *very high*, there is presently *low confidence* in the attribution to climate change. It is important to note that *low confidence* in attribution frequently arises due to the limited research available on small island environments.]

29.4. Projected Integrated Climate Change Impacts

Small islands face many challenges in using climate change projections for policy development and decision-making (Keener *et al*., 2012). Among these is the inaction inherent in the mismatch of the short-term time scale on which government decisions are generally taken compared with the long-term time scale required for decisions related to climate change. This is further magnified by the general absence of credible regional socio-economic scenarios relevant at the spatial scale at which most decisions are taken. Scenarios are an important tool to help decision makers disaggregate vulnerability to the direct physical impacts of the climate signal from the vulnerability associated with socio-economic conditions and governance. There is however a problem in generating formal climate scenarios at the scale of small islands since they are generally much smaller than the resolution of the global climate models. This is because the grid squares in the Global Circulation Models (GCMs) used in the SRES scenarios over the last decade, were between 200 and 600 km^2 that provides inadequate resolution over the land areas of most small islands. This has recently improved with the new RCP scenario GCMs with grid boxes generally between 100 and 200 km^2 in size.

The scale problem has been usually addressed by the implementation of statistical downscaling models that relate GCM output to the historical climate of a local small island datapoint. The limitation of this approach is the need for observed data ideally for at least three decades for a number of representative points on the island, in order to establish the statistical relationships between GCM data and observations. In most small islands long-term quality-controlled climate data are generally sparse, so that in widely dispersed islands such as in the Pacific, observational records are usually supplemented with satellite observations combined with dynamical downscaling computer models (Australian Bureau of Meteorology [ABoM] and CSIRO, 2011a; Keener *et al*., 2012). However where adequate local data are available for several stations for at least 30 years, downscaling techniques have demonstrated that they can provide projections at fine scales ranging from about 10 – 25 km^2 (e.g. Charlery and Nurse, 2010; ABoM and CSIRO, 2011a). Even so, most projected changes in climate for the Caribbean, Pacific, Indian Ocean and Mediterranean islands, generally apply to the region as a whole and this may be adequate to determine general trends in regions where islands are close together.

29.4.1. Non-Formal Scenario-Based Projected Impacts

Scenarios are often constructed by using a qualitative or broad order of magnitude climate projections approach based on expected changes in some physical climate signal from literature review rather than projections based on direct location specific modelling. Usually this is proposed as a 'what if' question which is then quantified using a numerical method. For example in the Pacific, digital elevation models of Fiji's islands have been used to identify high risk areas for flooding based on six scenarios for sea-level rise from 0.09 to 0.88 m in combination with six scenarios for storm surge with return intervals from 1 to 50 years (Gravelle and Mimura, 2008). Another example of qualitative modelling from the Pacific is a case study from Nauru which uses local data and knowledge of climate to assess the GCM projections. It suggests that Nauru should plan for continued ENSO variability in the future with dry years during La Niña and an overall increase in mean rainfall and extreme rainfall events. Climate adaptation concerns which arise include water security and potential changes in extreme wet events which affect infrastructure, and human health (Brown *et al.,* 2013a). Climate change also poses risks for food security in the Pacific islands, including agriculture and fisheries (Barnett, 2011) Projections have also been used in the islands of the Republic of Baharain to estimate proness to inundation for sea-level rise of 0.5, 1.0 and 1.5 m (Al-Jeneid *et al*., 2008). Similarly, in the Caribbean the elevation equivalent of a projected sea-level rise of 1 m has been superimposed on topographic maps to estimate that 49-60% of tourist resort properties would be damaged, potentially transforming the competitive position and sustainability of coastal tourism destinations in the region (Scott *et al*., 2012c). This method has also been used to quantify the area loss for over 12 900 islands and over 3000 terrestrial vertebrates in the tropical Pacific region for three sea-level rise scenarios. The study estimated that for sea-level rise of 1 m, 37 island endemic species in this region risk complete inundation (Wetzel *et al*., 2013).

29.4.2. Projected Impacts for Islands based on Scenario Projections

Another approach to scenario development is to use the region specific projections more directly. It is worth noting that the broad synthesis in the AR4 of medium emissions climate scenario projections for small island regions (Mimura *et al*., 2007) shows concordance with the new RCP scenarios (see Table 29-1 and new RCP projections in Figure 29-3). For example, the SRES A1B medium emissions scenario suggests about a 1.8 to 2.3 °C median annual increase in surface temperature in the Caribbean, Indian Ocean and Pacific Ocean small islands regions by 2100 compared to a 1980-1999 baseline, with an overall annual decrease in precipitation of about 12% in the Caribbean (Table 11.1 in AR4 WG1; AR5 WG 1, 14.7.4) and a 3-5 per cent increase in the Indian and Pacific Oceans small island regions. Comparative projections for the new RCP4.5 scenario suggests about a 1.2 to 2.3 °C increase in surface temperature by 2100 compared to a 1986-2005 baseline and a decrease in precipitation of about 5 or 6 per cent in the Caribbean and Mediterranean respectively signaling potential future problems for agriculture and water availability compared to a 1-9 per cent increase in the Indian Ocean and Pacific Ocean small islands regions (Table 29.1). However, there are important spatial and high-island topography differences. Thus for example, among the more dispersed Pacific islands where the equatorial regions are *likely* to get wetter and the sub-tropical high pressure belts drier (as reported by AR5 WG I) in regions directly affected by the South Pacific Convergent Zone (SPCZ) and western portion of the Inter-Tropical Convergent Zone (ITCZ), the rainfall outlook is uncertain (AR5 WG1, 14.7.13). Projections for the Mediterranean islands also differ from those for the tropical small islands. Throughout the Mediterranean region, the length, frequency, and/or intensity of warm spells or heat waves are *very likely* to increase to the year 2100 (AR5 WGI, 14.7.6). Sea-level rise projections in the small islands regions for RCP4.5 are similar to the global projections of 0.41 to 0.71m (WGI AR5 13.5.1) ranging from 0.5-0.6 m by 2100 compared to 1986-2005 in the Caribbean, Pacific and Indian Ocean to 0.4-0.5 m in the Mediterranean and North Indian Ocean (Table 29-1).

[INSERT TABLE 29-1 HERE
Table 29-1: Climate change projections for the intermediate low (500-700 ppm CO_2-e) RCP4.5 scenario for six Small Islands regions. The table shows the 25th, 50th (median) and 75th percentiles for surface air temperature and precipitation based on averages from 42 CMIP5 global models (adapted from WGI AR5 Table 14.1). Mean net regional sea-level change is evaluated from 21 CMIP5 models and includes regional non-scenario components (adapted from WGI AR5 Figure 13-20).]

In the main regions in which most tropical or sub-tropical small island states are located, there are few independent peer reviewed scientific publications providing downscaled climate data projections, and even less illustrating the experience gained from their use for policy making. A possible 2 °C temperature increase by the year 2100 has potentially far reaching consequences for sentinel ecosystems such as coral reefs that are important to tropical islands (see Chapter 6.2.2.4.4.). This is because 'Degree Heating Months' (DHM) >2 °C-month are the determining threshold for severe coral bleaching (Donner, 2009). For example in a study of sea surface temperature (SST) across all coral reef regions using GCM ensemble projections forced with five different SRES future emissions scenarios, Donner (2009) concluded that even warming in the future from the current accumulation of greenhouse gases in the atmosphere could cause over half of the world's coral reefs to experience harmfully frequent thermal stress by 2080. Further, this timeline could be brought forward to as early as 2030 under the A1B medium emissions scenario. He further stated that thermal adaptation of 1.5 °C would only delay the thermal stress forecast by 50–80 years. Donner (2009) also estimated the year of likelihood of a severe mass coral bleaching event due more than once every 5 years, to be 2074 in the Caribbean, 2088 in the western Indian Ocean, 2082 in the central Indian Ocean, 2065 in Micronesia, 2051 in the central Pacific, 2094 in Polynesia and 2073 in the eastern Pacific small islands regions. Using the new RCP scenarios by comparison, van Hooidonk *et al*. (2013) found that the onset of annual bleaching conditions is associated with about 510 ppm CO^2 equivalent. The conclusion based on outputs from a wide range of emissions scenarios and models is that preserving >10 per cent of coral reefs worldwide would require limiting warming to less than 1.5±1.3 °C compared to pre-industrial levels (Frieler *et al*., 2013).

Small island economies can also be objectively shown to be at greater risk from sea-level rise in comparison to other geographic areas since most of their population and infrastructure are in the coastal zone. This is demonstrated in a study using the Climate Framework for Uncertainty, Negotiation and Distribution (FUND) model to assess the economic impact of substantial sea-level rise in a range of socio-economic scenarios downscaled to the national level, including the four SRES storylines (Anthoff *et al*., 2010). Although this study showed that in magnitude, a few regions will experience most of the absolute costs of sea-level rise by 2100, especially East Asia, North America, Europe and South Asia, these same results when expressed as percent of GDP showed that most of the top ten and four of the top five most impacted are small islands from the Pacific (Federated States of Micronesia, Palau, Marshall Islands, Nauru) and Caribbean (Bahamas). The point is made that the damage costs for these small island states are enormous in relation to the size of their economies (Nicholls and Tol, 2006) and that together with deltaic areas they will find it most difficult to locally raise the finances necessary to implement adequate coastal protection (Anthoff *et al*., 2010).

In the Caribbean, downscaled climate projections have been generated for some islands using the Hadley Centre PRECIS regional model (Taylor *et al*., 2007; Stephenson *et al*., 2008). For the SRES A2 and B2 scenarios the PRECIS regional climate model projects an increase in temperature across the Caribbean of 1–4 °C compared to a 1960-1990 baseline, with increasing rainfall during the latter part of the wet season from November–January, in the northern Caribbean (i.e. north of 22°N) and drier conditions in the southern Caribbean linked to changes in the Caribbean Low Level Jet (CLLJ) with a strong tendency to drying in the traditional wet season from June–October (Whyte *et al*., 2008; Campbell *et al*., 2011; Taylor *et al*., 2013). Projected lengthening seasonal dry periods, and increasing frequency of drought are expected to increase demand for water throughout the region under the SRES A1B scenario (Cashman *et al*., 2010). Decrease in crop yield is also projected in Puerto Rico for the SRES B1 (low), A2 (mid-high) and A1F1 scenarios during September although increased crop yield is suggested during February (Harmsen *et al*., 2009). Using a tourism demand model linked to the SRES A1F1 A2 B1 and B2 scenarios, the projected climate change heating and drying impacts are also linked to potential aesthetic, physical and thermal effects that are estimated to cause a change in total regional tourist expenditure of about +321, +356, -118 and -146 million US dollars from the least to the most severe emissions scenario respectively (Moore, 2010).

In the Indian Ocean, representative downscaled projections have been generated for Australia's two Indian Ocean territories, the Cocos (Keeling) Islands and Christmas Island using the CSIRO Mark 3.0 climate model with the SRES A2 high emissions scenario (Maunsell Australia Pty Ltd., 2009). Future climate change projections for the two islands for 2070 include an approximate 1.8 °C increase in air temperature by 2070, probable drier dry seasons and wet seasons, about a 40 cm rise in sea-level and a decrease in the number of intense tropical cyclones.

In the western tropical Pacific, extensive climate projections have been made for several Pacific Island Countries based on downscaling from an ensemble of models (ABoM and CSIRO, 2011b). The temperature projections in this region dominated by oceans seem less than those seen globally, ranging from +1.5 to 2.0 °C for the B1 low emissions scenario to +2.5 to 3.0 °C for the A2 high emissions scenario by the year 2090 relative to a 20 year period centred on 1990. Notably, extreme rainfall events that currently occur once every 20 years on average are generally simulated to occur four times per 20-year period, on average, by 2055 and seven times per 20-year period, on average, by 2090 under the A2 (high emissions) scenario (ABoM and CSIRO, 2011b). The results are not very different from the tropical Pacific RCP4.5 projections with projected temperature increases of about +1.2 to 1.4 °C by 2100 and an increase in rainfall of about 4% (Table 29-1). A comprehensive assessment of the vulnerability of the fisheries and aquaculture sectors to climate change in 22 Pacific island countries and territories focused on two future time-frames (2035 and 2100) and two SRES emissions scenarios, B1 (low emissions) and A2 (high emissions) (Bell *et al*., 2013). Many anticipated changes in habitat and resource availability such as coral reef-based fisheries are negative. By contrast, projected changes in tuna fisheries and freshwater aquaculture/fisheries can be positive with implications for government revenue and island food security (Bell *et al*., 2013). Simulation studies on changes in stocks of skipjack and bigeye tuna in the tropical Pacific area summarized in Table 29-2 and also discussed in 7.4.2.1 and 30.6.2.1.1. Some of these projected changes may favour the large international fishing fleets that can shift operations over large distances compared to local, artisanal fishers (Polovina *et al*., 2011).

[INSERT TABLE 29-2 HERE
Table 29-2: Summary of projected percentage changes in tropical Pacific tuna catches by 2035 and 2100 relative to 1980-2000 and the estimated resulting percentage changes to government revenue (After Bell *et al.*, 2011).]

In the Mediterranean islands of Mallorca, Corsica, Sardinia, Crete and Lesvos, Gritti *et al*. (2006) simulated the terrestrial vegetation biogeography and distribution dynamics under the SRES A1F1 and B1 scenarios to the year 2050. The simulations indicate that the effects of climate change are expected to be negligible within most ecosystems except for mountainous areas. These areas are projected to be eventually occupied by exotic vegetation types from warmer, drier conditions. Cruz *et al*. (2009) report similar results for the terrestrial ecosystems of Madeira Island in the Atlantic. Downscaled SRES A2 and B2 scenarios for the periods 2040 – 2069 and 2070 – 2099 suggest that the higher altitude native humid forest called the Laurissilva, may expand upwards in altitude, which could lead to a severe reduction of the heath woodland which because it has little upward area to shift may reduce in range or disappear at high altitudes resulting in the loss of rare and endemic species within this ecosystem.

29.4.3. RCP Projections and Implications for Small Islands

Utilizing updated historical greenhouse gas emissions data the scientific community has produced future projections for four plausible new global Representative Concentration Pathways (RCPs) in order to explore a range of global climate signals up to the year 2100 and beyond (e.g. Moss *et al*., 2010). Typical model ensemble representations of low, intermediate low, intermediate high and high RCP projections for annual temperature and precipitation in some small islands regions are presented in Figure 29-3. Highlighted in Figure 29-3 is the ensemble mean of each RCP. A more comprehensive compilation of quarterly global RCP projections can be found in the Annex I Atlas of Global and Regional Climate Projections in the WGI AR5 Report.

[INSERT FIGURE 29-3 HERE
Figure 29-3: Time series of RCP scenarios annual projected temperature and precipitation change relative to 1986-2005 for six small islands regions (using regions defined in AR5 WG1, Annex 1: Atlas of Global and Regional Climate Projections).] Thin lines denote one ensemble member per model, thick lines the CMIP5 multi-model mean. On the right-hand side the 5th, 25th, 50th (median), 75th and 95th percentiles of the distribution of 20-yr mean changes are given for 2081–2100 in the four RCP scenarios. Note that the model ensemble averages in the figure are for grid points over wide areas and encompass many different climate change signals. To get projections for a specific location and time period use the maps in the Atlas or the online interactive version at but please note that in regions with small islands the models basically simulate the climate of the surrounding ocean and local conditions on land may differ.]

During negotiations towards a new multi-lateral climate change regime Small Island Developing States (SIDS) have advocated that any agreement should be based on Global Mean Surface Temperature (GMST) increase 'well below' 1.5 °C above pre-industrial levels (Hare *et al*., 2011; Riedy and McGregor, 2011). Inspection of column 1 in Figure 29-3 suggests that for the Caribbean, Indian Ocean and Pacific SIDS in the tropics, the median projected regional increase is in the range 0.5-0.9 °C by 2100 compared to 1986-2005. This together with the temperature change that has already occurred since the industrial revolution suggests that a temperature 'well below' 1.5 °C is unlikely to be achieved with the lowest RCP2.6 projection (Peters *et al.*, 2013). By comparison temperature projections for the intermediate low RCP4.5 scenario, Table 29-1 and Figure 29-3 suggest possible 1.2-1.5 °C temperature increases in Caribbean, Indian Ocean and Pacific SIDS by 2100 compared to 1986-2005. Similarly, the projections for the Mediterranean would be about a 2.3 °C increase by 2100 compared to 1986-2005 that would represent a 2.7 °C increase compared to pre-industrial temperatures. Associated with this change, the Caribbean and Mediterranean regions may experience a noticeable decrease in mean rainfall while the Indian and Pacific Ocean SIDS may experience increased rainfall. These trends accelerate moderately for RCP 6.0 and steeply for RCP 8.5 (Table 29-1).

29.5. Inter- and Intra-Regional Trans-Boundary Impacts on Small Islands

Available literature since AR4 has highlighted previously less well understood impacts on small islands that are generated by processes originating in another region or continent well beyond the borders of an individual archipelagic nation or small island. These are inter-regional trans-boundary impacts. Intra-regional trans-boundary impacts originate from a within-region source (e.g. within the Caribbean). Some trans-boundary processes may have positive effects on the receiving small island or nation, though most that are reported have negative impacts. Deciphering a climate change signal in inter- and intra-regional trans-boundary impacts on small islands is not easy and usually involves a chain of linkages tracing back from island-impact to a distant climate or climate-related bio-physical or human process. Some examples are given below.

29.5.1. Large Ocean Waves from Distant Sources

Unusually large deep ocean swells, generated from sources in the mid- and high-latitudes by Extra-Tropical Cyclones (ETC) cause considerable damage on the coasts of small islands thousands of kilometres away in the tropics. Impacts include sea-flooding and inundation of settlements, infrastructure and tourism facilities as well as severe erosion of beaches (see also 5.4.3.4). Examples from small islands in the Pacific and Caribbean are common though perhaps the most significant instance, in terms of a harbinger of climate change and sea-level rise, occurred in the Maldives in April 1987 when long period swells originating from the Southern Ocean some 6000 km away caused major flooding, damage to property, destruction of sea defences and erosion of reclaimed land and islands (Harangozo, 1992). The Maldives and several other island groups in the Indian Ocean have been subject to similar ocean swell events more recently, most notably in May 2007 (Department of Meteorology, 2007).

In the Caribbean, northerly swells affecting the coasts of islands have been recognized as a significant coastal hazard since the 1950s (Donn and McGuinness, 1959). They cause considerable seasonal damage to beaches, marine ecosystems and coastal infrastructure throughout the region (Cambers, 2009; Bush *et al.*, 2009). These high-energy events manifest themselves as long period high-amplitude waves that occur during the northern hemisphere winter and often impact the normally sheltered, low-energy leeward coasts of the islands. Such swells have even reached the shores of Guyana on the South American mainland as illustrated by a swell event in October 2005 that caused widespread flooding and overtopping and destruction of sea defences (van Ledden *et al.*, 2009).

Distant origin swells differ from the 'normal' wave climate conditions experienced in the Caribbean, particularly with respect to direction of wave approach, wave height and periodicity and in their morphological impact (Cooper *et al.*, 2013). Swells of similar origin and characteristics also occur in the Pacific (Fletcher *et al.*, 2008; Keener *et al.*, 2012). These events frequently occur in the Hawaiian island where there is evidence of damage to coral growth by swell from the north Pacific, especially during years with a strong El Nino signal (Fletcher *et al*., 2008). Hoeke *et al*. (2013) describe inundation from mid-high latitude north and south Pacific waves respectively at Majuro (Marshall

Islands) in November and December 1979 and along the Coral Coast (Fiji) in May 2011. They also describe in detail an inundation event in December 2008 that was widespread throughout the western and central Pacific and resulted in waves surging across low-lying islands causing severe damage to housing and infrastructure and key natural resources that affected about 100,000 people across the region. The proximate cause of this event was swell generated in mid-latitudes of the North Pacific Ocean, more than 4000 km from the furthest affected island (Hoeke *et al.*, 2013).

Whereas the origin of the long period ocean swells that impact small islands in the tropical regions come from the mid-and high-latitudes in the Pacific, Indian and Atlantic oceans, there are also instances of unusually large waves generated from tropical cyclones that spread into the mid- and high- latitudes. One example occurred during 1999 when tide gauges at Ascension and St. Helena Islands in the central south Atlantic recorded unusually large deep-ocean swell generated from distant Hurricane Irene (Vassie *et al*., 2004). The impacts of increasing incidence or severity of storms or cyclones is generally considered from the perspective of direct landfall of such systems, whereas all of these instances serve to show 'the potential importance of swells to communities on distant, low-lying coasts, particularly if the climatology of swells is modified under future climate change' (Vassie *et al*., 2004). From the perspective of those islands that suffer damage from this coastal hazard on an annual basis, this is an area that warrants further investigation. Projected changes in global wind-wave climate to 2070-2100, compared to a base period 1979-2009, show considerable regional and seasonal differences with both decreases and increases in annual mean significant wave height. Of particular relevance in the present context is the projected increase in wave activity in the Southern Ocean which influences a large portion of the global ocean as swell waves propagate northwards into the Pacific, Indian and Atlantic oceans (Hemer *et al.*, 2013).

Deep ocean swell waves and elevated sea-levels resulting from ETCs are examples of *inter-regional* trans-boundary processes; locally generated Tropical Cyclones (TCs) provide examples of *intra-regional* trans-boundary processes. Whilst hurricane force winds, heavy rainfall and turbulent seas associated with TCs can cause massive damage to both land and coastal systems in tropical small islands, the impacts of sea waves and inundation associated with far distant ETCs are limited to the coastal margins. Nevertheless both storm types result in a range of impacts covering island morphology, natural and ecological systems, island economies, settlements and human well-being (see Figure 29-4).

[INSERT FIGURE 29-4 HERE
Figure 29-4: Tropical and extra-tropical cyclone impacts on the coasts of small islands. Four types of impacts are distinguished here, black arrows showing the connections between them, based on the existing literature. An example of the chain of impacts associated with two extra-tropical cyclones centred to the east of Japan is illustrated by the red arrows. Swell waves generated by these events in December 2008 reached islands in the southwest Pacific and caused extensive flooding (3) that impacted soil quality (8), freshwater resources (9), and damaged crops (10), buildings (15), and transport facilities (16) in the region (Example based on Hoeke *et al*., 2013).

Examples of tropical cyclone impacts on small island coasts with reference

1. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 2. Taveuni, Fiji, March 2010 (Etienne and Terry, 2012); 3. Cook Islands (de Scally, 2008); Society and Autral Islands, French Polynesia, February 2010 (Etienne, 2012); 4. Viti Levu, Fiji, March 1997 (Terry *et al.*, 2002); 5. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 6. Curacao, Bonaire, Netherlands Antilles, November 1999 (Scheffers and Scheffers, 2006); Hawaiian Islands (Fletcher *et al.*, 2008); 7. Bay Islands, Honduras, October 1998 (Cahoon *et al.*, 2003); 8. Marshall Islands, June 1905 (Spennemann, 1996); 9. Pukapuka atoll, Cook Islands, February 2005 (Terry and Falkland, 2010); 10. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 11. 12. 13. Tuamotu Islands, French Polynesia, 1982-83 (Dupon, 1987); 14. Grenada, September 2004 (OECS, 2004); 15. Grenada, September 2004 (OECS, 2004); Tubuai, Austral Islands, French Polynesia, February 2010 (Etienne, 2012); 16. Vanuatu, February 2004 (Richmond and Sovacool, 2012); Guadeloupe Island, October 2008 (Dorville and Zahibo, 2010); 17. Bora Bora, Raiatea, Maupiti, Tahaa, Huahine, Society Islands, February 2010 (Etienne, 2012); 18. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 19. Tuamotu, French Polynesia, 1982-83 (Dupon, 1987).

Examples of extra-tropical cyclone impacts on small island coasts with reference

1. Maldives, April 1987 (Harangozo, 1992); 2. Maldives, January 1955 (Maniku, 1990); 3. Maldives, April 1987 (Harangozo, 1992); 9. Solomon Islands, December 2008 (Hoeke *et al*., 2013); 10. Chuck, Pohnpei, Kosrae, Federated States of Micronesia, December 2008 (Hoeke *et al*., 2013); 15. Majuro, Marshall Islands, November 1979

(Hoeke *et al*., 2013); 16. Coral Coast, Viti Levu, Fiji, May 2011 (Hoeke *et al*., 2013); 17. Majuro, Kwajalein, Arno, Marshall Islands, December 2008 (Hoeke *et al*., 2013); 18. Bismark Archipelago, Papua New Guinea, December 2008 (Hoeke *et al*., 2013).]

29.5.2. Trans-Continental Dust Clouds and their Impact

The transport of airborne Saharan dust across the Atlantic and into the Caribbean has engaged the attention of researchers for some time. The resulting dust clouds are known to carry pollen, microbes, insects, bacteria, fungal spores and various chemicals and pesticides (Prospero *et al*., 2005; Middleton *et al*., 2008; Monteil, 2008; López-Villarrubia *et al*., 2010; Garrison *et al*., 2006). During major events, dust concentrations can exceed 100 µg m^{-3} (Prospero, 2006). Independent studies using different methodologies have all found a strong positive correlation between dust levels in the Caribbean and periods of drought in the Sahara, while concentrations show a marked decrease during periods of higher rainfall. Consequently, it is argued that higher dust emissions due to increasing aridity in the Sahel and other arid areas could enhance climate change effects over large areas, including the eastern Caribbean and the Mediterranean (Prospero and Lamb, 2003). Similar findings have been reported at Cape Verde where dust emission levels were found to be a factor of nine lower during the decade of the 1950s when rainfall was at or above normal, compared to the 1980s, a period of intense drought in the Sahel region (Nicoll *et al*., 2011). Dust from the Sahara has also reached the eastern Mediterranean (e.g. Santese *et al*., 2010) whilst dust from Asia has been transported across the Pacific and Atlantic oceans and around the world (Uno *et al*., 2009).

There is also evidence that the trans-boundary movement of Saharan dust into the island regions of the Caribbean, Pacific and Mediterranean is associated with various human health problems (Griffin, 2007) including asthma admissions in the Caribbean (Monteil, 2008; Monteil and Antoine, 2009; Prospero *et al*., 2008), cardiovascular morbidity in Cyprus in the Mediterranean (Middleton *et al.*, 2008) and is found to be a risk factor in respiratory and obstructive pulmonary disease in the Cape Verde islands (Martins *et al*., 2009). These findings underscore the need for further research into the link between climate change, airborne aerosols and human health in localities such as oceanic islands far distant from the continental source of the particulates.

29.5.3. Movement and Impact of Introduced and Invasive Species across Boundaries

Invasive species are coloniser species that establish populations outside their normal distribution ranges. The spread of invasive alien species is regarded as a significant trans-boundary threat to the health of biodiversity and ecosystems, and has emerged as a major factor in species decline, extinction and loss of biodiversity goods and services worldwide. This is particularly true of islands, where both endemicity and vulnerability to introduced species tend to be high (Kenis *et al.*, 2009; Reaser *et al*., 2007; Westphal *et al*., 2008; Rocha *et al*., 2009; Kueffer *et al*., 2010). The extent to which alien invasive species successfully establish themselves at new locations in a changing climate will be dependent on many variables, but non-climate factors such as ease of access to migration pathways, suitability of the destination, ability to compete and adapt to new environments, and susceptibility to invasion of host ecosystems are deemed to be critical. This is borne out for example by Le Roux *et al*. (2008) who studied the effect of the invasive weed *Miconia calvescens* in New Caledonia, Society Islands and Marquesas Islands; by Gillespie *et al.* (2008) in an analysis of the spread of *Leucaena leucocephala*, *Miconia calvescens*, *Psidium sp*. and *Schinus terebinthifolius* in the Hawaiian islands; and by Christenhusz and Toivonen (2008) who showed the potential for rapid spread and establishment of the oriental vessel fern, *Angiopteris evecta*, from the South Pacific throughout the tropics. Mutualism between an invasive ant and locally honeydew-producing insects has been strongly associated with damage to the native and functionally important tree species, *Pisonia grandis* on Cousine Island, Seychelles (Gaigher, *et al*., 2011).

Whilst invasive alien species constitute a major threat to biodiversity in small islands, the removal of such species can result in recovery and return of species richness. This has been demonstrated in Mauritius by Baider and Florens (2011) where some forested areas were weeded of alien plants and after a decade the forest had recovered close to its initial condition, They concluded, given the severity of alien plant invasion in Mauritius, that their example can 'be seen as a relevant model for a whole swath of other island nations and territories around the world particularly in the Pacific and Indian Oceans' (Baider and Florens, 2011).

The movement of aquatic and terrestrial invasive fauna within and across regions will almost certainly exacerbate the threat posed by climate change in island regions, and could impose significant environmental, economic and social costs. Recent research has shown that the invasion of the Caribbean Sea by the Indo-Pacific lionfish (*Pterois volitans*), a highly efficient and successful predator, is a major contributor to observed increases in algal dominance in coral and sponge communities in the Bahamas and elsewhere in the region. The consequential damage to these ecosystems has been attributed to a significant decline in herbivores due to predation by lionfish (Schofield, 2010; Albins and Hixon, 2008; Lesser and Slattery, 2011; Green *et al.*, 2011). While there is no evidence that the lionfish invasion is climate-related, the concern is that when combined with pre-existing stress factors the natural resilience of Caribbean reef communities will decrease (Albins and Hixon, 2013; Green *et al*., 2012), making them more susceptible to climate change effects such as bleaching. Englund (2008) has documented the negative effects of invasive species on native aquatic insects on Hawai'i and French Polynesia, and their potential role in the extirpation of native aquatic invertebrates in the Pacific. Similarly, there is evidence that on the island of Oahu introduced slugs appear to be 'skewing species abundance in favour of certain non-native and native plants', by altering the 'rank order of seedling survival rates', thereby undermining the ability of preferred species (e.g. the endangered *C. Superba*) to compete effectively (Joe and Daehler, 2008).

29.5.4. Spread of Aquatic Pathogens within Island Regions

The mass mortality of the black sea urchin, *Diadema antillarum*, in the Caribbean basin during the early 1980s demonstrates the ease with which ecological threats in one part of a region can be disseminated to other jurisdictions thousands of kilometres away. The die-off was first observed in the waters off Panama around January 1983, and within 13 months the disease epidemic had spread rapidly through the Caribbean Sea affecting practically all island reefs, as far away as Tobago some 2000 km to the south and Bermuda, some 4000 km to the east. The diadema population in the wider Caribbean declined between 90-95 per cent as a consequence of this single episode (Lessios, 1988, 1995) As *D. antillarum* is one of the principal grazers that removes macroalgae from reefs and thus promotes juvenile coral recruitment, the collateral damage was severe, as the region's corals suffered from high morbidity and mortality for decades thereafter (Carpenter and Edmunds, 2006; Idjadi *et al*., 2010).

There are other climate-sensitive diseases such as yellow, white and black band, white plague and white pox that travel across national boundaries and infect coral reefs directly. This is variously supported by examples from the Indo-Pacific and Caribbean relating to the role of bacterial infections in white syndrome and yellow band disease (Piskorska *et al*., 2007; Cervino *et al*., 2008), the impact of microbial pathogens as stressors on benthic communities in the Mediterranean associated with warming seawater (Danovaro *et al*., 2009, and an increasing evidence of white, yellow and black band disease associated with Caribbean and Atlantic reefs (Rosenberg *et al*., 2009; Brandt and McManus, 2009; Miller *et al.*, 2009a; Weil and Croquer, 2009; Weil and Rogers, 2011).

29.5.5. Trans-Boundary Movements and Human Health

For island communities the trans-boundary implications of existing and future human health challenges are projected to increase in a changing climate. For instance, the aggressive spread of the invasive giant African snail, *Achatina fulica*, throughout the Caribbean, Indo-Pacific islands and Hawai'i is not only assessed to be a severe threat to native snails and other fauna (e.g. native gastropods), flora and crop agriculture, but is also identified as a vector for certain human diseases such as meningitis (Reaser *et al*., 2007; Meyer *et al*., 2008; Thiengo *et al*., 2010).

Like other aquatic pathogens, ciguatoxins that cause ciguatera fish poisoning may be readily dispersed by currents across and within boundaries in tropical and sub-tropical waters. Ciguatoxins are known to be highly temperature-sensitive and may flourish when certain sea water temperature thresholds are reached, as has been noted in the South Pacific (Llewellyn, 2010), Cook Islands (Rongo and van Woesik, 2011), Kiribati (Chan *et al*., 2011), the Caribbean and Atlantic (Otero *et al*., 2010; Tester *et al*., 2010) and Mediterranean (Aligizaki and Nikolaidis, 2008) (see also 29.3.3.2).

29.6. Adaptation and Management of Risks

Islands face risks from both climate-related hazards that have occurred for centuries, as well as new risks from climate change. There have been extensive studies of the risks associated with past climate-related hazards and adaptations to these, such as tropical cyclones, drought, and disease, and their attendant impacts on human health, tourism, fisheries and other areas (Bijlsma *et al*., 1996; Cronk 1997; Solomon and Forbes 1999; Pelling and Uitto 2001). There have also been many studies that have used a variety of vulnerability, risk and adaptation assessment methods particularly in the Pacific that have recently been summarized by Hay *et al*., (2013). But for most islands, there is very little published literature documenting the probability, frequency, severity or consequences of climate change risks such as sea-level rise, ocean acidification, and salinisation of freshwater resources – or associated adaptation measures. Projections of future climate change risks are limited by: the lack of model skill in projecting the climatic variables that matter to small islands, notably: tropical cyclone frequency and intensity, wind speed and direction, precipitation, sea-level, ocean temperature and ocean acidification (Brown *et al*., 2013b); inadequate projections of regional sea levels (Willis and Church, 2012), and a lack of long term baseline monitoring of changes in climatic risk, or to ground-truth models (Voccia, 2012), such as risk of saline intrusion, risk of invasive species, risk of biodiversity loss, or risk of large ocean waves. In their absence, qualitative studies have documented perceptions of change in current risks (Fazey *et al.*, 2011; Lata and Nunn, 2012), reviewed effective coping mechanisms for current stressors (Bunce *et al*. 2009; Campbell et al., 2011) and have considered future scenarios of change (Weir and Virani 2011). These studies highlight that change is occurring, but they do not quantify the probability, speed, scale or distribution of future climate risks. The lack of quantitative published assessments of climate risk for many small islands means that future adaptation decisions have to rely on analogues of responses to past and present weather extremes and climate variability, or assumed/hypothesised impacts of climate change based on island type (Table 29-3). Differences in island type and differences in exposure to climate forcing and hazards vary with island form that provides a framework for consideration of vulnerability and adaptation strategies. Critical is a place-based understanding of island landscapes and of processes operating on individual islands (Forbes *et al.*, 2013).

[INSERT TABLE 29-3 HERE
Table 29-3: Summary of island types in the Pacific region and implications for hydro-meteorological hazards.]

29.6.1. Addressing Current Vulnerabilities on Small Islands

Islands are heterogeneous in geomorphology, culture, ecosystems, populations and hence also in their vulnerability to climate change Vulnerabilities and adaptation needs are as diverse as the variety of islands between regions and even within nation states (e.g. in Solomon Islands, Rasmussen *et al.*, 2011), often with little climate adaptation occurring in peripheral islands, for example in parts of the Pacific (Nunn *et al*. 2013). Quantitative comparison of vulnerability is difficult due to the paucity of vulnerability indicators. Generic indices of national level vulnerability continue to emerge (Cardona, 2007) but only a minority are focused on small islands (e.g. Blancard and Hoarau, 2013). The island-specific indicators that exist often suffer from lack of data (Hughes *et al*., 2012; Peduzzi *et al*., 2009), use indicators that are not relevant in all islands (Barnett and Campbell, 2010), or use data of limited quality for islands, such as sea-level rise (as used in Wheeler, 2011). As a result indicators of vulnerability for small islands often misrepresent actual vulnerability Recent moves towards participatory approaches that link scientific knowledge with local visions of vulnerability (see Park *et al.*, 2012) offers an important way forward to understanding island vulnerability in the absence of certainty in model-based scenarios.

Island vulnerability is often a function of four key stressors: socio-economic, physical, socio-ecological and climate-induced , whose reinforcing mechanisms are important in determining the magnitude of impacts. Socio-economic vulnerabilities are related to on-going challenges of managing urbanisation, pollution and sanitation, both in small island states and non-sovereign islands as highlighted by Storey and Hunter (2010) in Kiribati, López-Marrero and

Yarnal (2010) in Puerto Rico, and in Mayotte (France) (Le Masson and Kelman, 2011). Geo-physical characteristics of islands (see Table 29-2; Figure 29-1) create inherent physical vulnerabilities. Thus, for example the Azores (Portugal) face seismic, landslide and tsunami risks (Coutinho *et al*., 2009). Socio-ecological stresses, such as habitat loss and degradation, invasive species (described in Sax and Gaines, 2008), overexploitation, pollution, human encroachment and disease can harm biodiversity (Caujape-Castells *et al*., 2010; Kingsford *et al.*, 2009), and reduce the ability of socio-ecological systems to bounce back after shocks. To understand climate vulnerability on islands, it is necessary to assess all of these dimensions of vulnerability (Rasmussen *et al*., 2011). For example, with individual ecosystems, such as coral reef ecosystems – those already under stress from non-climate factors are more at risk from climate change than those that are unstressed (Maina *et al*., 2011; Hughes *et al*., 2003). Evidence is starting to emerge that shows the same applies at the island scale. In Majuro atoll (Marshall Islands), 34-37 years of aerial photography shows that socio-ecological stress is exacerbating shoreline change associated with sea-level rise, especially on the lagoon-side of islands (Ford, 2012; see also 29.3.1.1). Islands faced with multiple stressors can therefore be assumed to be more at risk from climate impacts.

Despite the limited ability of continental scale models to predict climate risks for specific islands, or the limited capacity of island vulnerability indicators, scenario based damage assessments can be undertaken. Storm surge risks have been effectively modeled for the Andaman and Nicobar Islands (Kumar *et al*., 2008). Rainfall induced landslide risk maps have been produced for both Jamaica (Miller *et al*., 2009b) and the Chuuk Islands (Federated States of Micronesia) (Harp *et al*., 2009). However the probability of change in frequency and severity of extreme rainfall events and storm surges remains poorly understood for most small islands. Other risks, such as the climate change driven health risks from the spread of infectious disease, loss of settlements and infrastructure, and decline of ecosystems that affect island economies, livelihoods and human well-being also remain under-researched. Nevertheless, it is possible to consider these risks along with the threat of rising sea level and suggest a range of contemporary and future adaptation issues and prospects for small islands (Table 29-4).

[INSERT TABLE 29-4 HERE
Table 29-4: Selected key risks and potential for adaptation for small islands from the present-day to the long-term.]

29.6.2. Practical Experiences of Adaptation on Small Islands

There is disagreement about whether islands and islanders have successfully adapted to past weather variability and climate change. Nunn (2007) argues that past climate changes have had a ‘crisis effect’ on prehistoric societies in much of the Pacific Basin. In contrast a variety of studies argue that past experiences of hydro-meteorological extreme events have enabled islands to become resilient to weather extremes (Barnett, 2001). Resilience appears to come from both a belief in their own capacity (Kuruppu and Liverman, 2011; Adger and Brown, 2009), and a familiarity with their environment and understanding of what is needed to adapt (Tompkins *et al*., 2009; Le Masson and Kelman, 2011). For example, compared to communities in the larger countries of Madagascar, Tanzania and Kenya, the Indian Ocean islands – the Seychelles and Mauritius – were found to have: comparatively high capacity to anticipate change and prepare strategies; self-awareness of human impact on environment; willingness to change occupation; livelihood diversity; social capital; material assets; access to technology and infrastructure, all of which produced high adaptive capacity (Cinner *et al.,* 2012). Despite this resilience, islands are assumed to be generically vulnerable to long term future climate change (Parks and Roberts, 2006; Myers, 2002).

There are many ways in which *in-situ* climate adaptation can be undertaken: reducing socio-economic vulnerabilities, building adaptive capacity, enhancing disaster risk reduction, or building longer term climate resilience (e.g. see McGray *et al*., 2007; Eakin *et al.*, 2009). Figure 29-5 highlights the implications of the various options. Not all adaptations are equally appropriate in all contexts. Understanding the baseline conditions and stresses (both climate and other) are important in understanding which climate change adaptation option will generate the greatest benefits. On small islands where resources are often limited, recognising the starting point for action is critical to maximising the benefits from adaptation. The following section considers the benefits of pursuing the various options.

[INSERT FIGURE 29-5 HERE
Figure 29-5: The impact of alternative climate change adaptation actions or policies.]

29.6.2.1. Building Adaptive Capacity with Traditional Knowledge, Technologies, and Skills on Small Islands

As in previous IPCC Assessments, there is continuing strong support for the incorporation of indigenous knowledge into adaptation planning. However this is moderated by the recognition that current practices alone may not be adequate to cope with future climate extremes or trend changes The ability of a small island population to deal with current climate risks may be positively correlated with the ability to adapt to future climate change, but evidence confirming this remains limited (such as Lefale, 2010). Consequently, this section focuses on evidence for adaptive capacity that reduces vulnerability to existing stressors, enables adaptation to current stresses, and supports current disaster risk management.

Traditional knowledge has proven to be useful in short term weather forecasting (e.g. Lefale, 2010) although evidence is inconclusive on local capacity to observe long-term climate change (e.g. Hornidge and Scholtes, 2011). In Solomon Islands, Lauer and Aswani (2010) found mixed ability to detect change in spatial cover of seagrass meadows. In Jamaica, Gamble *et al*. (2010) reported a high level of agreement between farmers' perception of increasing drought incidence and statistical analysis of precipitation and vegetation data for the area. In this case farmers perceptions clearly validated the observational data and vice versa. Despite some claims that vulnerability reduction in indigenous communities in small islands may be best tackled by combining indigenous and Western knowledge in a culturally compatible and sustainable manner (Mercer *et al.*, 2007), given the small number of studies in this area, there is not sufficient evidence to determine the effectiveness and limits to the use of traditional methods of weather forecasting under climate change on small islands.

Traditional technologies and skills can be effective for current disaster risk management but there is currently a lack of supporting evidence to suggest that they will be equally appropriate under changing cultural conditions and future climate changes on islands. Campbell (2009) identified that traditional disaster reduction measures used in Pacific islands focused around maintaining food security, building community cooperation, and protecting settlements and inhabitants. Examples of actions to maintain food security include: the production and storage of food surpluses – such as yam and breadfruit buried in leaf-lined pits to ferment; high levels of agricultural diversity to minimise specific damage to any one crop; and the growth of robust famine crops – unused in times of plenty which could be used in emergencies (Campbell, 2009). Two discrete studies from Solomon Islands highlight the importance of traditional patterns of social organisation within communities to support food security under social and environmental change (Reenberg *et al.*, 2008; Mertz *et al.*, 2010). In both studies the strategy of relying on traditional systems of organization for farming and land use management have been shown to work effectively – largely as there has been little cultural and demographic change. Nonetheless there are physical and cultural limits to traditional disaster risk management. In relation to the ability to store surplus production on atoll islands, on Rongelap in the Marshall Islands, surpluses are avoided, or are redistributed to support community bonds (Bridges and McClatchey, 2009). Further, traditional approaches that Pacific island communities have used for survival for millennia (such as building elevated settlements and resilient structures; and working collectively), have been abandoned or forgotten due to processes of globalisation, colonialism and development (Campbell, 2009). Ongoing processes of rapid urbanization, and loss of language and tradition suggest that traditional approaches may not always be efficacious in longer-term adaptation.

Traditional construction methods have long been identified across the Pacific as a means of reducing vulnerability to tropical cyclones and floods in rural areas. In Solomon Islands traditional practices include: elevating concrete floors on Ontong Java to keep floors dry during heavy rainfall events; building 'low, aerodynamic houses with sago palm leaves as roofing material on Tikopia' as preparedness for tropical cyclones; and in Bellona local perceptions are that houses constructed from modern materials and practices are more easily destroyed by tropical cyclones, implying that traditional construction methods are perceived to be more resilient in the face of extreme weather (Rasmussen *et al.*, 2009). In parallel, Campbell (2009) documents the characteristics of traditional building styles (in Fiji, Samoa and Tonga) where relatively steep hipped roofs, well bound connections and joints, and airtight spaces with few windows or doors offer some degree of wind resistance. Traditional building measures can also reduce damages associated with earthquakes – as evidenced in Haiti (Audefroy, 2011). By reducing damage caused by other stresses (such as earthquakes), adaptive capacity is more likely to be maintained. The quality of home construction is critical to its wind-resistance. If inadequately detailed, home construction will fail irrespective of method. While some traditional measures could be challenged as potentially risky – for example using palm leaves, rather than metal roofs as a preparation for tropical cyclone impacts – the documentation of traditional approaches, with an evaluation of their effectiveness remains urgently needed. Squatter settlements in urban areas, especially on steep hillsides in the Caribbean often use poor construction practices frequently driven by poverty and inadequate building code enforcement (Prevatt *et al*., 2010).

Traditional systems appear less effective when multiple civilization-nature stresses are introduced. For example in Reunion and Mayotte, population growth, and consequent rises in land and house prices have led low-income families to settle closer to hazardous slopes that are prone to landslides and to river-banks which are prone to flooding (Le Masson and Kelman, 2011). Traditional belief systems can also limit adaptive capacity. Thus, for example in two Fijian villages, approximately half of survey respondents identified divine will as the cause of climate change (Lata and Nunn, 2012). These findings reinforce earlier studies in Tuvalu (Mortreux and Barnett, 2009), and more widely across the Pacific (Barnett and Campbell, 2010). The importance of taking into account local interests and traditional knowledge in adaptation in small islands is emphasised by Kelman and West (2009) and McNamara and Westoby (2011), yet evidence does not yet exist that reveals the limits to such knowledge, such as in the context of rapid socio-ecological change, or the impact of belief systems on adaptive capacity.

While there is clear evidence that traditional knowledge networks, technologies and skills can be used effectively to support adaptation in certain contexts, the limits to these tools are not well understood. To date research in the Pacific and Caribbean dominates small island climate change work. More detailed studies on small islands in the central and western Indian Ocean, the Mediterranean and the central and eastern Atlantic would improve understanding on this topic.

29.6.2.2. Addressing Risks on Small Islands

Relative to other areas, small islands are disproportionately affected by current hydro-meteorological extreme events, both in terms of the percentage of the population affected, and losses as a percentage of GDP (Anthoff *et al*., 2010; Table 29-5). Under climate change the risks of damage and associated losses are expected to continue to rise (Nicholls and Cazenave, 2010). Yet much of the existing literature on climate risk in small islands does not consider how to address high future risks, but instead focuses on managing present day risks through risk transfer, risk spreading or risk avoidance. Risk transfer is largely undertaken through insurance; risk spreading through access to and use of common property resources, livelihood diversification, or mutual support through networks (see 29.6.2.3); and risk avoidance through structural engineering measures or migration (see 29.6.2.4).

[INSERT TABLE 29-5 HERE
Table 29-5: Top ten countries in the Asia-Pacific region based on absolute and relative physical exposure to storms and impact on GDP (between 1998 and 2009).]

Risk transfer through insurance markets has had limited uptake in small islands, as insurance markets do not function as effectively as they do in larger locations, in part due to a small demand for the insurance products (Heger *et al*., 2008). In the case of insurance for farmers, researchers found that a lack of demand for insurance products (in their study countries: Grenada, Jamaica, Fiji and Vanuatu) meant an undersupply of customized food insurance products, which in turn contributed to a lack of demand for insurance (Angelucci and Conforti, 2010). Alternatives exist such as index-based schemes that provide payouts based on the crossing of a physical threshold, e.g. when rainfall drops below a certain level, rather than on drought damage sustained (Linnerooth-Bayer and Mechler, 2009). The potential for index-based insurance for climate stressors on islands is under-researched and there remains limited evidence of the long-term effectiveness of index-based or pooled-risk insurance in supporting household level adaptation. Small island governments also face expensive climate risk insurance. The Caribbean Catastrophe Risk Insurance Facility (CCRIF) which has been operating since 2007 pools Caribbean-wide country-level risks into a central, more diversified risk portfolio – offering lower premiums for participating national governments (CCRIF, 2008). The potential for a similar scheme in the Pacific is being explored (ADB, 2009; Cummins and Mahul, 2009).

Risk can be spread socially e.g. through social networks and familial ties (see also 29.6.2.3), or ecologically, e.g. by changing resource management approach. Social networks can be used to spread risk among households. In Fiji, after Tropical Cyclone *Ami* in 2003, households whose homes were not affected by the cyclone increased their fishing effort to support those whose homes were damaged (Takasaki, 2011) – mutual support formed a central pillar for community-based adaptation. In the case of natural systems, risks can be spread through enhancing representation of habitat types and replication of species e.g. through the creation of marine protected areas, around key refuges that protect a diversity of habitat, that cover an adequate proportion of the habitat and that protect critical areas such as nursery grounds and fish spawning aggregation areas (McLeod *et al.*, 2009). Locally Managed Marine Areas – which involve the local community in the management and protection of their local marine environment – have proven to be effective in increasing biodiversity, and in reducing poverty in areas dependent on marine resources in several Pacific islands (Techera, 2008; Game *et al*., 2011). By creating a network of protected areas supported by local communities the risks associated with some forms of climate change can be spread and potentially reduced (Mills *et al*., 2010) although such initiatives may not preserve thermally sensitive corals in the face of rising SST.

Risk avoidance through engineered structures can reduce risk from some climate-related hazards (*medium evidence, medium agreement*). In Jamaica, recommendations to reduce rainfall-driven land surface movements resulting in landslides include: engineering structures such as soil nailing, gabion baskets (i.e. cages filled with rocks), rip rapped surfaces (i.e. permanent cover with rock) and retaining walls together with engineered drainage systems (Miller *et al*., 2009b). Engineering principles to reduce residential damage from hurricanes have been identified, tested, and recommended for decades in the Caribbean. However, expected levels of success have often not been achieved due to inadequate training of construction workers, minimal inspection of new buildings, and lack of enforcement of building code requirements (Prevatt *et al.,* 2010). Some island states do not even have the technical or financial capacity to build effective shore protection structures as highlighted by a recent assessment in south Tarawa, Kiribati (Duvat, 2013). In addition not all engineered structures are seen as effective risk avoidance mechanisms. In the Azores archipelago, a proliferation of permanent engineered structures along the coastline to prevent erosion have resulted in a loss of natural shoreline protection against wave erosion (Calado *et al.,* 2011)). In Barbados it is recognized that seawalls can protect human assets in areas prone to high levels of erosion, however they can also cause sediment starvation in other areas, interfere with natural processes of habitat migration and cause coastal squeeze – which may render them less desirable for long term adaptation (Mycoo and Chadwick, 2012) (see also 5.4.2.1). To reduce erosion risk an approach with less detrimental downstream effects that also supports tourism is beach nourishment. This is increasingly being recommended, for example in the Caribbean (Mycoo and Chadwick, 2012), the Mediterranean (Anagnostou *et al*., 2011), and western Indian Ocean (Duvat, 2009). Beach nourishment however is not without its challenges, as requirements such as site-specific oceanographic and wave climate data, adequate sand resources and critical engineering design skills may not be readily available in some small islands.

29.6.2.3. Working Collectively to Address Climate Impacts on Small Islands

More attention is being focused on the relevance and application of community-based adaptation (CBA) principles to island communities, to facilitate adaptation planning and implementation (Warrick, 2009; Kelman *et al*., 2011) and to tackle rural poverty in resource dependent communities (Techera, 2008). CBA research is focusing on empowerment that helps people to help themselves e.g. through marine catch monitoring (Breckwoldt and Seidel, 2012), while addressing local priorities and building on local knowledge and capacity. This approach to adaptation is being promoted as an appropriate strategy for small islands, since it is something done 'with' rather than 'to' communities (Warrick, 2009). Nonetheless externally driven programs to encourage community-level action have produced some evidence of effective adaptation. Both Limalevu *et al*. (2010) and Dumaru (2010) describe the outcomes of externally-led pilot CBA projects (addressing water security and coastal management) implemented in villages across Fiji, notably: more effective management of local water resources through capacity building; enhanced knowledge of climate change; and, the establishment of mechanisms to facilitate greater access to technical and financial resources from outside the community. More long term monitoring and evaluation of the effectiveness of community level action is needed.

Collaboration between stakeholders can lessen the occurrence of simple mistakes that can reduce the effectiveness of adaptation actions (*medium evidence, medium agreement*). Evidence from the Eastern Caribbean suggests that adaptations taken by individual households to reduce landslide risk – building simple retaining walls – can be ineffective compared to community level responses (Anderson *et al*., 2011). Landslide risk can be significantly reduced through better hillside drainage. In the Eastern Caribbean, community groups, with input from engineers, have constructed these networks of drains to capture surface runoff, household roof-water and grey water. Case studies from Fiji and Samoa in which multi-stakeholder and multi-sector participatory approaches were used to help enhance resilience of local residents to the adverse impacts of disasters and climate change (Gero *et al.*, 2011) further support this view. In the case of community based disaster risk reduction (CBDRR), Pelling (2011) notes that buy-in from local and municipal governments is needed, as well as strong pre-existing relationships founded on routine daily activities, to make CBDRR effective. Research from both Solomon Islands and the Cayman Islands reinforce the conclusion that drivers of community resilience to hazard maps closely onto factors driving successful governance of the commons, that is: community cohesion; effective leadership; and, community buy-in to collective action (Schwarz *et al.*, 2011; Tompkins *et al*., 2008). Where community organisations are operating in isolation, or where there is limited coordination and collaboration community vulnerability is expected to increase (Ferdinand *et al*., 2012). Strong local networks, and trusting relationships between communities and government appear to be key elements in adaptation, in terms of maintaining sustainable agriculture and in disaster risk management (*medium evidence, high agreement*).

All of these studies reinforce the earlier work of Barnett (2001), providing empirical evidence that supporting community-led approaches to disaster risk reduction and hazard management may contribute to greater community engagement with anticipatory adaptation. However, it is not yet possible to identify the extent to which climate resilience is either a coincidental benefit of island lifestyle and culture, or a purposeful approach, such as the community benefits gained from reciprocity among kinship groups (Campbell, 2009).

29.6.2.4. Addressing Long-Term Climate Impacts and Migration on Small Islands

Sea-level rise poses one of the most widely recognized climate change threats to low-lying coastal areas on islands (29.3.1). However long term climate impacts depend on the type of island (see Figure 29-1) and the adaptation strategy adopted. Small island states have 16% of their land area in low elevation coastal areas (<10m) as opposed to a global average of 2%, and the largest proportion of low elevation coastal urban land area: 13% (along with Australia and New Zealand), in contrast to the global average of 8% (McGranahan *et al.*, 2007). Statistics like these underpin the widely held view about small islands being 'overwhelmed' by rising seas associated with sea-level rise (Loughry and McAdam, 2008; Yamamoto and Esteban, 2010; Gordon-Clark, 2012; Berringer, 2012; Dema, 2012; Lazrus, 2012; Laczko and Aghazarm, 2009). Yet there remains *limited evidence* as to which regions (Caribbean, Pacific, Indian Ocean, west African islands) will experience the largest sea-level rise (Willis and Church, 2012) and which islands will experience the worst climate impacts. Nicholls *et al*. (2011) have modeled impacts of 4°C warming, producing a 0.5 to 2.0m sea-level rise, to assess the impacts on land loss and migration. With no adaptation occurring, they estimate that this could produce displacement of between 1.2 and 2.2 million people from the Caribbean, Indian Ocean and Pacific Ocean. More research is needed to produce robust agreement on the impact of sea-level rise on small islands, and on the range of adaptation strategies that could be appropriate for different island types under those scenarios. Research into the possible un-inhabitability of islands has to be undertaken sensitively to avoid short-term risks (i.e. to avoid depopulation and ultimately island abandonment) associated with a loss of confidence in an islands future (McNamara and Gibson, 2009; McLeman, 2011).

Due to the high costs of adapting on islands it has been suggested that there will be a need for migration (Nicholls *et al.*, 2011; Gemenne, 2011; Biermann and Boas, 2010; Voccia 2012). Relocation and displacement are frequently cited as outcomes of sea-level rise, salinisation and land loss on islands (Byravan and Rajan, 2006; Kolmannskog and Trebbi, 2010; see also 29.3.3.3). Climate stress is occurring at the same time as the growth in rural to urban migration. The latter is leading to squatter settlements that strain urban infrastructure – notably: sewerage, waste management, transport and electricity (Jones, 2005; Connell and Lea, 2002). Urban squatters on islands often live in highly exposed locations, lacking basic amenities, leaving them highly vulnerable to climate risks (Baker, 2012). However, a lack of research in this area makes it difficult to draw clear conclusions on the impact of climate change on the growing number of urban migrants in islands.

Recent examples of environmental stress driven relocation and displacement provide contemporary analogues of climate-induced migration. Evidence of post-natural disaster migration has been documented in the Caribbean in relation to hurricanes (McLeman and Hunter, 2010), and in the Carteret Islands, Papua New Guinea – where during an exceptionally high inundation event in 2008 (see 29.5.1.1) islanders sought refuge on neighbouring Bougainville island (Jarvis, 2010). Drawing any strong conclusions from this literature is challenging as there is little understanding of how to measure the effect of the environmental signal in migration patterns (Afifi *et al*., 2013; Krishnamurthy, 2012). While the example of the Carteret Islands cannot be described as evidence of adaptation to climate change, it suggests that under some extreme scenarios island communities may need to consider relocating in the future (Gemenne, 2011). In reality, financial and legal barriers are expected to inhibit significant levels of international environmentally induced migration in the Pacific (Barnett and Chamberlain, 2010).

29.6.3. Barriers and Limits to Adaptation in Small Island Settings

Since publication of the IPCC SAR in 1996, significant barriers to climate change adaptation strategies in island settings have been discussed in considerable detail. Barriers include inadequate access to financial, technological and human resources, issues related to cultural and social acceptability of measures, constraints imposed by the existing political and legal framework, the emphasis on island development as opposed to sustainability, and a tendency to focus on addressing short term climate variability rather than long term climate change, and community preferences for “hard” adaptation measures such as seawalls instead of “soft” measures such as beach nourishment (Sovacool, 2012). Heger *et al*. (2008) recognised that more diversified economies have more robust responses to climate stress, yet most small islands lack economies of scale in production, thus specialising in niche markets and developing monocultures (e.g. sugar or bananas). Non-sovereign island states face additional exogenous barriers to adaptation. For example, islands like Réunion and Mayotte benefit from the provision of social services somewhat similar to what obtains in the Metropole, but not the level of enforcement of building codes and land use planning as in France (Le Masson and Kelman, 2011). Owing to their nature and complexity, these constraints will not be easily eliminated in the short term and will require on-going attention if their impact is to be minimized over time. Exogenous factors, such as the comparatively few assessments of social vulnerability to climate change, adaptation potential or resilience for island communities (Barnett, 2010) limit current understanding. In part this is due to the particularities of islands – both their heterogeneity and their difference from mainland locations – as well as the limitations of climate models in delivering robust science for small islands. It remains the case that thirteen years after Nurse *et al*. (2001) noted that downscaled global climate models do not provide a complete or necessarily accurate picture of climate vulnerabilities on islands, there is still little climate impacts research that reflects local concerns and contexts (Barnett *et al.,* 2008).

While lack of access to adequate financial, technological and human resources is often cited as the most critical constraint, experience has shown that endogenous factors such as culture, ethics, knowledge and attitudes to risk are important in constraining adaptation. Translating the word ‘climate’ into Marshallese implies cosmos, nature and culture as well as weather and climate (Rudiak-Gould, 2012). Such cultural misunderstandings can create both barriers to action and novel ways of engaging with climate change. The lack of local support (due to encroachment on traditional lands) for the development of new infiltration galleries to augment freshwater supply on Tarawa atoll, Kiribati, highlights the importance of social acceptability (Moglia *et al.,* 2008a, 2008b). Such considerations have led to the conclusion that there is still much to be learned about the drivers of past adaptation and how ‘mainstreaming’ into national programs and policies, widely acclaimed to be a virtually indispensable strategy, can practically be achieved (Mercer *et al.,* 2007; Adger *et al.,* 2009; Mertz *et al.,* 2009).

Notwithstanding the extensive and ever-growing body of literature on the subject, there is still a relatively low level of awareness and understanding at the community level on many islands about the nature of the threat posed by climate change (Nunn, 2009). Even where the threat has been identified, it is often not considered an urgent issue, or a local priority, as exemplified in Malta (Akerlof *et al.,* 2010) and Funafuti, Tuvalu (Mortreux and Barnett, 2009). Lack of awareness, knowledge and understanding can function as an effective barrier to the implementation and ultimate success of adaptation programs. This is borne out in both Fiji and Kiribati where researchers found that spiritual beliefs, traditional governance mechanisms, and a short term approach to planning were barriers to community engagement and understanding of climate change (Kuruppu, 2009; Lata and Nunn, 2012). Although widely acknowledged to be critical in small islands, few initiatives pay little more than perfunctory attention to the importance of awareness, knowledge and understanding in climate change adaptation planning. Hence, the renewed call for adaptation initiatives to include and focus directly on these elements on an ongoing basis (e.g., Crump, 2008; Kelman and West, 2009; Kelman, 2010; Kuruppu and Liverman, 2011; Gero *et al.,* 2011) is timely, if these barriers are to be eventually removed.

29.6.4. Mainstreaming and Integrating Climate Change into Development Plans and Policies

There is a growing body of literature that discusses the benefits and possibilities of mainstreaming or integrating climate change policies in development plans. Various mechanisms through which development agencies as well as donor and recipient countries can seek to capitalize on the opportunities to mainstream are beginning to emerge (see for example Klein *et al.,* 2007; Mertz *et al.,* 2009). Agrawala and van Aalst (2008) provide examples from Fiji and elsewhere, of where synergies (and trade-offs) can be found in integrating adaptation to climate change into development cooperation activities, notably in the areas of: disaster risk reduction, community-based approaches to development, and building adaptive capacity. Boyd *et al.* (2009) support the need for more rapid integration of adaptation into development planning, to ensure that adaptation is not side-lined, or treated separately from sectoral policies. Although there are synergies and benefits to be derived from the integration of climate change and development policies, care is needed to avoid institutional overlaps, and differences in language and approach – which can give rise to conflict (Schipper and Pelling, 2006). Overall, there appears to be an emerging consensus around the views expressed by Swart and Raes (2007) that climate change and development strategies should be considered as complementary, and that some elements such as land and water management and urban, peri-urban and rural planning provide important adaptation, development and mitigation opportunities. While the potential to deliver such an integrated approach may be reasonably strong in urban centres on islands, there appears to be limited capacity to mainstream climate change adaptation into local decision making in out-lying islands or peripheral areas (Nunn *et al*., 2013).

29.7. Adaptation and Mitigation Interactions

Greenhouse gas emissions from most small islands are negligible in relation to global emissions, yet small islands will most probably be highly impacted by climate change (Srinivasan, 2010). ‘However, many small island governments and communities have chosen to attempt to reduce their greenhouse gas emissions because of the cost andthe potential co-benefits and synergies. Malta and Cyprus are obliged to do so in line with EU climate and energy policies. This section considers some of the inter-linkages between adaptation and mitigation on small islands and the potential synergies, conflicts, trade-offs and risks. Unfortunately there is relatively little research on the emissions reduction potential of small islands, and far less on the inter-linkages between climate change adaptation and emissions reduction in small islands. Therefore in this section a number of assumptions are made about how and where adaptation and mitigation actions interact.

29.7.1. Assumptions/Uncertainties Associated with Adaptation and Mitigation Responses

Small islands are not homogeneous. Rather they have diverse geo-physical characteristics and economic structures (see Table 29-2, Figure 29-1). Following Nunn (2009) the combination of island geography and economic types informs the extent to which adaptation and mitigation actions might interact. The geography and location of islands affect their sensitivity to hydro-meteorological and related hazards such as cyclones, floods, droughts, invasive alien species, vector borne disease, and landslides. On the other hand the capacity of island residents to cope is often related to income levels, resources endowment, technology and knowledge (see 29.6.2).

The potential for mitigation and emissions reductions in islands depends to a large extent on their size and stage of economic development. In the small and less developed islands key 'mitigation' sectors including energy, transport, industry, built environment, agriculture, forestry, or waste management sectors are generally relatively small (Metz *et al.*, 2007; Swart and Raes, 2007). Hence opportunities for emissions reductions are usually quite limited and are mostly associated with electricity generation and utilization of vehicles. More mitigation opportunities should exist in more economically advanced and larger islands that rely on forms of production that utilize fossil fuels, including manufacturing, and where vehicle usage is extensive and electricity driven home appliances, such as air conditioners and water heaters, are extensively used.

In the absence of significant mitigation efforts at the global scale, adaptation interventions could become very costly and difficult to implement, once certain thresholds of change are reached (Nelson, 2011; Birkmann, 2011). Nicholls *et al*. (2011) make a similar observation with respect to coastal protection as a response to sea-level rise. They suggest that if global mean temperatures increase by around 4 ^{0}C (which may lead to sea-level rise between 0.5 m and 2 m) the likelihood of successful coastal protection in some locations such as low-lying small islands, will be low. Consequently, it is argued that the relocation of communities would be a likely outcome in such circumstances (Nicholls *et al.*, 2011).

29.7.2. Potential Synergies and Conflicts

Metz *et al.* (2007) suggest that adaptation and mitigation interactions occur in one of four main ways: adaptations that result in greenhouse emissions reduction; mitigation options that facilitate adaptation; policy decisions that couple adaptation and mitigation effects; and, trade-offs and synergies between adaptation and mitigation. Each of these opportunities is considered using three examples: coastal forestry, energy supply, and tourism.

Small islands have relatively large coastal zones (in comparison to land area) and most development (as well as potential mitigation and adaptation activities) are located in the coastal zone. Coastal ecosystems (coral reefs, sea grasses and mangroves) play an important role in protecting coastal communities from wave erosion, tropical cyclones, storm surges, and even moderate tsunami waves (Cochard *et al*., 2008). Whilst coastal forests including both endemic and exotic species especially mangroves are seen as effective adaptation options ('bioshields' Feagin *et al.*, 2010) in the coastal zones, they also play an important role in mitigation as carbon sinks (van der Werf *et al*., 2009). Thus, the management and conservation of mangrove forests has the potential to generate synergies between climate change adaptation and mitigation. However, despite this knowledge population, development and agricultural pressures have constrained the expansion of island forest carbon stocks (Fox *et al*., 2010) while Gilman *et al*. (2008) note that such pressures can also reduce the buffering capacity of coastal vegetation systems.

Renewable energy resources on small islands have only recently been considered within the context of long-term energy security (Praene *et al.,* 2012; Chen *et al.*, 2007). Stuart (2006) speculates that the lack of uptake of renewable technologies to date might be due to historical commitments to conventional fossil fuel-based infrastructure, and a lack of resources to undertake research and development of alternatives. Those islands that have introduced renewable energy technologies have often done so with support from international development agencies (Dornan, 2011). Despite this, there remain significant barriers to the wider institutionalization of renewable technologies in small islands. Research in Europe and the United States has shown the mitigation and cost savings benefits of Energy Service Companies (ESCOs): companies that enter into medium-to-long term performance-based contracts with energy users, invest in energy efficiency measures in buildings and firms, and profit from the ensuing energy savings measures for the premises (see for example Steinberger *et al.*, 2009). Potential benefits exist in creating the opportunity for ESCOs to operate in small islands. Preliminary evidence from Fiji suggests that if the incentive mechanisms can be resolved, and information asymmetries between service providers and users can be aligned, ESCOs could provide an opportunity to expand renewable technologies (Dornan, 2009). IPCC (2011) presents examples of opportunities for renewable energy, including wind energy sources, as deployed in the Canary Islands.

The transition towards renewable energy sources away from fossil fuel dependence has been partly driven by economic motives, notably to avoid oil price volatility and its impact. The development of hydro-power (in Fiji for example) necessitates protection and management of the water catchment zones, and thus could lead to improved management of the water resources – a critical adaptation consideration for areas expected to experience a decrease in average rainfall as a result of climate change. Whilst the cost effectiveness of renewable technologies is critical, placing it within the context of water adaptation could enhance project viability (Dornan, 2009). Cost-benefit analyses have shown that in southeast Mediterranean islands photovoltaic generation and storage systems may be more cost-effective than existing thermal power stations (Kaldellis, 2008; Kaldellis *et al*., 2009).

Energy prices in small islands are among the highest anywhere in the world, mainly due to their dependence on imported fossil fuel, and limited ability to reap the benefits of economies of scale including bulk buying. Recent studies show that the energy sectors in small islands may be transformed into sustainable growth entities mainly through the judicious exploitation of renewable energy sources, combined with the implementation of energy efficiency measures (van Alphen *et al.*, 2008; Banuri, 2009; Mohanty, 2012; Rogers *et al.*, 2012). Realising the potential for such transformation, the countries comprising the Alliance of Small Island States (AOSIS) launched SIDS Dock, which is intended to function as a 'docking station' to connect the energy sector in SIDS with the international finance, technology and carbon markets with the objective of pooling and optimizing energy efficiency goods and services for the benefit of the group. This initiative seeks to decrease energy dependence in SIDS, while generating financial resources to support low carbon growth and adaptation interventions.

Many small islands rely heavily on the foreign exchange from tourism to expand and develop their economies, including the costs of mitigation and adaptation. Tourism, particularly in small islands, often relies on coastal and terrestrial ecosystems to provide visitor attractions and accommodation space. Recognising the relationship between ecosystem services and tourism in Jamaica, Thomas-Hope and Jardine-Comrie (2007) suggest that sustainable tourism planning should include activities undertaken by the industry, that is tertiary treatment of waste, and re-use of water, as well as composting organic material and investing in renewable energy. Gössling and Schumacher (2010) and others who have examined the linkages between greenhouse gas emissions and sustainable tourism argue that the tourism sector (operators and tourists) should pay to promote sustainable tourism, especially where they benefit directly from environmental services sustained by these investments.

29.8. Facilitating Adaptation and Avoiding Maladaptation

While there is a clear consensus that adaptation to the risks posed by global climate change is necessary and urgent in small islands, the implementation of specific strategies and options is a complex process that requires critical evaluation of multiple factors, if expected outcomes are to be achieved (Kelman and West, 2009; Barnett and O'Neill, 2012). These considerations may include, *inter alia*, prior experience with similar or related threats, efficacy of the strategies or options and their co-benefits, costs (monetary and non-monetary), availability of alternatives and social acceptability. In addition, previous work (e.g. Adger *et al.,* 2005) has emphasised the relevance of scale as a critical factor when assessing the efficacy and value of adaptation strategies, as the extent to which an option is perceived to be a success, failure or maladaptive may be conditioned by whether it is being assessed as a response to climate variability (shorter-term) or climate change (longer-term).

As in other regions, adaptation in islands is locally delivered and context specific (Tompkins *et al.,* 2010). Yet, sectors and communities on small islands are often so intricately linked that there are many potential pathways that may lead to maladaptation, be it via increased greenhouse gas emissions, foreclosure of future options, or burdensome opportunity costs on local communities. There is also a concern that some types of interventions may actually be maladaptive. For example, Barnett and O'Neill (2012) suggest that strategies such as resettlement and migration should be regarded as options of 'last resort' on islands, as they may actually discourage viable adaptation initiatives, by fostering over-dependence on external support. They further argue that a priori acceptance of adaptation as an efficacious option for places like the Pacific islands, may also act as a disincentive for reducing greenhouse gas emissions (Barnett and O'Neill, 2012).

Notwithstanding the observations of Barnett and O'Neill (2012), there is a concern that early foreclosure of this option might well prove maladaptive, if location-specific circumstances show such action to be efficacious in the longer-term. For example, Bunce *et al*. (2009) have shown that as an adaptive response to poverty, young fishers from Rodrigues Island periodically resort to temporary migration to the main capital island, Mauritius, where greater employment prospects exist. The case study of the residents of Nauru who contemplated resettlement in Australia after the collapse of phosphate mining (their only revenue source) in the1950s, provides helpful insight about the complex social, economic and cultural challenges associated with environmentally triggered migration (Tabucanon and Opeskin, 2011). Negotiations with the Government of Australia collapsed before a mutually acceptable agreement was reached, and the Nauruans opted to abandon the proposal to relocate (Tabucanon and Opeskin, 2011). Overall however, it is suggested that states contemplating long term, off-island migration may wish to consider early proactive planning, as resettlement of entire communities might prove to be socially, culturally and economically disruptive (Campbell, 2010; McMichael *et al.,* 2012; refer also to 29.3.3.3). A related challenge facing small islands is the need to find the middle ground between resettlement and objective assessment of other appropriate adaptation choices.

Similarly, while insurance is being promoted as an element of the overall climate change response strategy in some island regions, e.g. the Caribbean, concerns have been expressed about possible linkages to maladaptation. The potential consequences include the imposition of exorbitant premiums that are beyond the capacity of resource-scarce governments as the perception of climate change risks increase, discriminatory coverage of sectors that may not align with local priorities, and tacit encouragement for the state, individuals and the private sector to engage in behavior that is not risk-averse, e.g. development in hazard-prone areas (Herweijer *et al.,* 2009; Linnerooth-Bayer *et al.,* 2011; van Nostrand and Nevius, 2011; Thomas and Leichenko, 2011). Likewise, although the exploitation of renewable energy is vital to the sustainable development of small islands, more attention needs to be paid to the development of energy storage technologies, if rapid transition from conventional fuels is to be achieved in an efficient manner. This is especially important in the case of intermittent energy sources (e.g. solar and wind), as the cost of current storage technologies can frustrate achievement of full conversion to renewable energy. Thus to avoid the possibility of maladaptation in the sector, countries may wish to consider engaging in comprehensive planning, including considerations relating to energy storage (Krajačić *et al.,* 2010; Bazilian *et al.,* 2011).

Recent studies have demonstrated that opportunities exist in island environments for avoiding maladaptation. Studies have shown for example that decisions about adaptation choices and their implementation are best facilitated where there is constructive engagement with the communities at risk, in a manner that fosters transparency and trust (López-Marrero, 2010; van Aalst *et al*., 2008). Further, some analysts argue that adaptation choices are often subjective in nature and suggest that participatory stakeholder involvement can yield valuable information about the priorities and expectations that communities attach to the sector for which adaptation is being sought. The point is underscored by Moreno and Becken (2009) whose study of the tourism sector on the Mamanuca islands (Fiji), which clearly demonstrates that approaches which explicitly integrate stakeholders into each step of the process from vulnerability assessment right through to consideration of alternatives measures can provide a sound basis for assisting destinations with the implementation of appropriate adaptation interventions. This view is supported by Dulal *et al.* (2009), who argue that the most vulnerable groups in the Caribbean - the poor, elderly, indigenous communities and rural children – will be at greater risk of being marginalized, if adaptation is not informed by equitable and participatory frameworks.

Other studies reveal that new paradigms whose adoption can reduce the risk of maladaptation in island environments, are emerging across various sectors. In the area of natural resource management, Hansen *et al.* (2010) suggest that the use of protected areas for climate refugia, reduction of non-climate stressors on ecosystems, adoption of adaptive management approaches combined with reduction of greenhouse gas emissions wherever possible, may prove to be more effective response strategies than traditional conservation approaches. Other strategic approaches, including the implementation of multi-sectoral and cross-sectoral measures, also facilitate adaptation in a more equitable, integrated and sustainable manner. Similarly, ‘*no-regret’* measures such as wastewater recycling, trickle irrigation, conversion to non-fossil fuel based energy and transportation which offer collateral benefits with or without the threat of climate change, and ‘*low-regret’* strategies, which may only increase existing operational costs marginally, are becoming increasingly attractive options to island governments (Gravelle and Mimura, 2008; Heltberg *et al.,* 2009; Howard *et al.*, 2010). Together, these constitute valid risk management approaches, as they are designed to assist communities in making prudent, but necessary decisions in the face of an uncertain future.

Some authors suggest that caution is needed to ensure that donors are not driving the adaptation and mitigation agenda in small islands, as there is a risk that donor-driven adaptation or mitigation may not always address the salient challenges on small islands, and may lead to inadequate adaptation or a waste of scarce resources (Barnett, 2010; Nunn, 2009). Others argue that donor-led initiatives may unintentionally cause enhanced vulnerability by supporting adaptation strategies that are externally derived, rather than optimizing the benefits of local practices that have proven to be efficacious through time (Reenberg *et al.,* 2008; Kelman and West, 2009; Campbell and Beckford, 2009).

29.9. Research and Data Gaps

Several advances have taken place in our understanding of the observed and potential effects of climate change on small islands since the AR4. These cover a range of themes including: dynamic downscaling of scenarios appropriate for small islands; impacts of trans-boundary processes generated well beyond the borders of an individual nation or island; barriers to adaptation in small islands and how they may be overcome; the relationships between climate change adaptation and disaster risk reduction; and, the relationships between climate change adaptation, maladaptation and sustainable development.

It is also evident that much further work is required on these themes in small island situations, especially comparative research. Important information and data gaps and many uncertainties still exist on impacts, vulnerability and adaptation in small islands. These include:

- **Lack of climate change and socio-economic scenarios and data at the required scale for small islands**. Although some advances have been made (ABoM and CSIRO, 2011a, 2011b; Taylor *et al*., 2007), much of the work in the Caribbean, Pacific, Indian Ocean and Mediterranean islands, is focused at the regional scale rather than being country specific. Since most socio-economic decisions are taken at the local level, there is need for a more extensive database of simulations of future small island climates and socio-economic conditions at smaller spatial scales.
- **Difficulties in detecting and attributing past impacts on small islands to climate change processes.** Further investigation of the observed impacts of weather, climate and ocean events that may be related to climate change is required to clarify the relative role of climate change and non-climate change drivers.
- **Uncertainty in the projections is not a sufficiently valid reason to postpone adaptation planning in small islands**. In several small islands adaptation is being progressed without a full understanding of past or potential impacts and vulnerability. Whilst assessment of future impacts is hampered because of uncertainty in climate projections at the local island level, alternative scenarios based on a general understanding of broad trends could be used in vulnerability and sensitivity studies to guide adaptation strategies.
- **Need for a range of climate change-related projections beyond temperature and sea-level.** Generally climate-model projections of temperature and sea-level have been satisfactory, but there are strong requirements for projections for other variables that are of critical importance to small islands. These include rainfall and drought, wind direction and strength, tropical storms and wave climate, and recognition that trans-boundary processes are also significant in a small island context. While some such work has been undertaken for some parts of the Pacific (ABoM and CSIRO, 2011a, 2011b), similar work still needs to be carried out in other small island regions. In addition, the reliability of existing projections for some of the other parameters needs to be improved and the data should be in suitable formats for use in risk assessments.
- **Need to acknowledge the heterogeneity and complexity of small island states and territories.** Although small islands have several characteristics in common, neither the variety nor complexity of small islands is sufficiently reflected in the literature. Thus, transferring data and practices from a continental situation, or from one small island state to another, needs to be done with care and in a manner that takes full cognizance of such heterogeneity and complexity.
- **Within country/territory differences need to be better understood**. Many of the environmental and human impacts reported in the literature on islands have been attributed to the whole country, when in fact they refer only to the major centre or town or region. There is need for more work on rural areas, outer islands and secondary communities. Several examples of such research have been cited in this chapter. Also

it should be noted that some small island states are single islands and others highly fragmented multiple islands.

- **Lack of investment and attention to climate and environmental monitoring frameworks in small islands**. A fundamental gap in the ability to improve empirical understanding of present and future climate change impacts is the lack of climate and environmental monitoring frameworks that in turn hampers the level of confidence with which adaptation responses can be designed and implemented.
- **Economic and social costs of climate change impacts and adaptation options are rarely known**. In small island states and territories the costs of past weather, climate and ocean events is poorly known and further research is required to identify such costs, and to determine the economic and societal costs of climate change impacts and the costs of adaptation options to minimize those impacts.

The foregoing list is a sample of the gaps, needs and research agenda that urgently need to be filled for small islands. While some countries have begun to fill these gaps, this work needs to be replicated and expanded across all island regions to improve the database available for ongoing climate change assessments. Such information would raise the level of confidence in the adaptation planning and implementation process in small islands.

Frequently Asked Questions

FAQ 29.1: Why is it difficult to detect and attribute changes on small islands to climate change?
[to be inserted in Section 29.3.1.1]
In the last two or three decades many small islands have undergone substantial changes in human settlement patterns and in socio-economic and environmental conditions. Those changes may have masked any clear evidence of the effects of climate change. For example, on many small islands coastal erosion has been widespread and has adversely affected important tourist facilities, settlements, utilities and infrastructure. But specific case studies from islands in the Pacific, Indian and Atlantic oceans and the Caribbean have shown that human impacts play an important role in this erosion, as do episodic extreme events that have long been part of the natural cycle of events affecting small islands. So while coastal erosion is consistent with models of sea-level rise resulting from climate change, determining just how much of this erosion might have been caused by climate change impacts is difficult. Given the range of natural processes and human activities that could impact the coasts of small islands in the future, without more and better empirical monitoring the role of climate change-related processes on small islands may continue to be difficult to identify and quantify.

FAQ 29.2: Why is the cost of adaptation to climate change so high in small islands?
[to be inserted after Section 29.3.3.4]
Adaptation to climate change that involves infrastructural works generally require large up-front overhead costs, which in the case of small islands cannot be easily downscaled in proportion to the size of the population or territory. This is a major socio-economic reality that confronts many small islands, notwithstanding the benefits that could accrue to island communities through adaptation. Referred to as ‘indivisibility’ in economics, the problem can be illustrated by the cost of shore protection works aimed at reducing the impact of sea-level rise. The unit cost of shoreline protection per capita in small islands is substantially higher than the unit cost for a similar structure in a larger territory with a larger population. This scale-reality applies throughout much of a small island economy including the indivisibility of public utilities, services and all forms of development. Moreover, the relative impact of an extreme event such as a tropical cyclone that can affect most of a small island’s territory has a disproportionate impact on that state’s GDP, compared to a larger country where an individual event generally affects a small proportion of its total territory and its GDP. The result is relatively higher adaptation and disaster risk reduction costs per capita in countries with small populations and areas, especially those that are also geographically isolated, have a poor resource base and high transport costs

FAQ 29.3: Is it appropriate to transfer adaptation and mitigation strategies between and within small island countries and regions? *[to be inserted after Section 29.7.2]*
While lessons learned from adaptation and mitigation experiences in one island or island region may offer some guidance, caution must be exercised to ensure that the transfer of such experiences is appropriate to local biophysical, social, economic, political, and cultural circumstances. If this approach is not purposefully incorporated

into the implementation process, it is possible that maladaptation and inappropriate mitigation may result. It is therefore necessary to carefully assess the risk profile of each individual island so as to ensure that any investments in adaptation and mitigation are context specific. The varying risk profiles between individual small islands and small island regions have not always been adequately acknowledged in the past.

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Table 29-1: Climate change projections for the medium (500-700 ppm CO2-e) RCP4.5 scenario for the main Small Islands regions. The table shows the 25th, 50th (median) and 75th percentiles for surface temperature and precipitation based on averages from 42 CMIP5 global models (adapted from WGI AR5 Table 14.1). Mean net regional sea level change is evaluated from 21 CMIP5 models and includes regional non-scenario components (adapted from WGI AR5 Figure 13-20).

Small Island Region	RCP4.5 Annual Projected Change for 2081-2100 compared to 1986-2005						
	Temperature (^{O}C)			Precipitation (%)			Sea Level (m)
	25%	50%	75%	25%	50%	75%	Range
Caribbean	1.2	1.4	1.9	-10	-5	-1	0.5 – 0.6
Mediterranean	2.0	2.3	2.7	-10	-6	-3	0.4 - 0.5
Northern tropical Pacific	1.2	1.4	1.7	0	1	4	0.5 – 0.6
Southern tropical Pacific	1.1	1.2	1.5	0	2	4	0.5 – 0.6
North Indian Ocean	1.3	1.5	2.0	5	9	20	0.4 – 0.5
West Indian Ocean	1.2	1.4	1.8	0	2	5	0.5 – 0.6

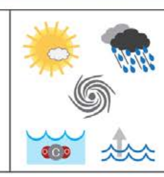
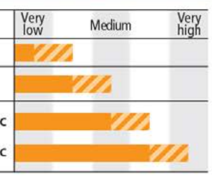
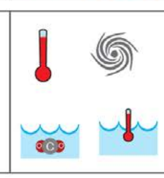
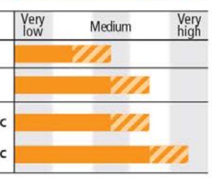
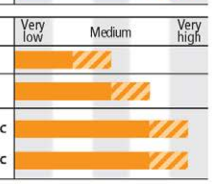
Table 29-2: Summary of projected percentage changes in tropical Pacific tuna catches by 2036 and 2100 relative to 1980-2000 and the estimated resulting percentage change to government revenue (after Bell *et al.*, 2011).

Tuna Fishery		**Year and SRES Scenario**		
		2035	**2100**	
		B1/A2	**B1**	**A2**
Skipjack tuna	**Western fishery**	+ 11%	-0.2%	-21%
	Eastern fishery	+37%	+43%	+27%
Bigeye tuna	**Western fishery**	-2%	-12%	-24%
	Eastern fishery	+3%	-4%	-18%
Skipjack tuna	**Total**	+19%	+12%	-7%
Bigeye tuna	**Total**	+0.3%	-9%	-27%
Total Change to Government Revenue (%)	**Federated States of Micronesia**	0.8 to 1.7%	-0.9 to -1.9%	
	Solomon Islands	0.01 to 0.16%	-0.03 to 0.77%	
	Kiribati	+11 to 18.4%	+7.2 to 12.0%	
	Tuvalu	+3.7 to 9.2%	+2.5 to 6.2%	

Table 29-3: Type of island in the Pacific region and implications for hydro-meteorological hazards (after Campbell, 2009).

Island type and size	**Island elevation, slope, rainfall**	**Implications for hazard**
Continental - Large - High biodiversity - Well developed soils	- High elevations - River flood plains - Orographic rainfall	River flooding more likely to be a problem than in other island types. In Papua New Guinea high elevations expose areas to frost (extreme during El Nino).
Volcanic High Islands - Relatively small land area - Barrier reefs - Different stages of erosion	- Steep slopes - Less well developed river systems - Orographic rainfall	Because of size few areas are not exposed to tropical cyclones. Streams and rivers subject to flash flooding. Barrier reefs may ameliorate storm surge.
Atolls - Very small land area - Small islets surround a lagoon - Larger islets on windward side - Shore platform on windward side - No or minimal soil	- Very low elevations - Convectional rainfall - No surface (fresh) water - Ghyben-Herzberg (freshwater) lens	Exposed to storm surge, 'king' tides and high waves. Narrow resource base. Exposed to fresh water shortages and drought. Water problems may lead to health hazards.
Raised Limestone Islands - Concave inner basin - Narrow coastal plains - No or minimal soil	- Steep outer slopes - Sharp karst topography - No surface water	Depending on height may be exposed to storm surge. Exposed to fresh water shortages and drought. Water problems may lead to health hazards.

Table 29-4: Selected key risks and potential for adaptation for small islands from the present-day to the long-term.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Loss of livelihoods, coastal settlements and infrastructure in small islands (*high confidence*)	Significant potential exists for adaptation in islands but will require additional external resources and technologies. It is unlikely that traditional community coping strategies will be effective in the future.		Figure 29-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	
Decline and possible loss of coral reef ecosystems in small islands through thermal stress (*high confidence*)	Limited coral reef adaptation responses, however, minimising the negative impact of anthrogopenic stresses (ie: water quality change, destructive fishing practices) may increase resilience.		29.3.1.2	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	
The interaction of rising global mean sea levels in the 21st century with high water level events will threaten low-lying coastal areas in small islands (*high confidence*)	High ratio of coastal area to land mass will make adaptation a significant financial and resource challenge for islands. Adaptation strategies could include: maintenance and restoration of coastal landforms and ecosystems, improved management of soils and freshwater resources, appropriate building codes and settlement patterns.		29.4.3, Table 29-1, WGI 13.5.1, Table 13.5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	

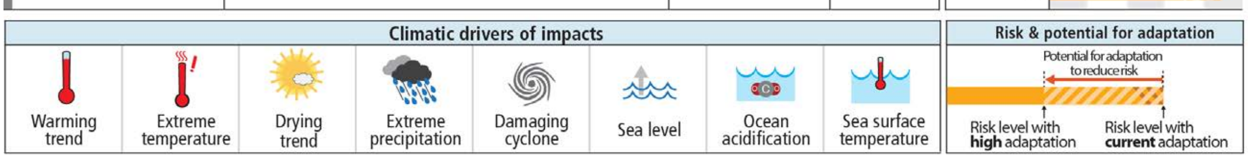


Table 29-5: Top ten countries in the Asia-Pacific region based on absolute and relative physical exposure to storms and impact on GDP (between 1998 and 2009) (after ESCAP and UNISDR, 2010).

Rank	Absolute exposure (millions affected)	Relative exposure (% of the population affected)	Absolute GDP loss ($billions)	Loss (as a % of GDP)
1	Japan (30.9)	**North Mariana Islands (58.2)**	Japan (1,226.7)	**North Mariana Islands (59.4)**
2	Philippines (12.1)	**Niue (25.4)**	Rep. of Korea (35.6)	**Vanuatu (27.1)**
3	China (11.1)	Japan (24.2)	China (28.5)	**Niue (24.9)**
4	India (10.7)	Philippines (23.6)	Philippines (24.3)	**Fiji (24.1)**
5	Bangladesh (7.5)	**Fiji (23.1)**	Hong Kong (13.3)	Japan (23.9)
6	Rep. of Korea (2.4)	**Samoa (21.4)**	India (8.0)	Philippines (23.9)
7	Myanmar (1.2)	**New Caledonia (20.7)**	Bangladesh (3.9)	**New Caledonia (22.4)**
8	Viet Nam (0.8)	**Vanuatu (18.3)**	**North Mariana Islands (1.5)**	**Samoa (19.2)**
9	Hong Kong (0.4)	**Tonga (18.1)**	Australia (0.8)	**Tonga (17.4)**
10	Pakistan (0.3)	**Cook Islands (10.5)**	**New Caledonia (0.7)**	Bangladesh (5.9)

Note: Small islands are highlighted in **bold**

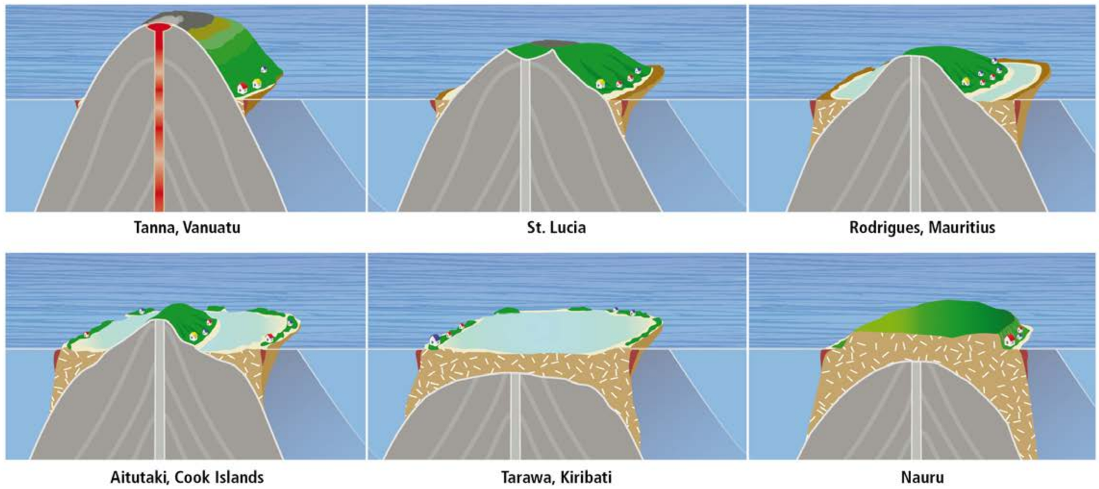


Figure 29-1: Representative tropical island typologies. From top-left: a young, active volcanic island (with altitudinal zones) and limited living perimeter reefs (purple zone at outer reef edge), through to an atoll (centre bottom) and raised limestone island (bottom right) dominated by ancient reef deposits (brown + white fleck). Atolls have limited, low-lying land areas but well developed reef/lagoon systems. Islands composed of 'continental rocks' are not included in this figure, but see Table 29-3]

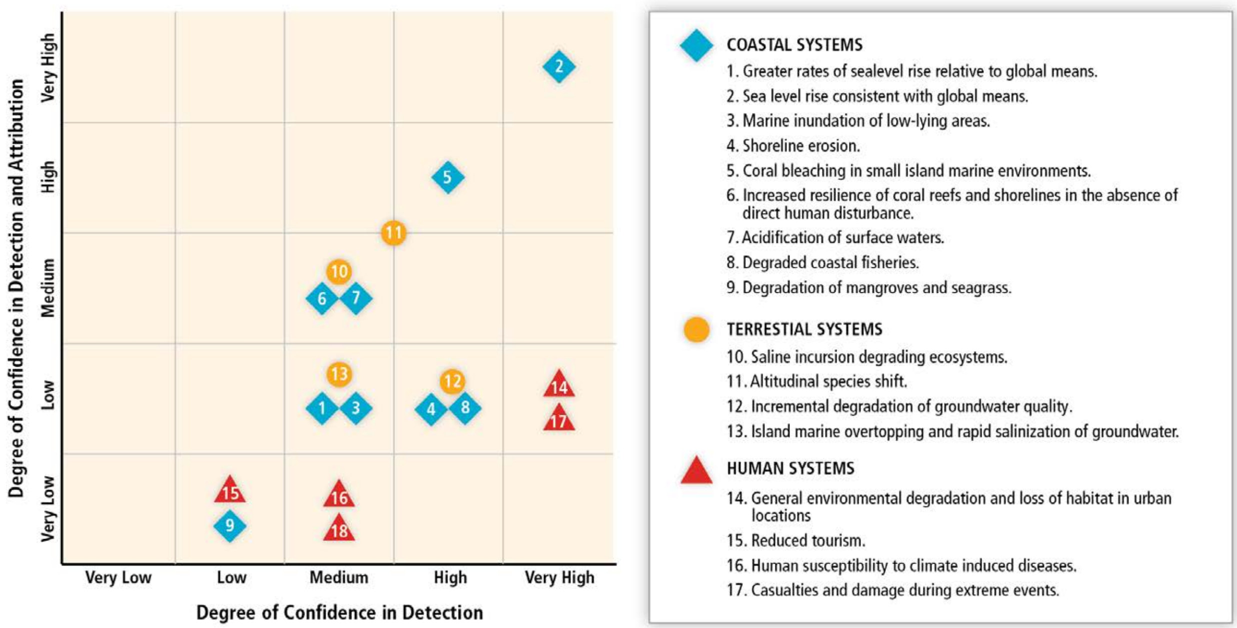


Figure 29-2: A comparison of the degree of confidence in the detection of observed impacts of climate change on tropical small islands with the degree of confidence in attribution to climate change drivers at this time. For example, the blue symbol No. 2 (Coastal Systems), indicates there is *very high confidence* in both the detection of 'sea-level rise consistent with global means' and its attribution to climate change drivers; whereas the red symbol No. 17 (Human Systems) indicates whilst detection of 'casualties and damage during extreme events' is *very high*, there is presently *low confidence* in the attribution to climate change. It is important to note that *low confidence* in attribution frequently arises due to the limited research available on small island environments.

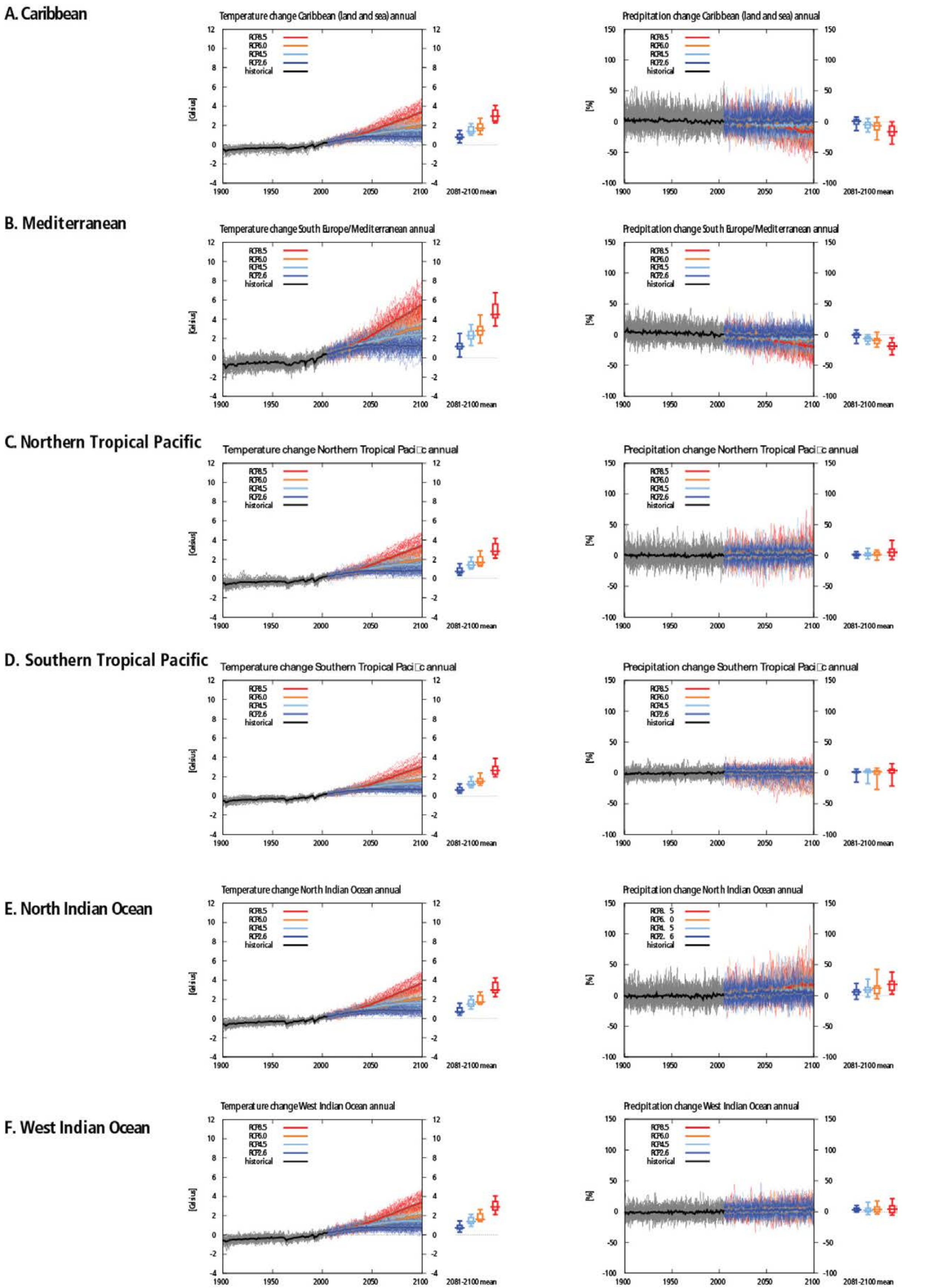

A. Caribbean
Temperature change Caribbean (land and sea) annual
Precipitation change Caribbean (land and sea) annual
B. Mediterranean
Temperature change South Europe/Mediterranean annual
Precipitation change South Europe/Mediterranean annual
C. Northern Tropical Pacific
Temperature change Northern Tropical Paci□c annual
Precipitation change Northern Tropical Paci□c annual
D. Southern Tropical Pacific
Temperature change Southern Tropical Paci□c annual
Precipitation change Southern Tropical Paci□c annual
E. North Indian Ocean
Temperature change North Indian Ocean annual
Precipitation change North Indian Ocean annual
F. West Indian Ocean
Temperature change West Indian Ocean annual
Precipitation change West Indian Ocean annual
RCP8.5
RCP6.0
RCP4.5
RCP2.6
historical
[Celsius]
[%]
2081-2100 mean

Figure 29-3: Time series of RCP scenarios annual projected temperature and precipitation change relative to 1986-2005 for six small islands regions (using regions defined in AR5 WG1, Annex 1: Atlas of Global and Regional Climate Projections).] Thin lines denote one ensemble member per model, thick lines the CMIP5 multi-model mean. On the right-hand side the 5th, 25th, 50th (median), 75th and 95th percentiles of the distribution of 20-yr mean changes are given for 2081–2100 in the four RCP scenarios. Note that the model ensemble averages in the figure are for grid points over wide areas and encompass many different climate change signals. To get projections for a specific location and time period use the maps in the Atlas or the online interactive version at but please note that in regions with small islands the models basically simulate the climate of the surrounding ocean and local conditions on land may differ. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

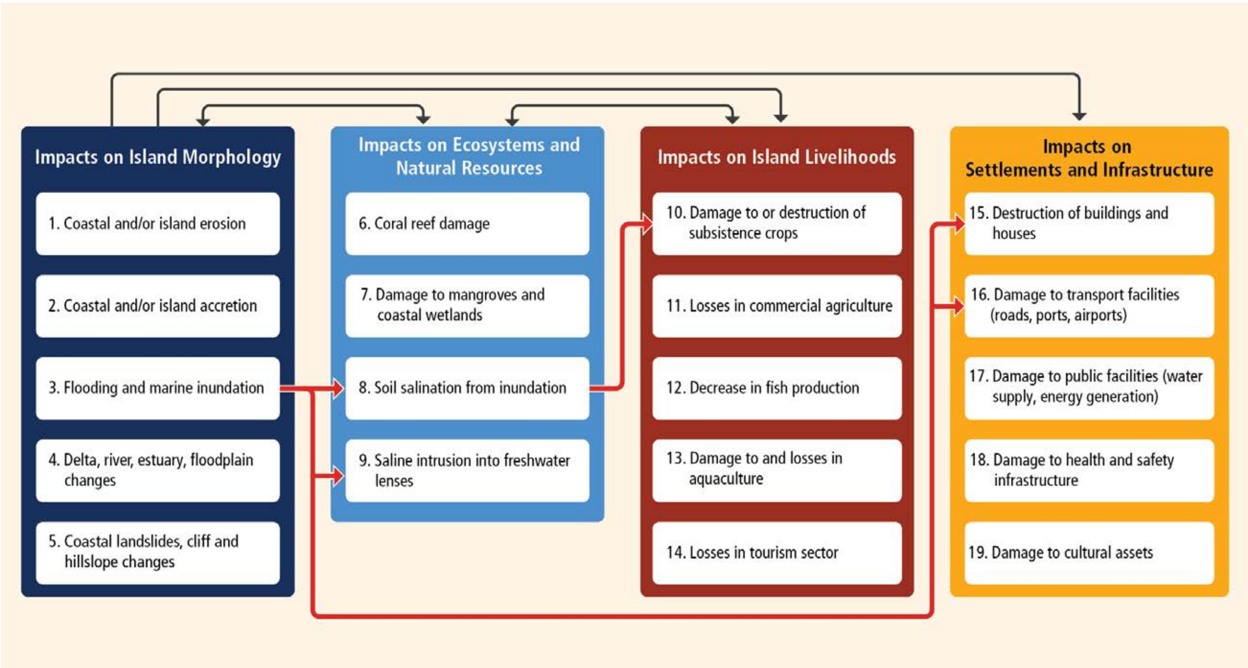


Figure 29-4: Tropical and extra-tropical cyclone impacts on the coasts of small islands. Four types of impacts are distinguished here, black arrows showing the connections between them, based on the existing literature. An example of the chain of impacts associated with two extra-tropical cyclones centred to the east of Japan is illustrated by the red arrows. Swell waves generated by these events in December 2008 reached islands in the southwest Pacific and caused extensive flooding (3) that impacted soil quality (8), freshwater resources (9), and damaged crops (10), buildings (15), and transport facilities (16) in the region (Example based on Hoeke *et al.*, 2013).

Examples of tropical cyclone impacts on small island coasts with reference

1. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 2. Taveuni, Fiji, March 2010 (Etienne and Terry, 2012); 3. Cook Islands (de Scally, 2008); Society and Autral Islands, French Polynesia, February 2010 (Etienne, 2012); 4. Viti Levu, Fiji, March 1997 (Terry *et al.*, 2002); 5. Society Islands, French Polynesia, February 2010 (Etienne, 2012); 6. Curacao, Bonaire, Netherlands Antilles, November 1999 (Scheffers and Scheffers, 2006); Hawaiian Islands (Fletcher *et al.*, 2008); 7. Bay Islands, Honduras, October 1998 (Cahoon *et al.*, 2003); 8. Marshall Islands, June 1905 (Spennemann, 1996); 9. Pukapuka atoll, Cook Islands, February 2005 (Terry and Falkland, 2010); 10. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 11. 12. 13. Tuamotu Islands, French Polynesia, 1982-83 (Dupon, 1987); 14. Grenada, September 2004 (OECS, 2004); 15. Grenada, September 2004 (OECS, 2004); Tubuai, Austral Islands, French Polynesia, February 2010 (Etienne, 2012); 16. Vanuatu, February 2004 (Richmond and Sovacool, 2012); Guadeloupe Island, October 2008 (Dorville and Zahibo, 2010); 17. Bora Bora, Raiatea, Maupiti, Tahaa, Huahine, Society Islands, February 2010 (Etienne, 2012); 18. Vanuatu, February 2004 (Richmond and Sovacool, 2012); 19. Tuamotu, French Polynesia, 1982-83 (Dupon, 1987).

Examples of extra-tropical cyclone impacts on small island coasts with reference

1. Maldives, April 1987 (Harangozo, 1992); 2. Maldives, January 1955 (Maniku, 1990); 3. Maldives, April 1987 (Harangozo, 1992); 9. Solomon Islands, December 2008 (Hoeke *et al*., 2013); 10. Chuck, Pohnpei, Kosrae, Federated States of Micronesia, December 2008 (Hoeke *et al*., 2013); 15. Majuro, Marshall Islands, November 1979 (Hoeke *et al*., 2013); 16. Coral Coast, Viti Levu, Fiji, May 2011 (Hoeke *et al*., 2013); 17. Majuro, Kwajalein, Arno, Marshall Islands, December 2008 (Hoeke *et al*., 2013); 18. Bismark Archipelago, Papua New Guinea, December 2008 (Hoeke *et al*., 2013).

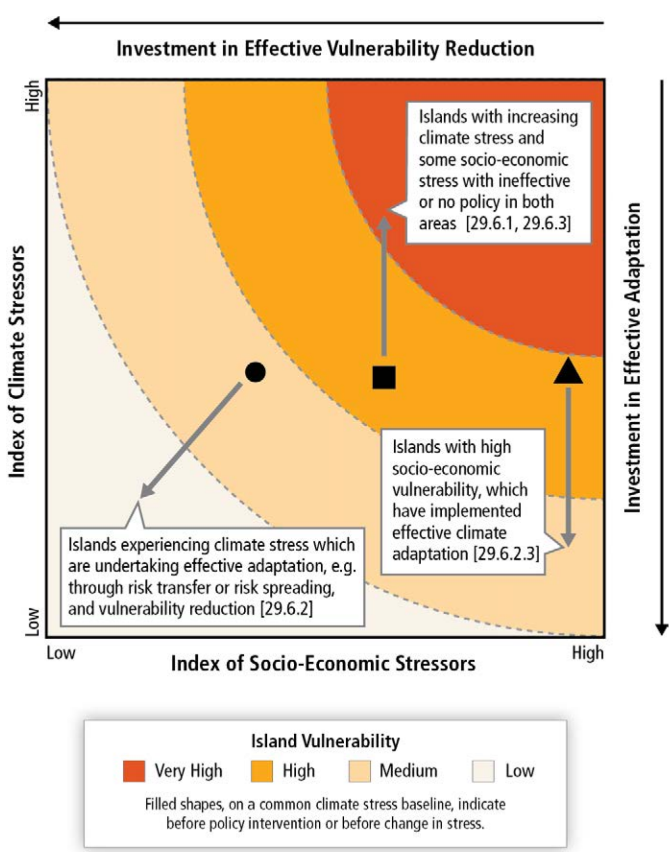


Figure 29-5. The impact of alternative climate change adaptation actions or policies.

Chapter 30. The Ocean

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Contents

Executive Summary

The Ocean plays a central role in Earth's climate and has absorbed 93% of the extra energy from the enhanced greenhouse effect and approximately 30% of anthropogenic CO_2 from the atmosphere. Regional responses are addressed here by dividing the Ocean into seven sub-regions: High Latitude Spring Bloom Systems (HLSBS), Eastern Boundary Upwelling Ecosystems (EBUE), Coastal Boundary Systems (CBS), Equatorial Upwelling Systems (EUS), Sub-Tropical Gyres (STG), Semi-Enclosed Seas (SES), and the Deep Sea (DS; >1000 m). The eighth region, Polar Seas, is dealt with by Chapter 28 [Figure 30-1; WGI 3.2.5, Box 3.1, 3.8].

Global average sea surface temperatures have increased since both the beginning of the 20th Century and the 1950s (*virtually certain*). The average sea surface temperature (SST) of the Indian, Atlantic and Pacific Oceans has increased by 0.65, 0.41 and 0.31°C respectively over the period 1950–2009 (*very likely*, p-value$\leq$0.05). Changes in the surface temperatures of the ocean basins are consistent with temperature trends simulated by ocean-atmosphere models with anthropogenic greenhouse gas forcing over the past century (*high confidence*). Sub-regions within the Ocean also show *robust evidence* of change, with the influence of long-term patterns of variability (e.g., Pacific Decadal Oscillation, PDO; Atlantic Multi-decadal Oscillation, AMO) contributing to variability at regional scales, and making changes due to climate change harder to distinguish and attribute [30.3.1, Figure 30-2e–g, Table 30-1; WGI 2.4.2-3, 3.2–3.8, 10.3.4, 14].

Uptake of CO_2 has decreased ocean pH (approximately 0.1 unit over 100 years), fundamentally changing ocean carbonate chemistry in all ocean sub-regions, particularly at high latitudes (*high confidence*). The current rate of ocean acidification is unprecedented within the last 65 Ma (*high confidence*) if not the last 300 Ma (*medium confidence*). Warming temperatures, declining pH and carbonate ion concentrations represent risks to the productivity of fisheries and aquaculture, and the security of regional livelihoods given the direct and indirect effects of these variables on physiological processes (e.g., skeleton formation, gas exchange, reproduction, growth, and neural function) and ecosystem processes (e.g., primary productivity, reef building, and erosion) (*high confidence*) [6.2, 6.3, 30.3.1, 30.3.2; 6.1.2; WGI 3.8.2, Box 3.2, 5.3.1].

Regional changes observed in winds, surface salinity, stratification, ocean currents, nutrient availability, and oxygen depth profile in many regions may be a result of anthropogenic greenhouse gas emissions (*low* to *medium confidences*). Marine organisms and ecosystems are *likely* to change in response to these regional changes, although evidence is limited and responses uncertain [30.3, 30.5; 6.2, 6.3; WGI 2.5, 2.7 3.3–3.8, 10.4.2, 10.4.4].

Most, if not all, of the Ocean will continue to warm and acidify, although the rates will vary regionally (*high confidence*). Differences between Representative Concentration Pathways (RCPs) are *very likely* to be minimal until 2040 (*high confidence*). Projected temperatures of the surface layers of the Ocean, however, diverge as the 21st Century unfolds and will be 1–3°C higher by 2100 under RCP8.5 than RCP2.6 across most ocean sub-regions. The projected changes in ocean temperature pose serious risks and vulnerabilities to ocean ecosystems and dependent human communities (*robust evidence*, *high agreement*, *high confidence*) [6.5, 30.3.1, 30.3.2, 30.7.1 Figure 30-2e–g, Table 30-3].

Rapid changes in physical and chemical conditions within ocean sub-regions have already affected the distribution and abundance of marine organisms and ecosystems. Responses of species and ecosystems to climate change have been observed from every ocean sub-region (*high confidence*). Marine organisms are moving to higher latitudes consistent with warming trends (*high confidence*), with fish and zooplankton migrating at the fastest rates, particularly in HLSBS regions. Changes to sea temperature have also altered the phenology or timing of key life-history events such as plankton blooms, and migratory patterns and spawning in fish and invertebrates over recent decades (*medium confidence*). There is *medium* to *high agreement* that these changes pose significant uncertainties and risks to fisheries, aquaculture and other coastal activities. Ocean acidification maybe driving similar changes (*low confidence*), although there is *limited evidence* and *low agreement* at present. The associated risks will intensify as ocean warming and acidification continue [Box CC-MB, 30.4, 30.5, 6.3, 6.4].

Regional risks and vulnerabilities to ocean warming and acidification can be compounded by non-climate related stressors such as pollution, nutrient runoff from land, and over-exploitation of marine resources, as well as natural climate variability (*high confidence*). These influences confound the detection and attribution of the impacts of climate change and ocean acidification on ecosystems yet may also represent opportunities for reducing risks through management strategies aimed at reducing their influence, especially in CBS, SES, and HLSBS [30.1.2, 30.5, 5.3.4, 18.3.3–4].

Recent changes to wind and ocean mixing within the highly productive HLSBS, EBUE, and EUS are *likely* to influence energy transfer to higher trophic levels and microbial processes. There is, however, *limited evidence* and *low agreement* on the direction and magnitude of these changes and their relationship to ocean warming and acidification (*low confidence*). In cases where NPP increases or is not consumed (e.g., Benguela EBUE, *low confidence*), the increased transfer of organic carbon to deep regions can stimulate microbial respiration and reduce O_2 levels (*medium confidence*). Oxygen concentrations are also declining in the tropical Pacific, Atlantic, and Indian Oceans (particularly EUS) due to reduced O_2 solubility at higher temperatures, and changes in ocean ventilation and circulation [Box CC-PP, 30.3.1, 30.3.2, 30.5.5–6, 6.3.3; WGI 3.8.3].

Global warming will result in more frequent extreme events and greater associated risks to ocean ecosystems (*high confidence*). In some cases (e.g., mass coral bleaching and mortality), projected increases will eliminate ecosystems, and increase risks and vulnerabilities to coastal livelihoods and food security (e.g., CBS in SE Asia; SES, CBS, and STG in the Indo-Pacific) (*medium* to *high confidence*). Reducing stressors not related to climate change represents an opportunity to strengthen the ecological resilience within these regions, which may help them survive some projected changes in ocean temperature and chemistry [5.4, 30.6.1, 30.5.3–4, 30.5.6, Figure 30-4, Box CC-CR, IPCC 2012].

The highly productive HLSBS in the North-eastern Atlantic has changed in response to warming oceans (*medium evidence*, *high agreement*), with a range of consequences for fisheries. These ecosystems are responding to recent warming, with the greatest changes being observed since the late 1970s in the phenology, distribution and abundance of plankton assemblages, and the reorganization of fish assemblages (*high confidence*). There is *medium confidence* that these changes will have both positive and negative implications depending on the particular HLSBS fishery and the time frame [Box CC-MB, Box 6-1, 6.4.1.2, 30.5.1, 30.6.2.1].

EUS, which support highly productive fisheries off equatorial Africa and South America, have warmed over the past 60 years (Pacific EUS: 0.43^{o}C, Atlantic EUS: 0.54^{o}C; *very likely*, p-value$\leq$0.05). While warming is consistent with changes in upwelling intensity, there is *low confidence* in our understanding of how EUS will change, especially in how El Niño-Southern Oscillation (ENSO) and other patterns of variability will interact in a warmer world. The risk, however, of changes to upwelling increases with average global temperature, posing significant uncertainties for dependent ecosystems, communities, and fisheries [30.5.2; WGI 14.4,].

The surface waters of the SES show significant warming from 1982 and most CBS show significant warming since 1950. Warming of the Mediterranean has led to the recent spread of tropical species invading from the Atlantic and Indian Oceans. Projected warming increases the risk of greater thermal stratification in some regions, which can lead to reduced O_2 ventilation and the formation of hypoxic zones, especially in the Baltic and Black Seas (*medium confidence*). In some CBS, such as the East China Sea and Gulf of Mexico, these changes are further influenced by the contribution of nutrients from coastal pollution contributing to the expansion of hypoxic (low O_2) zones. These changes are *likely* to influence regional ecosystems as well as dependent industries such as fisheries and tourism, although there is *low confidence* in the understanding of potential changes and impacts [Table 30-1, 30.5.3, 5.3.4.3].

Coral reefs within CBS, SES, and STG are rapidly declining as result of local (i.e., coastal pollution, overexploitation), and climate change (*high confidence*). Elevated sea temperatures drive impacts such as mass coral bleaching and mortality (*very high confidence*), with an analysis of the CMIP5 ensemble projecting the loss of coral reefs from most sites globally by 2050 under mid to high rates of ocean warming (*very likely*) [Figure 30-10, 30.5.3–4, 30.5.6, Box CC-CR].

The productive EBUE and EUS involve upwelling waters that are naturally high in CO_2 concentrations and low in pH, and hence are potentially vulnerable to ocean warming and acidification (*medium confidence*). There is *limited evidence* and *low agreement*, as to how upwelling systems are *likely* to change (*low confidence*). Declining O_2 and shoaling of the aragonite saturation horizon through ocean acidification increases the risk of upwelling water being low in pH and O_2 with impacts on coastal ecosystems and fisheries, as has been seen already (e.g., California Current EBUE). These risks and uncertainties are *likely* to involve significant challenges for fisheries and livelihoods along the west coasts of South America, Africa, and North America (*low* to *medium confidence*) [30.3.2.2, 30.5.2, 30.5.5, Box CC-UP, Box CC-PP].

Chlorophyll concentrations measured by satellites have decreased in the STG of the North Pacific, Indian and North Atlantic Oceans by 9%, 12% and 11%, respectively, over and above the inherent seasonal and interannual variability from 1998–2010 (*high confidence*; p-value$\leq$0.05). Significant warming over this period has resulted in increased water column stratification, reduced mixed layer depth and possibly declines in nutrient availability and ecosystem productivity (*limited evidence*, *medium agreement*). The short timeframe of these studies against well-established patterns of long-term variability lead to the conclusion that these changes are *about as likely as not* due to climate change [30.5.6, Table 30-1, Box CC-UP, 6.3.4].

The world's most abundant yet difficult to access habitat, the DS, is changing (*limited evidence*, *medium agreement*), with warming between 700–2000 m from 1957–2010 *likely* to involve a significant anthropogenic signal (*medium confidence*). Decreased primary productivity of surface waters (e.g., STG) is *likely* to reduce the availability of organic carbon to DS ecosystems. Understanding of the risks of climate change and ocean acidification to the DS is important given the size of the DS region but is limited (*low confidence*) [30.5.7, Figure 30-2; WGI 3.2.4, Figure 3.2, 3.9].

Changes to surface wind and waves, sea level, and storm intensity will increase the vulnerability of ocean-based industries such as shipping, energy and mineral extraction (*medium confidence*). Risks to equipment and people may be reduced through the design and use of ocean-based infrastructure, together with the evolution of policy (*medium agreement*). Risks and uncertainties will increase with further climate change. New opportunities as well as risks for shipping, energy and mineral extraction, and international issues over access and vulnerability, may accompany warming waters, particularly at high latitudes [30.3.1, 30.6.2, 28.2.2, 28.2.5, 28.3.4, 10.2.2, 10.4.4, IPCC 2012].

Changes to ocean temperature, chemistry and other factors are generating new challenges for fisheries, as well as benefits (*high agreement*). Climate change is a risk to the sustainability of capture fisheries and aquaculture development, adding to the threats of over-fishing and other non-climate stressors. In EUS and STG, shifts in the distribution and abundance of large pelagic fish stocks will have the potential to create 'winners' and 'losers' among island nations and economies. There has been a boost in fish stocks of high latitude fisheries in the HLSBS of the North Pacific and North Atlantic, partly as a result of 30 years of increase in temperature. This is *very likely* to continue, although some fish stocks will eventually decline. A number of practical adaptation options and supporting international policies can minimize the risks and maximize the opportunities [30.6, 30.7, 7.4.2, 29.4].

Adaptation strategies for ocean regions beyond coastal waters are generally poorly developed but will benefit from international legislation and expert networks, as well as marine spatial planning (*high agreement*). Fisheries and aquaculture industries with high-technology and/or large investments, as well as marine shipping and oil and gas industries, have high capacities for adaptation due to greater development of environmental monitoring, modeling and resource assessments. For smaller-scale fisheries and developing nations, building social resilience, alternative livelihoods, and occupational flexibility represent important strategies for reducing the vulnerability of ocean-dependent human communities. Building strategies that include climate forecasting and early-warning systems can reduce impacts of warming and ocean acidification in the short term. Overall, there is a strong need to develop ecosystem-based monitoring and adaptation strategies to mitigate rapidly growing risks and uncertainties to the coastal and oceanic industries, communities and nations (*high agreement*) [30.6, 7.3.2.4].

Significant opportunity exists within the Ocean and its sub-regions for reducing the CO_2 flux to the atmosphere (*limited evidence, medium agreement*). Ecosystems such as mangroves, seagrass and salt marsh offer important carbon storage and sequestration opportunities (e.g., Blue Carbon*; limited evidence*, *medium agreement*). Blue Carbon strategies can also be justified in terms of the ecosystem services provide by coastal vegetated habitats such as protection against coastal erosion and storm damage, and maintenance of habitats for fisheries species. Sequestration of anthropogenic CO_2 into deep ocean areas still faces considerable hurdles with respect to the expense, legality and vulnerability of storage sites and infrastructure. There are also significant opportunities with the Ocean for the development of offshore renewable energy such as wind and tidal power [30.6.1, 30.6.4].

International frameworks for collaboration and decision-making are critically important for coordinating policy that will enable mitigation and adaptation by the Ocean sectors to global climate change (e.g., United Nations Convention on the Law of the Sea, UNCLOS). These international frameworks offer an opportunity to solve problems collectively, including improving fisheries management across national borders (e.g., reducing illegal, unreported and unregulated fishing, IUU), responding to extreme events, and strengthening international food security. Given the importance of the Ocean to all countries, there is a need for the international community to progress rapidly to a 'whole of ocean' strategy for responding to the risks and challenges posed by anthropogenic ocean warming and acidification [30.7.2].

30.1. Introduction

The Ocean exerts a profound influence as part of the Earth, interacting with its atmosphere, cryosphere, land, and biosphere to produce planetary conditions. It also directly influences human welfare through the provision and transport of food and resources, as well as by providing cultural and economic benefits, and indirectly through the regulation of atmospheric gas content and the distribution of heat and water across the planet. Chapter 30 examines the extent to which regional changes to the Ocean can be accurately detected and attributed to anthropogenic climate change and ocean acidification, building on the conclusions of Chapter 6, which focuses on the marine physiological and ecological responses to climate change and ocean acidification. Detailed assessment of the role of recent physical and chemical changes within the Ocean to anthropogenic climate change is provided in WGI (particularly Chapters 2, 3, 13, and 14). In Chapter 30, impacts, risks, and vulnerabilities associated with climate change and ocean acidification are assessed for seven ocean sub-regions, and the expected consequences and adaptation options for key ocean-based sectors are discussed. Polar oceans (defined by the presence of sea ice in the north and by the Polar Front in the south) are considered in Chapter 28.

While climate change affects coastal and low-lying sub-regions of multiple nations, detailed discussion of potential risks and consequences for these regions occurs in the relevant chapters of this report (e.g., WGII Chapters 5 and 29 as well as other regional sections).

30.1.1. Major Sub-Regions within the Ocean

The Ocean represents a vast region that stretches from the high tide mark to the deepest oceanic trench (11,030 m) and occupies 71% of the earth's surface. The total volume of the Ocean is approximately 1.3 billion km^3, with approximately 72% of this volume being below 1000 m (Deep Sea (DS), 30.5.7). There are considerable challenges in assessing the regional impacts of climate change on the Ocean. Devising an appropriate structure in order to explore the influence of climate change across the entire Ocean region and the broad diversity of life forms and habitats is challenging. [*Longhurst*, 1998] identified over 50 distinct ecological provinces in the Ocean, defined by physical characteristics and the structure and function of phytoplankton communities. Longhurst's scheme, however, yields far more sub-regions than could be sensibly discussed in the space allocated within AR5. Consequently, we have used comparable principles but have divided the non-polar ocean into seven larger sub-regions similar to *Barber* [1988]. We recognize that these sub-regions do not always match physical-chemical patterns or specific geographies, and that they interact strongly with terrestrial regions through weather systems and the exchange of materials. Different ocean sub-regions may also have substantially different primary productivities and fishery catch. Notably, over 80% of fishery catch is associated with three ocean sub-regions: Northern Hemisphere High Latitude Spring Bloom Systems (HLSBS), Coastal Boundary Systems (CBS), and Eastern Boundary Upwelling Ecosystems

(EBUE; Table SM30-1, Figure 30-1). The DS (>1000m) is included as a separate category that overlaps with the six other ocean sub-regions dealt with in Chapter 30.

[INSERT FIGURE 30-1 HERE
Figure 30-1: (a) Separation of the world's non-polar oceans into seven major sub-regions (excluding the polar oceans, which are considered in Chapter 28). The chlorophyll-*a* signal measured by SeaWiFS and averaged over the period from Sep 4, 1997 to 30 Nov 2010 (NASA) is provides a proxy for differences in marine productivity (with the caveats provided in Box CC-PP). Ecosystem structure and functioning, as well as key oceanographic features provided the basis for separating the Ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea (DS) habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). Numbers refer to: 1 = High Latitude Spring Bloom Systems (HLSBS); 2 = Equatorial Upwelling Systems (EUS); 3 = Semi-Enclosed Seas (SES); 4 = Coastal Boundary Systems (CBS); 5 = Eastern Boundary Upwelling Ecosystems (EBUE); 6 = Sub-Tropical Gyres (STG); and 7 = DS (>1000 m). (b) Relationship between fish catch and area for each ocean sub-region is shown in (a). Red columns: average fish catch (as millions tons yr^{-1}) for the period 1970–2006. Blue columns: area (millions km^2). The four left-hand columns (sub-regions HLSBS-North, CBS, EBUE, and SES) cover 20 % of the world oceans' area and deliver 80% of the world's fish catches. The values for the percent area of the Ocean, primary productivity, and fishery catch for the major sub-regions are listed in Table SM30-1.].

30.1.2. Detection and Attribution of Climate Change and Ocean Acidification in Ocean Sub-Regions

The central goal of Chapter 30 is to assess the recent literature on the Ocean as a region for changes that can be attributed to climate change and/or ocean acidification. Detailed assessments of recent physical and chemical changes in the Ocean are outlined in WGI Chapters 2, 3, 6, 10, 13, and 14 (AR5). The detection and attribution of climate change and ocean acidification on marine organisms and ecosystems is addressed in Chapter 6. Chapter 30 draws on these chapters to investigate regional changes in the physical, chemical, ecological, and socio-economic aspects of the Ocean and the extent to which they can be attributed to climate change and ocean acidification.

Generally, successful attribution to climate change occurs when the full range of possible forcing factors is considered and those related to climate change are found to be the most probable explanation for the detected change in question [18.2.1.1]. Comparing detected changes with the expectations of well-established scientific evidence also plays a central role in the successful attribution of detected changes. We attempt to do this for seven sub-regions of the Ocean. There are a number of general limitations to the detection and attribution of impacts to climate change and ocean acidification that are discussed elsewhere [18.2.1] along with challenges [18.2.2]. Different approaches and 'best practice' guidelines are discussed in WGI Chapters 10 and 18 as well as in several other places [*Hegerl et al.*, 2007; *Hegerl et al.*, 2010; *Stott et al.*, 2010]. The fragmentary nature of ocean observing, structural uncertainty in model simulations, the influence of long-term variability, and confounding factors unrelated to climate change (e.g., pollution, introduced species, overexploitation of fisheries) represent major challenges [*Halpern et al.*, 2008; *Hoegh-Guldberg et al.*, 2011b; *Parmesan et al.*, 2011]. Different factors may also interact synergistically or antagonistically with each other and climate change, further challenging the process of detection and attribution [*Hegerl et al.*, 2007; *Hegerl et al.*, 2010].

30.2. Major Conclusions from Previous Assessments

An integrated assessment of the impacts of climate change and ocean acidification on the Ocean as a region was not included in recent IPCC assessments, although a chapter devoted to the Ocean in the Second Assessment Report (SAR) did "attempt to assess the impacts of projected regional and global climate changes on the oceans" [*Ittekkot et al.*, 1996]. The fact that assessments for ocean and coastal systems are spread throughout previous IPCC assessment reports reduces the opportunity for synthesizing the detection and attribution of climate change and ocean acidification across the physical, chemical, ecological, and socio-economic components of the Ocean and its sub-regions. The IPCC Fourth Assessment Report (AR4) concluded, however, that while terrestrial sub-regions are warming faster than the oceans, "Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been taking up over 80% of the heat being added to the

climate system." AR4 also concluded that sea levels had risen due to the thermal expansion of the Ocean but recognized that our understanding of the dynamics of glaciers and ice sheets was "too limited to assess their likelihood or provide a best estimate or an upper boundary for sea level rise" (AR4, SPM). Changes to ocean temperature and density have been identified as having the potential to alter large-scale ocean circulation. AR4 concluded that with respect to the Meridional Overturning Circulation (MOC) "it is *very likely* that up to the end of the 20th Century the MOC was changing significantly at interannual to decadal time scales" (AR4, WGI Chapter 5, Box 5.1), despite limited evidence of a slowing MOC.
According to AR4, "sea-level rise over the last 100–150 years is probably contributing to coastal erosion in many places", including the east coast of the United States and the United Kingdom (AR4, WGII Chapter 1). The AR4 assessment was *virtually certain* that rising atmospheric CO_2 had changed carbonate chemistry of the ocean (i.e., buffering capacity, carbonate and bicarbonate concentrations), and that a decrease in surface pH of 0.1 had occurred over the global ocean (calculated from the uptake of anthropogenic CO_2 between 1750 and 1994 ([*Sabine et al.*, 2004; *Raven et al.*, 2005]; AR4, 5.4.2.3, WGI Table 7.3). Large-scale changes in ocean salinity were also observed from 1955–1998 and were "characterized by a global freshening in sub-polar latitudes and salinification of shallower parts of the tropical and subtropical oceans". In this case, freshening was observed in the Pacific, with increased salinity being observed in the Atlantic and Indian Oceans (AR4, WGI 5.3.2–5.3.5). These changes in surface salinity were qualitatively consistent with expected changes to surface freshwater flux. Freshening of mid and high latitude waters together with increased salinity at low latitudes were seen as evidence "of changes in precipitation and evaporation over the oceans".

Substantial evidence indicated that changing ocean conditions have extensively influenced marine ecosystems (AR4, WGII Table 1.5). AR4 noted that there is an "accumulating body of evidence to suggest that many marine ecosystems, including managed fisheries, are responding to changes in regional climate caused predominately by warming of air and sea surface temperatures (SST) and to a lesser extent by modification of precipitation regimes and wind patterns" (AR4, WGII 1.3.4.2). Observed changes in marine ecosystems and managed fisheries reported within AR4 included: changes to plankton community structure and productivity, the phenology and biogeography of coastal species, intertidal communities on rocky shores and kelp forests, and the distribution of pathogens and invasive species. Changes were also observed in coral reefs (primarily increased mass coral bleaching and mortality), migratory patterns and trophic interactions of marine birds, reptiles, and mammals, as well as of a range of other marine organisms and ecosystems (AR4, WGII Table 1.5), although a separate exercise in detection and attribution of changes to climate change (as done for terrestrial studies) was not done as part of AR4.

30.3. Recent Changes and Projections of Future Ocean Conditions

Evidence that increasing concentrations of atmospheric CO_2 have resulted in the warming and acidification of the upper layers of the Ocean has strengthened since AR4. Understanding the full suite of physical and chemical changes to the Ocean is critical to the interpretation of the past and future responses of marine organisms and ecosystems, especially with respect to the implications for coastal and low-lying areas.

30.3.1. Physical Changes

30.3.1.1. Heat Content and Temperature

The Ocean has absorbed 93% of the extra heat arising from the enhanced greenhouse effect (1971–2010), with most of the warming (64%) occurring in the upper (0–700 m) ocean (1971–2010; WGI Section 3.2.3, Figure 3.2, Box 3.1). It is *virtually certain* that global average sea surface temperatures (SST) have increased since the beginning of the 20th Century, with improvements and growth of data sets and archives, and the understanding of errors and biases since AR4 (WGI 2.4.2). It is *virtually certain* that the upper ocean (0–700m depth) has warmed from 1971–2010 (Figure 30-2a), while it is *likely* that the surface layers of the Ocean have warmed from the 1870s to 1971. Rates of increase in temperature are highest near the surface of the Ocean (>0.1°C decade^{-1} in the upper 75 m from 1971 to 2010) decreasing with depth (0.015°C decade^{-1} at 700 m; Figure 30-2b, c). It is *very likely* that the intensification of this warming near the surface has increased thermal stratification of the upper ocean by about 4%

between 0–200 m depth from 1971–2010 in all oceans north of 40°S. It is *likely* that the Ocean has warmed between 700–2000 m from 1957–2010, with the warming signal becoming less apparent or non-existent at deeper depths (WGI 3.2.1–3.2.3, Figures 3.1–3.2, Figure 3.9). These changes include a significant anthropogenic signal (*virtually certain*) [*Gleckler et al.*, 2012; *Pierce et al.*, 2012], with the surface waters of all three ocean basins warming at different rates, that all exceed those expected if there were no changes to greenhouse gas forcing over the past century (Figure 30-2e-g). In this respect, the observed record also falls within the range of historical model outputs that include observed increases in the concentration of greenhouse gases as opposed to models that do not (Figure 30-2 e-g).

Data archives such as HadISST1.1 contain sea surface temperatures (SST) reconstructed from a range of sources, allowing an opportunity to explore mean monthly, gridded, global SST from 1870 to the present [*Rayner et al.*, 2003]. We used the published HadISST1.1 data set (higher temporal and spatial resolution than HadSST3) to explore trends in historic SST within our sub-regions (Figure 30-1a; see definition of regions in Figure SM30-1 and Table SM30-2, column 1). The median SST for 1871–1995 from the Comprehensive Ocean-Atmosphere Data Set (COADS) were merged with data from the UK Met Office Marine Data Bank (MDB) to produce monthly globally-complete fields of SST on a 1° latitude-longitude SST grid from 1870 to date.

The surface layers of the three ocean basins have warmed (p-value$\leq$0.05, *very likely*), with the Indian Ocean (0.11℃ decade^{-1}) warming faster than the Atlantic (0.07℃ decade^{-1}) and Pacific (0.05℃ decade^{-1}) Oceans *(high confidence)* (Table 30-1). This is consistent with the depth-averaged (0–700 m) temperature trend observed from 1971–2010 (Figure 30-2a).

While some regions (e.g., North Pacific) did not show a clear warming trend, most regions showed either significant warming in the average temperature, or significant warming in either/or the warmest and coolest months of the year, over the period 1950–2009 (HadISST1.1 data, Table 30-1). Trends in SST show considerable sub-regional variability (Table 30-1, Figure 30-2a). Notably, the average temperature of most HLSBS did not increase significantly from 1950–2009 (except in the Indian Ocean; Table 30-1) yet the temperatures of the warmest month (North and South Atlantic, and South-eastern Pacific) and of the coolest month (North and South Atlantic, and South Pacific) showed significant upward trends over this period (p-value$\leq$0.05; Table 30-1).

The two EUS warmed from 1950–2009 (Pacific EUS, 0.07℃ decade^{-1} and Atlantic EUS, 0.09℃ decade^{-1}; Table 30-1). The average monthly SST of the SES did not warm significantly, although the temperature of the coolest month increased significantly within the Baltic Sea (0.35°C decade^{-1} or 2.11°C from 1950–2009), as did the temperatures of the warmest months in the Black (0.14°C decade^{-1} or 0.83°C from 1950–2009), Mediterranean (0.11°C decade^{-1} or 0.66°C from 1950–2009) and Red (0.05°C decade^{-1} or 0.28°C from 1950–2009) Seas over the period 1950–2009 (*very likely*) (Table 30-1). Studies over shorter periods (e.g., 1982–2006, [*Belkin*, 2009]) report significant increases in average SST of the Baltic (1.35°C), Black (0.96°C), Red (0.74°C), and Mediterranean (0.71°C) Seas. Such studies are complicated by the influence of patterns of long-term variability and by the small size and land-locked nature of SES. Coastal Boundary Systems (except the Caribbean and Gulf of Mexico) all showed highly significant (p-value$\leq$0.05) warming (0.09°C–0.13°C.decade^{-1}, Table 30-1). Among the EBUE, the Canary and Californian current regions exhibited a significant rate of change in the average SST (0.09°C decade^{-1} and 0.12°C decade^{-1}, respectively; p-value$\leq$0.05), while the Benguela and Humboldt currents did not show significant temperature changes from 1950–2009 (p-value>0.05; Table 30-1). There was some variability between current systems in terms of the behavior of the coolest and warmest months. The temperature of the coolest month increased significantly from 1950–2009 in the case of the Benguela and California currents (0.06°C decade^{-1} and 0.12°C decade^{-1} respectively, p-value$\leq$0.05), while there was a significant increase in the temperature of the warmest month in the case of the Canary and Humboldt currents (0.11°C decade^{-1} and 0.10°C decade^{-1}, respectively, Table 30-1).

The average temperature of STG showed complex patterns with increasing temperatures (1950–2009) in the Indian, South Atlantic, and South Pacific Oceans (*very likely*) (0.11, 0.08, and 0.06°C decade^{-1}, respectively; p-value$\leq$0.05), but not in the North Atlantic or North Pacific Ocean (p-value>0.05). These rates are half the value reported over shorter periods (e.g., 1998–2010, Table 1 in [*Signorini and McClain*, 2012] and based on NOAA_OI_SST_V2 data). Given the sensitivity of coral reefs to temperature ([*Eakin et al.*, 2010; *Strong et al.*, 2011; *Lough*, 2012]; Box CC-CR), trends in key coral reef regions were also examined using the World Resources Institute's *Reefs at Risk* report (www.wri.org) to identify HadISST1.1 grid cells containing coral reefs (Figure 30-4b). Grouping the results into six major coral reef regions, we found that coral reef waters (with the notable exception of the Gulf of Mexico and Caribbean) have shown strong increases in average temperature (0.07–0.13°C decade^{-1}) as well as the temperature of the coolest (0.07–0.14°C decade^{-1}) and warmest months (*very likely*) (0.07–0.12°C decade^{-1}; Table 30-1). These trends in temperature have resulted in an absolute increase in sea temperature of 0.44–0.79°C from 1950–2009.

[INSERT FIGURE 30-2 HERE
Figure 30-2: (a) Depth-averaged 0–700 m temperature trend for 1971–2010 (longitudinal versus latitude, colors and gray contours in °C per decade). (b) Zonally averaged temperature trends (latitude versus depth, colors and gray contours in °C per decade) for 1971–2010, with zonally averaged mean temperature over plotted (black contours in °C). (c) Globally-averaged temperature anomaly (Time versus depth, colors and grey contours in °C) relative to the 1971–2010 mean. (d) Globally-averaged temperature difference between the Ocean surface and 200 m depth (Black: annual values; red: five year running mean). Panels (a)–(d) from WGI Figure 3.1. (e)–(g) Observed and simulated variations in past and projected future annual average SST over three ocean basins (excluding regions within 300 km of the coast). The black line shows estimates from HadISST1.1 observational measurements. Shading denotes the 5–95 percentile range of climate model simulations driven with 'historical' changes in anthropogenic and natural drivers (62 simulations), historical changes in 'natural' drivers only (25), and the Representative Concentration Pathways: Dark Blue: RCP2.6; Light Blue: RCP4.5; Green: RCP6.0, and Red: RCP8.5). Data are anomalies from the 1986–2006 average of the HadISST1.1 data (for the HadISST1.1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-2.]

[INSERT FIGURE 30-3 HERE
Figure 30-3: Velocity at which sea surface temperature (SST) isotherms shifted (km decade^{-1}) over the period 1960–2009 calculated using HaDISST1.1, with arrows indicating the direction and magnitude of shifts. Velocity of climate change is obtained by dividing the temperature trend in °C decade^{-1} by the local spatial gradient °C km^{-1}. The direction of movement of SST is denoted by the direction of the spatial gradient and the sign of the temperature trend: towards locally cooler areas with a local warming trend or towards locally warmer areas where temperatures are cooling. Adapted from [*Burrows et al.*, 2011].]

[INSERT TABLE 30-1 HERE
Table 30-1: Regional changes in sea surface temperature (SST) over the period 1950–2009 using the Ocean regionalization specified in Figure 30-1a (for further detail of regions defined for analysis, see Figure SM30-1 and Table 30-2, column 1). A linear regression was fitted to the average of all 1×1 degree monthly SST data extracted from the HadISST1.1 data set [*Rayner et al.*, 2003] for each sub-region over the period 1950–2009. All SST values less than -1.8°C, together with all SST pixels that were flagged as being sea ice, were reset to the freezing point of seawater (-1.8°C) to reflect the sea temperature under the ice. Separate analyses were also done to explore trends in the temperatures extracted from the coldest-ranked and the warmest-ranked month of each year (Table SM30-2). The table includes the slope of the regression (°C decade^{-1}), the p-value for the slope being different from zero and the total change over 60 years (i.e., the slope of linear regression multiplied by 6 decades) for each category. The p-values that exceed 0.05 plus the associated slope and change values have a gray background, denoting the lower statistical confidence in the slope being different from zero (no slope). Note, changes with higher p-values may still describe informative trends although the level of confidence is lower that the slope is different from zero.]

Given the essential role that temperature plays in the biology and ecology of marine organisms (Box CC-MB, 6.2, 6.3, [*Pörtner*, 2002; *Poloczanska et al.*, 2013]), the speed of isotherm migration ultimately determines the speed at which populations must either move, adapt or acclimate to changing sea temperatures [*Pörtner*, 2002; *Burrows et al.*, 2011; *Hoegh-Guldberg*, 2012]. *Burrows et al.* [2011] calculated the rate at which isotherms are migrating as the ratio of the rate of SST change (°C yr^{-1}) to the spatial gradient of temperature (°C km^{-1}) over the period 1960–2009 (Figure 30-3). While many of these temperature trajectories are towards the polar regions, some are not and are influenced by features such as coastlines. This analysis and others (e.g., North Atlantic, *González-Taboada and Anadón* [2012]) reveals that isotherms in the Ocean are moving at high velocities (up to 200 km decade^{-1}), especially at low latitudes (*high confidence*) (Figure 30-3). Other sub-regions showed smaller velocities with contracting isotherms (cooling) in some areas (e.g., the Central and North Pacific, and Atlantic Oceans, Figure 30-3). There are also changes in the timing of seasonal temperatures in both spring and fall/autumn [*Burrows et al.*, 2011; *Poloczanska et al.*, 2013] which, together with other variables (e.g., light, food availability, geography), are *likely* to affect biological processes such as the migration of species to higher latitudes, and the timing and synchrony of reproductive and other seasonal behaviors.

Significant excursions of sea temperature above long-term summer temperature maxima (or below long-term temperature minima) significantly affect marine organisms and ecosystems [*Hoegh-Guldberg*, 1999; *Bensoussan et al.*, 2010; *Crisci et al.*, 2011; *Harley*, 2011]. Consequently, calculating heat stress as a function of exposure time and size of a particular temperature anomaly has proven useful in understanding recent changes to organisms and ecosystems (e.g., coral reefs and thermal anomalies, [*Strong et al.*, 2011]). The total heat stress accumulated over the period 1981–2010 was calculated using the methodology of [*Donner et al.*, 2007] and a reference climatology based on 1985–2000 in which the highest monthly SST was used to define the thermal threshold, above which accumulated thermal stress was calculated as 'exposure time multiplied by stress' or Degree Heating Months (DHM) as the running total over four consecutive months. While most sub-regions of the Ocean experienced an accumulation of heat stress (relative to a climatology based on the period 1985–2000), equatorial and high latitude sub-regions in the Pacific and Atlantic Oceans have the greatest levels of the accumulated heat stress (Figure 30-4a). These are areas rich in thermally-sensitive coral reefs (Figure 30-4b, [*Strong et al.*, 2011]). There was also a higher proportion of years that have had at least one stress event (DHM>1) in the last 30 years (1981–2010, Figure 30-4c) than in the preceding 30 years (1951–1980, Figure 30-4c, d.

[INSERT FIGURE 30-4 HERE
Figure 30-4: Recent changes in thermal stress calculated using HadISST1.1 data. A monthly climatology was created by averaging the HadISST monthly SST values over the period 1985–2000 to create twelve averages, one for each month of the year. The Maximum Monthly Mean (MMM) climatology was created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each SST value, but only allowing values to be recorded if they were greater than zero [*Donner et al.*, 2007]. Two measures of the change in thermal stress were calculated as a result: (a) The total thermal stress for the period 1981–2010, calculated by summing all monthly thermal anomalies for each grid cell. (b) The location of coral reef grid cells used in Table 30-1 and for comparison to regional heat stress here. Each dot is positioned over a 1×1 degree grid cell within which lies at least one carbonate coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's *Reefs at Risk* report (http://www.wri.org). The six regions are as follows: Red – Western Pacific Ocean; Yellow – Eastern Pacific Ocean; Dark Blue – Caribbean & Gulf of Mexico; Green – Western Indian Ocean; Pink – Eastern Indian Ocean; and Light Blue – Coral Triangle & SE Asia. (c) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951–1980 and (d) 1981–2010.]

The three ocean basins will continue warming under moderate (RCP4.5) to high (RCP8.5) emission trajectories (*high confidence*) and will only stabilize over the second half of the century in the case of low range scenarios such as RCP2.6 (Figure 30-2 e-g; WGI, AI.4–AI.8). Projected changes were also examined for specific ocean sub-regions using ensemble averages from AOGCM simulations available in the CMIP5 archive (Table SM30-3) for the four scenarios of the future (Representative Concentration Pathways: RCP2.6, RCP4.5, RCP6.0 and RCP8.5; [*van Vuuren et al.*, 2011]). Ensemble averages for each RCP are based on simulations from 10–16 individual models (Table SM30-3). The subset of CMIP5 models were chosen because each has historic runs enabling the derivation of the MMM climatology from 1985–2000, ensuring that all anomalies were comparable across time periods and across RCPs (Figure 30-10). Model hind-cast changes matched those observed for ocean sub-regions for the period 1980–2009 (HadISST1.1; Figure 30-2), with the model ensemble slightly overestimating the extent of change across the different ocean sub-regions (slope of observed/model = 0.81, $r^2 = 0.76$, p-value$\leq$0.001). In this way, the absolute amount of change projected to occur in the ocean sub-regions was calculated for near-term (2010–2039) and long-term (2070–2099) periods (Table SM30-4). In the near-term, changes in the temperature projected for the surface layers of the Ocean are largely indistinguishable between the different RCP pathways due to the similarity in forcing until 2040. By the end of the century, however, SST across the ocean sub-regions were 1.8–3.3°C higher under RCP8.5 than those projected to occur under RCP2.6 (Table SM30-4; Figure 30-2 e–g). The implications of these projected changes on the structure and function of oceanic systems are discussed below.

30.3.1.2. Sea Level

The rate of sea level rise since the mid-19th Century has been larger than the mean rate during the previous two millennia (*high confidence*). Over the period 1901–2010, Global Mean Sea Level (GMSL) rose by 0.19 (0.17–0.21) m (WGI Figure SPM, 3.7, 5.6, 13.2). It is *very likely* that the mean rate of global averaged sea level rise was 1.7 [1.5–1.9] mm yr^{-1} between 1901 and 2010, 2.0 [1.7–2.3] mm yr^{-1} between 1971 and 2010 and 3.2 [2.8–3.6] mm yr^{-1} between 1993 and 2010 (WGI SPM, 3.7). These observations are consistent with thermal expansion of the Ocean due to warming plus the addition of water from loss of mass by melting glaciers and ice sheets. Current rates of sea level rise vary geographically, and can be higher or lower than the GMSL for several decades at time due to fluctuations in natural variability and ocean circulation (Figure 30-5). For example, rates of sea level rise are up to three times higher than the GMSL in the Western Pacific and South-east Asian region, and decreasing in many parts of the Eastern Pacific for the period 1993–2012 as measured by satellite altimetry (Figure 30-5; WGI 13.6.5).

Sea level rise under increasing atmospheric greenhouse gas concentrations will continue for hundreds of years, with the extent and rate of the increase in GMSL being dependent on the emission scenario followed. Central to this analysis is the millennial-scale commitment to further sea level rise that is *likely* to arise from the loss of mass of the Greenland and Antarctic ice sheets (WGI 13.5.4, Figure 13.13). Sea level rise is *very likely* to increase during the 21st Century relative to the period 1971–2010 due to increased ocean warming and the continued contribution of water from loss of mass from glaciers and ice sheets. There is *medium confidence* that median sea level rise by 2081–2100 relative to 1986-2005 will be (5–95% range of process-based models): 0.44 m for RCP2.6, 0.53 m for RCP4.5, 0.55 m for RCP6.0, and 0.74 m for RCP8.5. Higher values of sea level rise are possible but are not backed by sufficient evidence to enable reliable estimates of the probability of specific outcomes. Many semi-empirical model projections of GMSL rise are higher than process-based model projections (up to about twice as large), but there is no consensus in the scientific community about their reliability and there is thus *low confidence* in their projections (WGI 13.5.2–3; Table 13.6, Figure 13.12).

It is considered *very likely* that increases in sea level will result in greater levels of coastal flooding and more frequent extremes by 2050 (WGI 13.7.2; [*IPCC*, 2012]). It is *about as likely as not* that the frequency of the most intense storms will increase in some ocean basins, although there is *medium agreement* that the global frequency of tropical cyclones is *likely* to decrease or remain constant (WGI 14.6, 14.8). While understanding of associated risks is relatively undeveloped, coastal and low-lying areas, particularly in the southern Asia, Pacific Ocean and North Atlantic regions, face increased flood risk (5.3.3.2, 8.2.3.4, 9.3.4.4. Future impacts of sea level rise include increasing penetration of storm surges into coastal areas and changing patterns of shoreline erosion (5.3), as well as the inundation of coastal aquifers by saltwater (5.4.2.5, 29.3.2). Regionally, some natural ecosystems may reduce in extent (e.g., mangroves), although examples of habitat expansion have been reported [*Brown et al.*, 2011]. Overall, changes to sea level are *very likely* to modify coastal ecosystems such as beaches, salt marshes, coral reefs and mangroves (5.4.2, Box CC-CR), especially where rates of sea level rise are highest (e.g., South-east Asia and the Western Pacific).

[INSERT FIGURE 30-5 HERE
Figure 30-5. Map of the rate of change in sea surface height (geocentric sea level) for the period 1993–2012 derived from satellite altimetry. Also shown are relative sea level changes (gray lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is shown (red lines) with each tide gauge time series. The relatively large short-term oscillations in local sea level (gray lines) are due to the natural climate variability and ocean circulation. For example, the large regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation. Figure originally presented in WGI (FAQ 13.1, Figure 1).

30.3.1.3. Ocean Circulation, Surface Wind, and Waves

Circulation of atmosphere and ocean (and their interactions) drives much of the chemical, physical, and biological characteristics of the Ocean, shaping phenomena such as ocean ventilation, coastal upwelling, primary production, and biogeochemical cycling. Critical factors for transporting nutrients from deep waters to the marine primary producers in the upper layers of the ocean include wind-driven mixing and upwelling.

There has been a poleward movement of circulation features, including a widening of the tropical belt, contraction of the northern polar vortex, and a shift of storm tracks and jet streams to higher latitudes (*medium confidence*, WGI 2.7.5, 2.7.6, 2.7.8, Box 2.5). Long-term patterns of variability (years to decades) continue to prevent robust conclusions regarding long-term changes in atmospheric circulation and winds in many cases (WGI 2.7.5). There is *high confidence*, however, that the increase in northern mid-latitude westerly winds from the 1950s to the 1990s, and the weakening of the Pacific Walker circulation from the late 19th Century to the 1990s have been largely offset by recent changes (WGI 2.7.5, 2.7.8, Box 2.5). Wind stress has increased since the early 1980s over the Southern Ocean (*medium confidence*) (WGI 3.4.4), and tropical Pacific since 1990 (*medium confidence*), while zonal mean wind stress may have declined by 7% in the equatorial Pacific from 1862–1990 due to weakening of the tropical Walker circulation (*medium confidence*) (WGI 3.4.4; [*Vecchi et al.*, 2006]). For example, it is *very likely* that the sub-tropical gyres of the major ocean basins have expanded and strengthened since 1993. However, the short-term nature of observing means that these changes are *as likely as not* to be due to decadal variability and/or due to longer term trends in wind forcing associated with climate change (WGI 3.6). Other evidence of changes in ocean circulation is limited to relatively short-term records that suffer from low temporal and spatial coverage. Therefore, there is *very low confidence* that multi-decadal trends in ocean circulation can be separated from decadal variability (WGI 3.6.6). There is no evidence of a long-term trend in large-scale currents such as the Atlantic Meridional Overturning Circulation (AMOC), Indonesian Throughflow (ITF), the Antarctic Circumpolar Current (ACC), or the transport of water between the Atlantic Ocean and Nordic Seas [WGI 3.6, Figures 3.10, 3.11].

Winds speed may have increased within the regions of EBUE (*low confidence* in attribution to climate; e.g. California Current, WGI 2.7.2). Changing wind regimes have the potential to influence mixed layer depth (MLD) and upwelling intensity in highly productive sub-regions of the world's oceans, although there is *low agreement* as to whether or not upwelling will intensify or not under rapid climate change ([*Bakun*, 1990; *Bakun et al.*, 2010]; Box CC-UP). Surface waves are influenced by wind stress, although understanding trends remains a challenge due to limited data. There is *medium confidence* that Significant Wave Height (SWH) has increased since the mid-1950s over much of the North Atlantic north of 45°N, with typical winter season trends of up to 20 cm per decade (WGI 3.4.5). There is *low confidence* in the current understanding of how SWH will change over the coming decades and century for most of the Ocean. It remains an important knowledge gap (WGI 3.4).

30.3.1.4. Solar Insolation and Clouds

Solar insolation plays a crucially important role in the biology of many marine organisms, not only as a source of energy for photosynthesis but also as a potential co-stressor in the photic zone (with temperature), as is seen during mass coral bleaching and mortality events (e.g., [*Hoegh-Guldberg*, 1999]). Global surface solar insolation (from the NCEP/NCAR Reanalysis Project, *Kalnay et al.* [1996]) decreased by 4.3 W m^{-2} $decade^{-1}$ from the 1950s until 1991, after when it increased at 3.3 W m^{-2} $decade^{-1}$ until 1999 [*Ohmura*, 2009; *Wild*, 2009], matching a broad suite of evidence from many land-based sites (WGI, 2.3.3). While there is consistency between independent data sets for particular regions, there is substantial ambiguity and therefore *low confidence* in observations of global-scale cloud variability and trends (WGI 2.5.7). There is also *low confidence* in projections of how cloudiness, solar insolation and precipitation will change as the planet warms due to the large interannual and decadal variability (ENSO, PDO), short observation time series and uneven spatial sampling, particularly in the early record (before 1950; WGI 2.5.8).

30.3.1.5. Storm Systems

As agents of water column mixing, storms (from small atmospheric disturbances to intense tropical cyclones) can remix nutrients from deeper areas into the photic zone of the Ocean, stimulating productivity. Storms can also reduce local sea temperatures and associated stress by remixing heat into the deeper layers of the Ocean [*Carrigan and Puotinen*, 2011]. Large storms can destroy coastal infrastructure and coastal habitats such as coral reefs and mangrove forests, which can take decades to recover [*Lotze et al.*, 2011; *De'ath et al.*, 2012]. While there is *low* *confidence* for long-term trends in tropical cyclone activity globally (largely due to the lack of reliable long-term data sets), it is *virtually certain* that the frequency and intensity of the strongest tropical cyclones in the North Atlantic have increased since the 1970s (WGI 2.6.3). There is *medium agreement* that the frequency of the most intense cyclones in the Atlantic has increased since 1987 (WGI 2.6.3) and *robust evidence* of interdecadal changes in the storm track activity within the North Pacific and North Atlantic [*Lee et al.*, 2012]. It is also *very likely* that there has been a decrease in the number of land-falling tropical cyclones along the East Australian coast since the 19th Century (WGI 2.6.3, [*Callaghan and Power*, 2011]). It is *likely* that these patterns are influenced by interannual variability such as ENSO, with land-falling tropical cyclones being twice as common in La Niña versus El Niño years (*high confidence*) [*Callaghan and Power*, 2011]. There has been an increase in the number of intense wintertime extra-tropical cyclone systems since the 1950s in the North Pacific. Similar trends have been reported for the Asian region, although analyzes are limited in terms of the spatial and temporal coverage of reliable records (WGI 2.6.4). There is *low confidence*, however, in large-scale trends in storminess or storminess proxies over the last century due to the lack of long-term data and inconsistencies between studies (WGI 2.6.4).

30.3.1.6. Thermal Stratification

As heat has accumulated in the Ocean there has been a 4% increase in thermal stratification of the upper layers in most ocean regions (0–200 m, 40-year record) north of 40°S (WGI 3.2.2). Increasing thermal stratification has reduced ocean ventilation and the depth of mixing in many ocean sub-regions (*medium confidence*) WGI 3.8.3). This in turn reduces the availability of inorganic nutrients and consequently primary productivity (*medium confidence*) (6.3.4). In the STG, which dominate the three major ocean basins (30.5.6), satellite-derived estimates of surface chlorophyll and primary production decreased between 1999 and 2007 (Box CC-PP). In contrast, however, *in situ* observations at fixed stations in the North Pacific and North Atlantic Oceans (Hawaii Ocean Time-series or HOT, and Bermuda Atlantic Time-series Study, BATS), showed increases in nutrient and chlorophyll levels and primary production over the same period, suggesting that other processes (e.g., ENSO, PDO, NAO, winds, eddies, advection) can counteract broad-scale trends at local scales (Box CC-PP). The continued warming of the surface layers of the Ocean will *very likely* further enhance stratification and potentially limit the nutrient supply to the euphotic zone in some areas. The response of upwelling to global warming is *likely* to vary between regions and represents a complex interplay between local and global variables and processes (Box CC-UW).

30.3.2. Chemical Changes

30.3.2.1. Surface Salinity

The global water cycle is dominated by evaporation and precipitation occurring over ocean regions, with surface ocean salinity varying with temperature, solar radiation, cloud cover, and ocean circulation [*Deser et al.*, 2004]. Changes in salinity influence stratification of water masses and circulation. Ocean salinity varies regionally (Figure 30-6a) and is an outcome of the balance between evaporation and precipitation ([*Durack and Wijffels*, 2010]; WGI 3.3). Evaporation-dominated regions (Figure 30-6b) such as the STG, and Atlantic and Western Indian Oceans (WGI 3.3.3) have elevated salinity, while areas of high precipitation such as the North Pacific, North-eastern Indian Ocean, South-east Asia, and the eastern Pacific have relatively low salinities (WGI 3.3.3, Figure 30-6a). It is *very likely* that large-scale trends in salinity have also occurred in the Ocean interior, deriving from changes to salinity at the surface and subsequent subduction (WGI 3.3.2–3.3.4).

Salinity trends are consistent with the amplification of the global hydrological cycle [*Durack et al.*, 2012; *Pierce et al.*, 2012], a consequence of a warmer atmosphere *very likely* producing the observed trend in greater precipitation, evaporation, atmospheric moisture (Figure 30-6b), and extreme events (WGI 2.6.2.1, 3.3.4; [*IPCC*, 2012]). Spatial patterns in salinity and evaporation-precipitation are similar, providing indirect evidence that these processes have been enhanced since the 1950s [WGI 3.3.2–3.3.4, Figures 3.4, 3.5 and 3.20d, FAQ 3.3]. These trends in salinity are *very likely* to have a discernible contribution from anthropogenic climate change (WGI 10.4.2). The combined changes in surface salinity and temperature are consistent with changes expected due to anthropogenic forcing of the climate system and are inconsistent with the effects of natural climate variability, either internal to the climate system (e.g., ENSO, PDO; Figure 30-6c, d) or external to it (e.g., solar forcing or volcanic eruptions; [*Pierce et al.*, 2012]). There is *high confidence* between climate models that the observed trends in ocean salinity will continue as average global temperature increases [*Durack and Wijffels*, 2010; *Terray et al.*, 2012]. Ramifications of these changes are largely unknown but are of interest given the role of ocean salinity and temperature in fundamental processes such as the Atlantic Meridional Overturning Circulation (AMOC).

[INSERT FIGURE 30-6 HERE
Figure 30-6: (a) The 1955–2005 climatological-mean sea surface salinity [*Antonov et al.*, 2010] color contoured at 0.5 PSS78 intervals (black lines). (b) Annual mean evaporation-precipitation averaged over the period 1950–2000 (NCEP) color contoured at 0.5 m yr–1 intervals (black lines). (c) The 58-year (2008 minus 1950) sea surface salinity change derived from the linear trend (PSS78), with seasonal and ENSO signals removed [*Durack and Wijffels*, 2010] color contoured at 0.116 PSS78 intervals (black lines). (d) The 30-year (2003–2007 average centered at 2005, minus the 1960–1989 average centered at 1975) sea surface salinity difference (PSS78) color contoured at 0.06 PSS78 intervals (black lines). Contour intervals in (c) and (d) are chosen so that the trends can be easily compared, given the different time intervals in the two analyzes. White areas in (c) and (d) are marginal seas where the calculations are not carried out. Regions where the change is not significant at the 99% confidence level are stippled in gray. Figure originally presented as WGI Figure 3.4 in WGI.]

30.3.2.2. Ocean Acidification

The Ocean has absorbed approximately 30% of atmospheric CO_2 from human activities resulting in decreased ocean pH and carbonate ion concentrations, and increased bicarbonate ion concentrations (Box CC-OA, WG1 Box 3.2; Figure SM30-2). The chemical response to increased CO_2 dissolving into the Ocean from the atmosphere is known with *very high confidence* (WGI 6.4.4). Factors such as temperature, biological processes, and sea ice (WGI 6.4) play significant roles in determining the saturation state of seawater for polymorphs (i.e. different crystalline forms) of calcium carbonate. Consequently, pH and the solubility of aragonite and calcite are naturally lower at high latitudes and in upwelling areas (e.g., eastern Pacific upwelling, Californian Current'), where organisms and ecosystems may be relatively more exposed to ocean acidification as a result ([*Feely et al.*, 2012; *Gruber et al.*, 2012]; Figure 30-7a, b; Figure SM30-2). Aragonite and calcite concentrations vary with depth, with under-saturation occurring at deeper depths in the Atlantic (calcite: 3500–4500 m, aragonite: 400–3000 m) as opposed to the Pacific and Indian Oceans (calcite: 100–3000 m, aragonite: 100–1200 m; [*Feely et al.*, 2004; *Orr et al.*, 2005; *Feely et al.*, 2009]; Figure 30-8).

[INSERT FIGURE 30-7 HERE
Figure 30-7: Projected ocean acidification from 11 CMIP5 Earth System models under RCP8.5 (other RCP scenarios have also been run with the CMIP5 models): (a) Time series of surface pH shown as the mean (solid line) and range of models (filled), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red) and the Southern Ocean (blue). (b) Maps of the median model's change in surface pH from 1850–2100. Panel (a) also includes mean model results from RCP2.6 (dashed lines). Over most of the Ocean, gridded data products of carbonate system variables are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following [*Orr et al.*, 2005]. Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), the results are shown without bias correction. The bias correction reduces the range of model projections by up to a factor of 4, e.g., in panel (a) compare the large range of model projections for the Arctic (without bias correction) to the smaller range in the Southern Ocean (with bias correction). Figure originally presented in WGI Figure 6.28 in WGI.]

[INSERT FIGURE 30-8 HERE
Figure 30-8: Projected aragonite saturation state from 11 CMIP5 Earth System models under RCP8.5 scenario: (a) time series of surface carbonate ion concentration shown as the mean (solid line) and range of models (filled), given as area weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue); maps of the median model's surface ΩA in (b) 2010, (d) 2050, and (f) 2100; and zonal mean sections (latitude versus depth) of ΩA in 2100 over (c) the Atlantic Ocean and (e) the Pacific Ocean, while the ASH (Aragonite Saturation Horizon) is shown for 2010 (dotted line) and 2100 (solid line). Panel (a) also includes mean model results from

RCP2.6 (dashed lines). As for Figure 30-7, gridded data products of carbonate system variables [*Key et al.*, 2004] are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following [*Orr et al.*, 2005]. Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), results are shown without bias correction. Reprinted from Figure 6.29 in WGI.]

Surface ocean pH has decreased by approximately 0.1 pH units since the beginning of the Industrial Revolution (*high confidence*) (Figure 30-7a; WGI 3.8.2, Box 3.2), with pH decreasing at the rate of -0.0013 and -0.0024 pH units yr^{-1} (WGI 3.8.2, Table 3.2). The presence of anthropogenic CO_2 diminishes with depth. The saturation horizons of both polymorphs of calcium carbonate, however, are shoaling rapidly (1–2 m yr^{-1}, and up to 5 m yr^{-1} in regions such as the California Current [*Orr et al.*, 2005; *Feely et al.*, 2012]. Further increases in atmospheric CO_2 are *virtually certain* to further acidify the Ocean and change its carbonate chemistry (Figures S30.2, 30.7 and 30.8). Doubling atmospheric CO_2 (~RCP4.5; [*Rogelj et al.*, 2012]) will decrease ocean pH by another 0.1 units and decrease carbonate ion concentrations by approximately 100 µmol kg^{-1} in tropical oceans (Figure 30-8a) from the present day average of 250 µmol kg^{-1} (*high confidence*). Projected changes for the open Ocean by 2100 (Figures 30.7, 30.8) range from a pH change of -0.14 unit with RCP2.6 (421 ppm CO_2, +1ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP8.5 (936 ppm CO_2, +3.7ºC, 56% reduction of carbonate ion concentration). The saturation horizons will also become significantly shallower in all oceans (with the aragonite saturation horizon between 0 and 1500 m in the Atlantic Ocean and 0 and 600 m (poles versus equator) in the Pacific Ocean ([*Sabine et al.*, 2004; *Orr et al.*, 2005]; WGI 6.4, Figure 6.28). Trends towards under-saturation of aragonite and calcite will also partly depend on ocean temperature, with surface polar waters expected to become seasonally under-saturated with respect to aragonite and calcite within a couple of decades (Figure 30-8c–f, Box CC-OA[*McNeil and Matear*, 2008]).

Overall, observations from a wide range of laboratory, mesocosm and field studies reveal that marine macro-organisms and ocean processes are sensitive to the levels of ocean acidification projected under elevated atmospheric CO_2 (*high confidence*) (Box CC-OA, 6.3.2, [*Munday et al.*, 2009; *Kroeker et al.*, 2013]). Ecosystems that are characterized by high rates of calcium carbonate deposition (e.g., coral reefs, calcareous plankton communities) are sensitive to decreases in the saturation states of aragonite and calcite (*high confidence*). These changes are *very likely* to have broad consequences such as the loss of three-dimensional coral reef frameworks [*Hoegh-Guldberg et al.*, 2007; *Manzello et al.*, 2008; *Fabricius et al.*, 2011; *Andersson and Gledhill*, 2013; *Dove et al.*, 2013] and restructuring of food webs at relatively small (~50 ppm) additional increases in atmospheric CO_2. Projected shoaling of the aragonite and calcite saturation horizons are *likely* to impact deep water (100–2000 m) communities of scleractinian corals and other benthic organisms as atmospheric CO_2 increases ([*Orr et al.*, 2005; *Guinotte et al.*, 2006]; WGI 6.4), although studies from the Mediterranean and of seamounts off SW Australia report that some deep water corals may be less sensitive [*Thresher et al.*, 2011; *Maier et al.*, 2013]. Organisms are also sensitive to changes in pH with respect to physiological processes such as respiration and neural functions (6.3.2). Due to the relatively short history, yet growing effort, to understand the implications of rapid changes in pH and ocean carbonate chemistry, there are a growing number of organisms and processes reported to be sensitive. The impacts of ocean acidification on marine organisms and ecosystems continues to raise serious scientific concern, especially given that the current rate of ocean acidification (at least 10–100 faster than the recent glacial transitions [*Caldeira and Wickett*, 2003; *Hoegh-Guldberg et al.*, 2007]) is unprecedented within the last 65 Ma (*high confidence*) [*Ridgwell and Schmidt*, 2010] and possibly 300 Ma of Earth history (*medium confidence*) ([*Hönisch et al.*, 2012]; 6.1.2).

30.3.2.3. Oxygen Concentration

Dissolved O_2 is a major determinant of the distribution and abundance of marine organisms (6.3.3). Oxygen concentrations vary across ocean basins and are lower in the eastern Pacific and Atlantic basins, and northern Indian Ocean (Figure 30-9b, 6.1.1.3). In contrast, some of the highest concentrations of O_2 are associated with cooler high latitude waters (Figure 30-9b). There is *high agreement* among analyzes providing *medium confidence* that O_2 concentrations have decreased in the upper layers of the Ocean since the 1960s, particularly in the equatorial Pacific and Atlantic Oceans (WGI Figure 3.20, 3.8.3). A formal fingerprint analysis undertaken by *Andrews et al.* [2013] concluded that recent decreases in oceanic O_2 are due to external influences (*very likely*). Conversely, O_2 has increased in the North and South Pacific, North Atlantic and Indian Oceans, consistent with greater mixing and ventilation due to strengthening wind systems (WGI 3.8.3). The reduction in O_2 concentration in some areas of the Ocean is consistent with that expected from higher ocean temperatures and a reduction in mixing (increasing stratification) (WGI 3.8.3). Analysis of ocean O_2 trends over time [*Helm et al.*, 2011b] reveals that the decline in O_2 solubility with increased temperature is responsible for no more than 15% of the observed change. The remaining 85%, consequently, is associated with increased deep-sea microbial respiration and reduced O_2 supply due to increased ocean stratification (WGI Box 6.5 Figure 1). In coastal areas, eutrophication can lead to increased transport of organic carbon into adjacent ocean habitats where microbial metabolism is stimulated, resulting in a rapid drawdown of O_2 [*Weeks et al.*, 2002; *Rabalais et al.*, 2009; *Bakun et al.*, 2010].

The development of hypoxic conditions (generally defined as O_2 concentrations below ~60 μmol kg^{-1}) over recent decades has been documented across a wide array of ocean sub-regions including some SES (e.g., Black and Baltic Seas), the Arabian Sea, and the California, Humboldt, and Benguela Current systems, where eruptions of hypoxic, sulfide-laden water have also occurred in some cases [*Weeks et al.*, 2002]. Localized, seasonal hypoxic 'dead zones' have emerged in economically valuable coastal areas such as the Gulf of Mexico [*Turner et al.*, 2008; *Rabalais et al.*, 2010], the Baltic Sea [*Conley et al.*, 2009] and the Black Sea [*Kideys*, 2002; *Ukrainskii and Popov*, 2009] in connection with nutrient fluxes from land. Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, the minimum O_2 threshold (less than 2 mg l^{-1} or ~60 $mmol^{-1}$) is found at 300 m depth and upwelling of increasingly hypoxic waters is well documented [*Karstensen et al.*, 2008]. Hypoxic waters in the northern Arabian Sea and Bay of Bengal are located close to continental shelf areas. Long-term measurements reveal that O_2 concentrations are declining in these waters, with *medium evidence* that economically significant mesopelagic fish populations are being threatened by a reduction in suitable habitat as respiratory stress increases [*Koslow et al.*, 2011]. It should be noted that hypoxia profiles based on a critical threshold of 60 μmol kg^{-1} can convey an overly simplistic message given that critical concentrations of O_2 in this regard are very much species, size, temperature, and life history stage specific. This variability in sensitivity is, however, a critical determinant for any attempt to understand how ecosystems will respond to changing future O_2 levels (6.3.3).

There is *high agreement* among modeling studies that O_2 concentrations will continue to decrease in most parts of the Ocean due to the effect of temperature on O_2 solubility, microbial respiration rates, ocean ventilation, and ocean stratification (Figure 30-9c, d; WGI Table 6.14 [*Andrews et al.*, 2013]), with implications for nutrient and carbon cycling, ocean productivity, marine habitats, and ecosystem structure (6.3.5). The outcomes of these global changes are *very likely* to be influenced by regional differences such as wind stress, coastal processes, and the supply of organic matter.

[INSERT FIGURE 30-9 HERE
Figure 30-9: (a) Simulated changes in dissolved O_2 (mean and model range as shading) relative to 1990s for RCP2.6, RCP4.5, RCP6.0, and RCP8.5. (b) Multi-model mean dissolved O_2 (mmol m^{-3}) in the main thermocline (200–600 m depth average) for the 1990s, and changes in the 2090s relative to 1990s for RCP2.6 (c) and RCP8.5 (d). To indicate consistency in the sign of change, regions are stippled when at least 80% of models agree on the sign of the mean change. These diagnostics are detailed in [*Cocco et al.*, 2013] in a previous model inter-comparison using the SRES-A2 scenario and have been applied to CMIP5 models here. Models used: CESM1-BGC, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MPI-ESM-LR, MPI-ESM-MR, NorESM1. Figure originally presented in WGI Figure 6.30 in WGI.]

30.4. Global Patterns in the Response of Marine Organisms to Climate Change and Ocean Acidification

Given the close relationship between organisms and ecosystems with the physical and chemical elements of the environment, changes are expected in the distribution and abundance of marine organisms in response to ocean warming and acidification (6.3, Box CC-MB, Box CC-OA). Our understanding of the relationship between ocean warming and acidification reveals that relatively small changes in temperature and other variables can result in often large biological responses that range from simple linear trends to more complex non-linear outcomes. There has been a rapid increase in studies that focus on the influence and consequences of climate change for marine ecosystems since AR4 ([*Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al.*, 2013], representing an opportunity to examine, and potentially attribute, detected changes within the Ocean to climate change. Evidence of global and regional responses of marine organisms to recent climate change have been shown through assessments of multiple studies focused on single-species, populations, and ecosystems [*Tasker*, 2008; *Thackeray et al.*, 2010; *Przeslawski et al.*, 2012; *Poloczanska et al.*, 2013]. The most comprehensive assessment, in terms of geographic spread and number of observed responses, is that of *Poloczanska et al.* [2013]. This study reveals a coherent pattern in observed responses of ocean life to recent climate change across regions and taxonomic groups, with 81% of responses by organisms and ecosystems being consistent with expected changes to recent climate change (*high confidence*) (Box CC-MB). On average, spring events in the Ocean have advanced by 4.4 ± 0.7 days decade^{-1} (mean ± SE) and the leading edges of species' distributions have extended (generally poleward) by 72.0 ± 0.35 km decade^{-1}. Values were calculated from data series ranging from the 1920s to 2010, although all series included data after 1990. The fastest range shifts generally occurred in regions of high thermal velocity (the speed and direction at which isotherms move [*Burrows et al.*, 2011], 30.3.1.1). Subsequently, [*Pinsky et al.*, 2013], using a database of 360 fish and invertebrate species and species groups from coastal waters around North America, showed differences in the speed and directions that species shift can be explained by differences in local climate velocities (Box CC-MB).

30.5. Regional Impacts, Risks, and Vulnerabilities: Present and Future

This section explores the impacts, risks, and vulnerabilities of climate change for the seven sub-regions within the Ocean. There is considerable variability from region to region, especially in the extent and interaction of climate change and non-climate change stressors. While the latter may complicate attribution attempts in many sub-regions, interactions between the two groups of stressors may also represent opportunities to reduce the overall effects on marine organisms and processes by environmental changes being driven by climate change (including ocean acidification) [*Crain et al.*, 2008; *Griffith et al.*, 2012].

30.5.1. High Latitude Spring Bloom Systems

High Latitude Spring Bloom Systems (HLSBS) stretch from 35ºN to the edge of the winter sea ice (and from 35ºS to the polar front) and provide 36% of world's fish catch (Figure 30-1b). Although much of the North Pacific is iron limited [*Martin and Fitzwater*, 1988] and lacks a classical spring bloom [*McAllister et al.*, 1960], strong seasonal variability of primary productivity is pronounced at all high latitudes because of seasonally varying photoperiod and water column stability [*Racault et al.*, 2012]. Efficient transfer of marine primary and secondary production to higher trophic levels, including commercial fish species, is influenced by both the magnitude and the spatial and temporal synchrony between successive trophic production peaks [*Hjort*, 1914; *Cushing*, 1990; *Beaugrand et al.*, 2003; *Beaugrand and Reid*, 2003].

30.5.1.1. Observed Changes and Potential Impacts

30.5.1.1.1. North Atlantic

The average temperature of the surface waters of the North Atlantic HLSBS has warmed by 0.07°C decade^{-1}, resulting in an increase in sea temperature of 0.44°C between 1950 and 2009 (*likely*) (p-value = 0.15; Table 30-1). Over the same period, both winter and summer temperatures have increased significantly (0.05°C decade^{-1} and 0.12°C decade^{-1} respectively, p-value$\leq$0.05). Since the 1970s, the Atlantic Ocean has warmed more than any other ocean basin (0.3ºC decade^{-1}; Figure 30-2a, WGI 3.2.2), with greatest warming rates over European continental shelf areas such as the southern North Sea, the Gulf Stream front, the sub-polar gyres and the Labrador Sea [*MacKenzie and Schiedek*, 2007b; a; *Levitus et al.*, 2009; *Lee et al.*, 2011; *González-Taboada and Anadón*, 2012]. Basin-wide warming in the North Atlantic since the mid-1990s has been driven by global warming and the current warm phase of the Atlantic Multidecadal Oscillation (AMO) ([*Wang and Dong*, 2010]; WGI 14.7.6).

The North Atlantic is one of the most intensively fished ocean sub-regions. The major areas for harvesting marine living resources span the eastern North American, European and Icelandic shelves [*Livingston and Tjelmeland*, 2000]. In addition, the deep regions of the Nordic Seas and the Irminger Sea contain large populations of pelagic fish such as herring, blue whiting and mackerel, and mesopelagic fish such as pearlsides and redfish. The region covers a wide latitudinal range from 35º–80ºN and, hence, a large span in thermal habitats. This is reflected in the latitudinal gradient from subtropical/temperate species along the southern fringe to boreal/arctic species along the northern fringe.

Climate change is *virtually certain* to drive major changes to the northern fringes of the Atlantic HLSBS by 2100. For the Barents Sea region, which borders the HLSBS and Arctic regions, modeling projections from 1995–2060 (SRES B2 scenario) gave an increase in phytoplankton production of 8%, an increase in Atlantic zooplankton production of 20%, and a decrease of Arctic zooplankton production of 50% [*Ellingsen et al.*, 2008]. These changes result in a total increase in zooplankton production in the HLSBS section of the Barents Sea and a decrease in the Arctic section. Together with poleward shifts of fish species, a substantial increase in fish biomass and catch is also *very likely* at the northern fringes of the HLSBS [*Cheung et al.*, 2011]. However, for some species like capelin, which feeds in summer at the ice edge and spawns in spring at the southern Atlantic Norwegian/Murman coast of the Barents Sea, the continuous temperature increase is *very likely* to cause discontinuous changes in conditions. The limited migration potential for this small pelagic fish is also *likely* to drive an eastwards shift in spawning areas to new spawning grounds along the Novaja Semlja coast[*Huse and Ellingsen*, 2008].

Observations of fish and other species moving to higher latitudes [*Beare et al.*, 2005; *Perry et al.*, 2005; *Collie et al.*, 2008; *Lucey and Nye*, 2010] within the North Atlantic HLSBS are consistent with results of modeling exercises [*Stenevik and Sundby*, 2007; *Cheung et al.*, 2011]. Examples from the Barents (28.2.2.1, Nordic, and North Seas (Box 6-1; 23.4.6) show how warming from the early 1980s influenced North Atlantic ecosystems, where substantial biological impacts such as large-scale modification of the phenology, abundance and distribution of plankton assemblages and reorganization of fish assemblages have been observed [*Beaugrand et al.*, 2002; *Edwards*, 2004; *Edwards and Richardson*, 2004; *Tasker*, 2008; *Nye et al.*, 2009; *Head and Pepin*, 2010; *Simpson et al.*, 2011]. The ranges of some cold-water zooplankton assemblages in the North-east Atlantic have contracted towards the Arctic since 1958, and were replaced by warm-water zooplankton assemblages (specifically copepods) (*high confidence*), which moved up to 1000 km northward [*Beaugrand et al.*, 2002; *Beaugrand*, 2009]. Although changes to surface circulation may have played a role [*Reid et al.*, 2001], the primary driver of the shift was shown to be regional warming [*Beaugrand et al.*, 2002; *Beaugrand*, 2004]. Reorganization of zooplankton communities and an observed decline in mean size has implications for energy transfer to higher trophic levels including commercial fish stocks ([*Beaugrand et al.*, 2003; *Kirby and Beaugrand*, 2009; *Lindley et al.*, 2010], 23.4.6). Warm-water species of fish have increased in abundance on both sides of the North Atlantic (*medium confidence*) [*Beare et al.*, 2005; *Collie et al.*, 2008; *Genner et al.*, 2010; *Hermant et al.*, 2010; *Lucey and Nye*, 2010; *Simpson et al.*, 2011]. Diversity of zooplankton and fish has increased as more diverse warm-water assemblages extend northward in response to changing environmental conditions (*high confidence*) ([*Kane*, 2007; *Hiddink and ter Hofstede*, 2008; *Beaugrand*, 2009; *Mountain and Kane*, 2010; *ter Hofstede et al.*, 2010], Box 6-1, 23.6.5).

The past decade has been the warmest decade ever recorded in the Barents Sea, resulting in large populations of krill shrimp, and pelagic and demersal fish stocks linked to the Atlantic and boreal ecosystem of the Barents Sea (*high confidence*) ([*Johannesen et al.*, 2012]; 28.2.2.1). Recruitment to boreal fish stocks such as cod, haddock, and herring has increased [*Eriksen et al.*, 2012]. The relatively warm Atlantic waters have advanced northward and eastward [*Årthun et al.*, 2012] and sea-ice has retreated along with the Arctic water masses. As a result, boreal euphausiids, which are mainly confined to Atlantic water, have increased in biomass and distribution [*Dalpadado et al.*, 2012] enhancing growth of young cod *Gadus morhua* (boreal) as well as the more Arctic (arcto-boreal) capelin (*Mallotus villosus*). The abundance of amphipods of more Arctic origin has decreased, resulting in poorer feeding conditions for polar zooplankton predators such as polar cod (*Boreogadus saida).* Blue whiting (*Micromesistius poutassou*), which spawns west of the British Isles and feeds on zooplankton in the Norwegian Sea during the summer, extended their summer feeding distribution into the Barents Sea during the recent warm period.

The Norwegian Sea is one of the two core regions for the herbivore copepod *Calanus finmarchicus,* an important prey species for pelagic fish and early life-stages of all fish around the rim of this high latitude sea including the North Sea and the Barents Sea [*Sundby*, 2000]. *C. finmarchicus* is the main food item for some of the world's largest fish stocks such as the Norwegian spring-spawning herring (*Clupea harengus*), blue whiting (*M. poutassou*), and northeast Atlantic mackerel (*Scomber scombrus*). These stocks have increased considerably during the recent warming that started in the early 1980s [*Huse et al.*, 2012]. The individual size of herring has also increased, enabling longer feeding migrations to utilize boreal zooplankton occurring closer to distant Arctic water masses. Mackerel (*Scomber scombrus*) has advanced northward and westward into Icelandic waters [*Astthorsson et al.*, 2012] and was even observed in East Greenland water in summer 2013 [*Nøttestad et al.*, 2013]. Since 2004, the sum of spawning stock biomass of the three pelagic fish species (herring, blue whiting, and mackerel) leveled out at around 16 million tons.

Observed changes in the phenology of plankton groups in the North Sea over the past 50 years are driven by climate forcing, in particular regional warming (*high confidence)* [*Edwards and Richardson*, 2004; *Wiltshire and Manly*, 2004; *Wiltshire et al.*, 2008; *Lindley et al.*, 2010; *Lindley and Kirby*, 2010; *Schluter et al.*, 2010], although responses are species-specific with substantial variation within functional groups ([*Edwards and Richardson*, 2004]; Box 6-1). For example, the peak maximum abundance of the copepod *C. finmarchicus* advanced by 10 days from the 1960s to the 2000s, but its warm-water equivalent, *C. helgolandicus*, did not advance [*Bonnet et al.*, 2005]. In the North Sea, bottom temperatures in winter have warmed by 1.6°C (1980–2004; [*Dulvy et al.*, 2008]). The whole demersal fish community shifted deeper by 3.6 m decade^{-1} over the period 1980–2004, although mean latitude of the whole community did not show net displacement [*Dulvy et al.*, 2008]. Within the community, cool-water specialists generally shifted northward while abundant warm-water species shifted southward, reflecting winter warming of the southern North Sea. The cold winter temperatures of the shallow regions of the southern North Sea have acted to exclude species with warm-water affinities. Trawl survey data from the rapidly-warming southern North Sea suggests waves of immigration by southern species such as red mullet (*Mullus surmuletus*), anchovy (*Engraulis encrasicholus*), and sardines (*Sardina pilchardus*), linked to increasing population sizes and warming temperatures [*Beare et al.*, 2004; *Beare et al.*, 2005].

In the North-east Atlantic, range expansions and contractions linked to changing climate have also been observed in benthic crustaceans, bivalves, gastropods, and polychaetes (*medium confidence*) [*Mieszkowska et al.*, 2007; *Beukema et al.*, 2009; *Berke et al.*, 2010]. For example, the southern range limit of the common intertidal barnacle *Semibalanus balanoides* contracted northward along European coastlines at a rate of 15–50 km decade^{-1} since 1872, and its retreat is attributed to reproductive failure as winter temperatures warm [*Southward et al.*, 2005; *Wethey and Woodin*, 2008]. *Chthamalus montagui*, its warm-water competitor, increased in abundance to occupy the niche vacated by *S. balanoides (high confidence)* [*Southward et al.*, 1995; *Poloczanska et al.*, 2008].

Many of the longest and most comprehensive time series used to investigate the ecological consequences of climate fluctuations and fishing, that span periods of cooling and warming over the past century, are from the North-east Atlantic [*Toresen and Østvedt*, 2000; *Southward et al.*, 2005; *Sundby and Nakken*, 2008; *Edwards et al.*, 2010; *Poloczanska et al.*, 2013]. Meta-analysis of 288 long-term datasets (spanning up to 90 years) of zooplankton, benthic invertebrates, fish, and seabirds from the OSPAR Commission Maritime Area in the North-east Atlantic showed widespread changes in distribution, abundance, and seasonality that were consistent (77%) with expectations from enhanced greenhouse warming [*Tasker*, 2008]. The study bought together evidence of changes in ocean climate and ecological responses across a range of species that encompassed both exploited and unexploited species from a variety of information types including peer-reviewed reports from International Council for the Exploration of the Sea (ICES) Working Groups. In particular, observations indicated poleward shifts in zooplankton communities, increasing abundance of fish species in the northern part of their ranges and decreases in southern parts, and the expansion of benthic species into more northerly or less coastal areas (*high confidence*).

The major portion of the literature on the influence of climate change on the North Atlantic region covers time spans that are longer than for most other sub-regions of the Ocean. Even here, however, the bulk of the literature is limited to the last 30–50 years. The few publications covering the first half of the 20th Century represent an important longer-term perspective on the influence of climate change [*Toresen and Østvedt*, 2000; *Drinkwater*, 2006; *Sundby and Nakken*, 2008; *Bañón*, 2009; *Astthorsson et al.*, 2012]. For example, distinct changes in fauna were associated with a pronounced warming period over 1920–1940 [*Wood and Overland*, 2010], when fish and other fauna shifted northward [*Iversen*, 1934; *Southward et al.*, 2005; *Drinkwater*, 2006; *Hátún et al.*, 2009]. The major lesson from these reports is that a rapid large-scale temperature increase occurred in the high latitude North Atlantic between the 1920s and 1940s, with basin-scale consequences for marine ecosystems that are comparable to warming and observed impacts over the last 30 years. The former event was of great concern within the scientific community, particularly during the late 1940s and early 1950s [*Iversen*, 1934; *Tåning*, 1949; *Tåning*, 1953; *Southward*, 1980]. However, with the subsequent long-term cooling in the 1970s, discussion around climate responses was discontinued [*Southward*, 1980]. The centennial-long perspective indicates that multi-decadal variability has played a major role in changes observed over the past 30 years. The 150-yr instrumental record shows distinct warm phases of the Atlantic Multidecadal Oscillation (AMO) during approximately 1930–1965 and from 1995, and cool phases between approximately 1900–1930 and 1960–1995 (WGI 14.7.6). However, it is *virtually certain* that the enhanced warming in recent decades cannot be explained without external forcing (WGI 10.3.1.1.3). Understanding the changes in interdecadal variability over the next century is particularly important. The current warm phase of the AMO is *likely* to terminate in the next few decades, leading to a cooling influence in the North Atlantic and potentially offsetting some of the effects of global warming (WGI 14.7.6, 11.3.2.4.1). Over the transition period, the climate of the North Atlantic is *likely* to change more rapidly than during previous transitions since 1900.

30.5.1.1.2. North Pacific

Sub-decadal variability in the North Pacific HLSBS is dominated by ENSO ([*Trenberth*, 1990]; WGI 14.4). Unlike the North Atlantic HLSBS, the North Pacific HLSBS does not show any significant trends in temperature over time, *very likely* as a consequence of climate variability influences on long-term warming patterns (1950–2009; Table 30-1). Decadal and longer periods of variability in the North Pacific are reflected in the principal mode, the Pacific Decadal Oscillation (PDO; WGI 14.7.3), with periodicities in SST of both 15–25 y and 50–70 y [*Minobe*, 1997; *Mantua and Hare*, 2002]. Further modes of climate variability include the North Pacific Gyre Oscillation (NPGO; [*Di Lorenzo et al.*, 2008; *Chhak et al.*, 2009]. The PDO exhibits SST anomalies of one sign along the eastern boundary and the opposite sign in western and central Pacific. The PDO has been reported to have an anthropogenic component [*Bonfils and Santer,* 2011] but confidence in this is *very low* (*limited evidence, low agreement*) (WGI 10.3.3). The interplay of the phases of these modes of variability has strong influence on high latitude Pacific ecosystems (*very high confidence*). In the space of three years, the eastern North Pacific fluctuated from one of the warmest years in the past century (2005) to one of the coldest (2008) [*McKinnell et al.*, 2010; *McKinnell and Dagg*, 2010]. This rapid change was accompanied by large changes in primary productivity, zooplankton communities, and fish and seabird populations [*McKinnell et al.*, 2010; *McKinnell and Dagg*, 2010; *Batten and Walne*, 2011; *Bi et al.*, 2011; *Keister et al.*, 2011].

Climate transitions among phases of variability tend to be characterized by abrupt reorganization of the ecosystems as dynamic trophic relationships among species alter [*Hunt et al.*, 2002; *Peterson and Schwing*, 2003; *Litzow and Ciannelli*, 2007; *Litzow et al.*, 2008; *Alheit*, 2009]. Periods of broad-scale environmental change were observed across high latitude ecosystems in the North Pacific HLSBS (eastern Bering Sea and Gulf of Alaska) during 1976–78, 1987–89 and 1998–99. These periods were associated with regime shifts in foraging fish that occurred in 1979–82, 1988–92 and 1998–2001. The changes indicate how basin-scale variability such as the PDO can manifest across distinct ecosystems [*Overland et al.*, 2008; *Link et al.*, 2009a; *Link et al.*, 2009b]. Phenological shifts observed in the zooplankton communities of the North Pacific were *very likely* in response to decadal climate variability, with distinct changes noted after the climate shifts of the 1970s and 1990s [*Mackas et al.*, 1998; *Peterson and Schwing*, 2003; *Chiba et al.*, 2006]. Modeling evidence suggests a weak shift in PDO towards more occurrences of the negative phase but credibility of projections remains uncertain (WGI 14.7.3). It is *about as likely as not* that the PDO will change its form or behavior in the future (WGI 14.7.3).

The Kuroshio-Oyashio Extension (KOE) in the North-west Pacific displays pronounced decadal-scale variability [*Yatsu et al.*, 2008; *Sugisaki et al.*, 2010]. 'Warm periods' in the mid-1970s and late-1980s were accompanied by dramatic changes in pelagic ecosystems and sardine and anchovy stocks [*Chiba et al.*, 2008; *Yatsu et al.*, 2008]. Observations and climate model simulations indicate that global warming is *likely* to further alter the dynamics of the Kuroshio Current and the KOE over the coming century [*McPhaden and Zhang*, 2002; *Sakamoto et al.*, 2005; *Wu et al.*, 2012; *Zhang et al.*, 2013]. Alteration of the KOE will alter the timing, magnitude, and structure of spring blooms in the western Pacific and have implications for pelagic fish recruitment, production, and biogeochemical cycles [*Ito et al.*, 2004; *Hashioka et al.*, 2009; *Yatsu et al.*, 2013].

Commercial catches of salmon species in the North Pacific HLSBS follow decadal fluctuations in climate [*Hare and Mantua*, 2000; *Mantua and Hare*, 2002]. Catches peaked in the warm periods of the 1930s–1940s and 1990s–2000s, with 2009 yielding the highest catch to date, and warming trends are *about as likely as not* to have contributed to recent peaks in some sub-regions [*Morita et al.*, 2006; *Irvine and Fukuwaka*, 2011]. Poleward range shifts of some large pelagic fish in the western North Pacific, such as yellowtail *Seriola quinqueradiata* and Spanish mackerel *Scomberomorus niphonius*, were attributed, in part, to regional warming (*high confidence*) and these two species are projected to shift 39–71 km poleward from the 2000s to 2030s under SRES A1B [*Tian et al.*, 2012; *Jung et al.*, 2013]. Anticipating ecological responses to future anthropogenic climate change also requires evaluation of the role of changes to climate beyond warming *per se*. For example, declining sea level pressure (SLP) in the North Pacific is *likely* influenced by anthropogenic forcing [*Gillett et al.*, 2003; *Gillett and Stott*, 2009] (WGI 10.3.3.4) and SLP in turn is related to atmospheric climate parameters (e.g., turbulent mixing via wind stress) that regulate commercially significant fish populations [*Wilderbuer et al.*, 2002].

The northern fringe of the Bering Sea is among the most productive of marine sub-regions and includes the world's largest single-species fishery, walleye pollock *Theragra chalcogramma* [*Hunt et al.*, 2010]. This region underwent major changes in recent decades as a result of climate variability, climate change, and fishing impacts ([*Litzow et al.*, 2008; *Mueter and Litzow*, 2008; *Jin et al.*, 2009; *Hunt et al.*, 2010]; 28.2.2.1). Seasonal sea ice cover declined since the 1990s (to 2006), although there is no linear trend between 1953 and 2006, and the initiation of spring ice retreat over the south-eastern Bering Sea shelf became earlier [*Wang et al.*, 2007a; *Wang et al.*, 2007b]. Concurrent with the retreat of the 'cold pool', an area of reduced water temperature (<2°C) on the northern Bering Sea shelf that is formed as a consequence of sea ice and is maintained over summer [*Hunt et al.*, 2010], bottom trawl surveys of fish and invertebrates show a significant community-wide northward distribution shift and a colonization of the former cold pool areas by sub-arctic fauna (*high confidence*) [*Wang et al.*, 2006a; *Mueter and Litzow*, 2008].

Over a vast region of the eastern Pacific stretching from southern Chile to the Aleutian Islands, waters low in dissolved O_2 (Oxygen Minimum Zone, OMZ) are found at 300 m depth [*Karstensen et al.*, 2008]. Sporadic upwelling of these low-O_2 waters along the continental shelf is well documented, where biological respiration can further reduce dissolved O_2 levels and result in hypoxic or anoxic conditions that lead to mortality of coastal fishes and invertebrates [*Grantham et al.*, 2004; *Chan et al.*, 2008]. The magnitude and severity of seasonal hypoxic conditions in shallow-shelf waters of the eastern North Pacific HLSBS increased in recent decades [*Bograd et al.*, 2008; *Chan et al.*, 2008]. In addition, minimum pH values in the water column usually occur near the depths of the OMZ (WGI Box 3.2). A shoaling of the aragonite saturation horizon has *likely* resulted in low-aragonite conditions within the density layers being upwelled on the shelf of the west coast of the USA, increasing the risk of seasonally-upwelled water being relatively acidified [*Feely et al.*, 2008] with observed impacts on Pacific oyster (*Crassostrea gigas*) hatcheries [*Barton et al.*, 2012]. In the time period 1991–2006, reductions in pH in the North Pacific between 800 m and ~100 m were attributed in approximately equal measure to anthropogenic and natural variations ([*Byrne et al.*, 2010]; WGI 3.8.2, Figure 3.19).

30.5.1.1.3. Southern Hemisphere

The seasonal peaks in phytoplankton productivity in the southern hemisphere are much less pronounced and of smaller magnitude than those at northern hemisphere high latitudes [*Yoder et al.*, 1993]. The southern hemisphere HLSBS is broadly bounded by the sub-tropical front (STF) and the sub-Antarctic front. Associated with the STF is intense biological activity of bloom-forming coccolithophores (phytoplankton) [*Brown and Yoder*, 1994]. The calcifying plankton assemblages play a key role in carbon cycles in the region and the transport of carbon to deep ocean sediments. The coccolithophore *Emiliania huxleyi* extended its range south of 60° in the South-west Pacific (141–145°E) over the two decades since 1983 [*Cubillos et al.*, 2007]. Although the drivers for this range extension are not clear, it was proposed that the extension is facilitated by surface warming or changes in the abundance of grazing zooplankton.

Large regions of the sub-Antarctic and Arctic surface waters are *likely* to become undersaturated with respect to aragonite during winter by 2030, which will impact calcifying plankton and Southern Ocean ecosystems ([*McNeil and Matear*, 2008; *Bednaršek et al.*, 2012]; 28.2.2.2). Shell weights of the modern foraminifer *Globigerina bulloides* in the sediments of the sub-Antarctic region of the HLSBS south of Australia were observed to be 30–35% lower than those from sediment cores representing pre-industrial periods, consistent with a recent decline in pH [*Moy et al.*, 2009]. Examination of the pteropod *Limacina helicina antarctica* captured from polar waters further south, show severe levels of shell dissolution consistent with the shoaling of the aragonite saturation horizon and indicate that the impact of ocean acidification is already occurring [*Bednaršek et al.*, 2012].

While the South Pacific HLSBS has not shown warming overall, both the warmest and coolest months show a slight, but significant, increase over time (both 0.05°C decade^{-1} from 1950–2009, p-value $\leq$ 0.05, Table 30-1), although some areas within this sub-region have warmed. For example, the western Tasman Sea has shown enhanced warming since 1900 as compared to average global trends (*high confidence*). This has been driven by changes in large-scale wind-forcing leading to a southward expansion of the South Pacific STG and intensification of the southward-flowing East Australian Current (EAC; [*Cai*, 2006; *Hill et al.*, 2008; *Wu et al.*, 2012]; WG1 3.6.2). Model simulations suggest both stratospheric ozone depletion and greenhouse forcing contribute to the observed trend in wind stress [*Cai and Cowan*, 2007]. Coinciding with this warming and intensified EAC is the observation that a number of benthic invertebrates, fish, and zooplankton are now found further south than they were in the mid-20th Century [*Ling*, 2008; *Pitt et al.*, 2010; *Last et al.*, 2011]. Warming facilitated the establishment of the grazing urchin *Centrostephanus rodgersii* in eastern Tasmania during the late 1970s (*high confidence*), which has resulted in deleterious effects on macroalgal beds [*Ling*, 2008; *Ling et al.*, 2008; *Ling et al.*, 2009; *Banks et al.*, 2010].

30.5.1.2. Key Risks and Vulnerabilities

Projected changes to the temperature of surface waters match those of the past 50 years, with average sea temperatures in the HLSBS regions projected to increase by 0.35–1.17°C in the near-term (2010–2039) and by 1.70–4.84°C over the long-term (2010–2099) under the 'Business as usual' (BAU) RCP8.5 scenario (Table SM30-4). Under the lower-case scenario considered here (RCP2.6), projected rates of regional warming are much lower (0.12-0.79°C) in the near-term, with slight cooling for some regions in the long-term (-0.16–1.46°C). Risks to HLSBS from warming of surface waters include changes to primary production and carbon cycling, and the reorganization of ecosystems in response to warmer and more acidified oceans. Both primary production and the timing of the spring bloom in HLSBS are very sensitive to environmental change. Latitudinal shifts in the distribution of phyto- and zooplankton communities will alter seasonality, community composition, and bloom dynamics [*Beaugrand*, 2009; *Ito et al.*, 2010; *Shoji et al.*, 2011]. Alteration of the structure and composition of plankton communities can propagate through high latitude food webs due to tight trophic linkages [*Edwards and Richardson*, 2004; *Beaugrand et al.*, 2010; *Beaugrand and Kirby*, 2010]. Mechanisms are complex, and tend to be non-linear, with impacts on ecosystems, fisheries, and biogeochemical cycles being hard to project with any certainty (Box CC-PP). A reorganization of commercial fish stocks, with attendant social and economic disruption, is a key risk of ongoing climate change in HLSBS sub-regions. AR4 reported that the productivity of some marine fisheries is *likely* to increase in the North Atlantic (AR4 WGII 10.4.1, 12.4.7). A large number of publications since then has substantially extended such documentation and begun to elucidate the nuances in how marine ecosystems and organisms respond [*Sumaila et al.*, 2011].

An additional risk exists for sub-polar areas from the loss of seasonal sea ice. Decreases in seasonal sea ice are *very likely* to lead to increases in the length of the growth season and the intensity of the light available to fuel phytoplankton growth and, hence, enhance primary production and attending modifications of ecosystem structure [*Arrigo et al.*, 2008]. In the long-term, however, primary production may decrease due to the reduced supply of nutrients to the surface layers (Box CC-PP). The decline in Arctic sea ice will open ecological dispersal pathways, as well as new shipping routes (30.6.2.3), between the North Atlantic and the North Pacific; large numbers of the Pacific diatom *Neodenticula seminae* were found in the North Atlantic in 1999 [*Reid et al.*, 2007].

HLSBS are also vulnerable to rapid changes in the carbonate chemistry of ocean waters. Ocean acidification will produce additional and large-scale challenges. There is *medium agreement* that calcifying organisms in these regions will be negatively affected by ocean acidification with substantial impacts on higher trophic levels, although there is *limited evidence* at this point.

30.5.2. Equatorial Upwelling Systems

The largest upwelling systems are found in the equatorial regions of the eastern Pacific and Atlantic Oceans (Figure 30-1a). Equatorial Upwelling Systems (EUS) produce highly productive 'cold tongues' that stretch westward across equatorial areas, which is different to other upwelling systems (e.g., EBUE; 30.5.5). The associated upwelling is a consequence of the Earth's rotation and easterly (westward) winds and currents, which drive water northwards and southwards at the northern and southern edges of these sub-regions. As result, cold, nutrient-rich, and high CO_2/low pH waters are transported from the deeper layers of the Ocean to the surface, driving high levels of primary productivity that support 4.7% of total global fisheries productivity (Table SM30-1, Figure 30-1b). Interannual modes of variability (e.g., ENSO; WGI 14.4) dominate EUS, particularly in the Pacific [*Barber et al.*, 1994; *McCarthy et al.*, 1996; *Signorini et al.*, 1999; *Le Borgne et al.*, 2002; *Christian and Murtugudde*, 2003; *Mestas-Nuñez and Miller*, 2006; *Pennington et al.*, 2006; *Wang et al.*, 2006b]. Upwelling of the Pacific EUS declines during El Niño events, when the trade winds weaken, or even reverse, and is strengthened during La Niña events. ENSO periodicity controls primary productivity and consequently has a strong influence over associated fisheries production [*Mestas-Nuñez and Miller*, 2006]. The Intertropical Convergence Zone (ITCZ; WGI 14.3.1.1), an important determinant of regional ocean temperature, is located at the edges of the Indian and Pacific equatorial upwelling zone and influences a range of variables including productivity, fisheries, and precipitation. The EUS are also affected by interdecadal variability (e.g., Interdecadal Pacific Oscillation (IPO); [*Power et al.*, 1999]; WGI 11.2.2, 14.3).

30.5.2.1. Observed Changes and Potential Impacts

The average sea temperature associated with the EUS has increased significantly (p-value$\leq$0.05) by 0.43°C and 0.54°C from 1950–2009 in the Pacific and Atlantic EUS, respectively [Table 30-1). In the Pacific, regional variability in SST trends is driven by the temporal patterns in El Niño-Southern Oscillation and the more frequent El Niño Modoki or Central Pacific El Niño events in recent decades (*high confidence*) ([*Ashok et al.*, 2007; *Yu and Kao*, 2007; *Lee and McPhaden*, 2010]; WGI 14.2.4.4). The faster warming of the Atlantic EUS is *likely* to be associated with a weakening of upwelling [*Tokinaga and Xie*, 2011]. Sea level rise in the eastern equatorial Pacific has been decreasing by up to –10 mm yr^{-1} since 1993 ([*Church et al.*, 2006]; Figure 30-5).
Coral reefs in the EUS of the eastern Pacific (e.g., Galápagos and Cocos islands) have relatively low species diversity and poorly developed carbonate reef frameworks, due to the low pH and aragonite saturation of upwelling waters (*high confidence*) [*Glynn*, 2001; *Manzello et al.*, 2008; *Manzello*, 2010]. Prolonged periods of elevated temperature associated with El Niño have negatively affected corals, kelps and associated organisms, and induced several possible local extinctions (*high confidence*) [*Glynn*, 2011]. Since 1985, coral reefs from west of South America to the Gilbert Islands of Kiribati have experienced the highest levels of thermal stress relative to other areas [*Donner et al.*, 2010]. In 1982/1983, mass coral bleaching and mortality affected most of the reef systems within the eastern equatorial Pacific [*Glynn*, 1984; *Baker et al.*, 2008]. Subsequent canonical El Niño and Central Pacific El Niño events in 1997/8, 2002/3, 2004/5, and 2009/10 (WGI 14.4.2, Figure 14.13) triggered mass coral bleaching by adding to the background increases in sea temperatures (*high confidence*) [*Donner et al.*, 2010; *Obura and Mangubhai*, 2011; *Vargas-Ángel et al.*, 2011]. In some locations, impacts of El Niño have also interacted with other anthropogenic changes, such as those arising from changes to fishing pressure [*Edgar et al.*, 2010], further complicating the attribution of recent ecological changes to climate change.

30.5.2.2. Key Risks and Vulnerabilities

Climate models indicate that ENSO is *virtually certain* to continue to be a major driver of oceanic variability over the coming century, although not all models can accurately replicate its behavior (WGI 9.5.3). Superposition of a warming ocean on future ENSO activity (possibly modified in frequency and intensity) is *likely* to result in oceanic conditions that are different from those experienced during past El Niño and La Niña events [*Power and Smith*, 2007]. Temperatures within EUS sub-regions are projected to continue to warm significantly (p-value$\leq$0.05). Under RCP8.5, SST of the Atlantic EUS is projected to increase by 0.81°C over 2010–2039 and 2.56°C over 2010–2099, with similar increases projected for the Pacific EUS (Table SM30-4). Differences between RCPs for the two EUS become clear beyond mid-century, with warming of SST over 2010–2099 being 0.43°C and 0.46°C under RCP2.6 and 3.01°C and 3.03°C under RCP8.5, for Pacific and Atlantic EUS respectively (Table SM30-4). These projected increases in sea temperature will increase heat stress and ultimately irreversibly degrade marine ecosystems such as coral reefs (*very likely*). Further increases in atmospheric CO_2 will cause additional decrease in pH and aragonite saturation of surface waters (adding to the low pH and aragonite saturation of upwelling conditions), with significant differences between emission trajectories by the middle of the century. These changes in ocean carbonate chemistry are *very likely* to negatively affecting some marine calcifiers, although many of the species from this region are adapted to the low aragonite and calcite saturation states that result from equatorial upwelling, albeit with much lower rates of calcification [*Manzello*, 2010; *Friedrich et al.*, 2012]. A substantial risk exists with respect to the synergistic interactions between sea temperature and declining pH, especially as to how they influence a large number of key biological processes (Box CC-OA).

There is *low confidence* in the current understanding of how (or if) climate change will influence the behavior of ENSO and other long-term climate patterns ([*Collins et al.*, 2010]; WGI 12.4.4.2). There is also *low agreement* between different CMIP5 GCMs on how ocean warming will affect ENSO, with no significant change to ENSO amplitude in half the models examined, and both increasing and decreasing activity in others [*Guilyardi et al.*, 2012]. These differences appear to be a consequence of the delicate balance within ENSO between dampening and amplifying feedbacks, and the different emphasis given to these processes within the different GCMs [*Collins et al.*, 2010]. Other studies have looked at the interaction between the STG and EUS, and warming of surface waters in the Pacific, with at least one study projecting the possible expansion of the STG at the expense of the EUS [*Polovina et al.*, 2011]. In the latter case, the area of equatorial upwelling within the North Pacific would decrease by 28%, and primary production and fish catch by 15%, by 2100. Many of the projected changes imply additional consequences for pelagic fisheries due to the migration of fish stocks deriving from changing distribution of particular sea temperatures [*Lehodey et al.*, 2006; *Lehodey et al.*, 2008; *Cheung et al.*, 2010; *Lehodey et al.*, 2011; *Sumaila et al.*, 2011; *Bell et al.*, 2013b]. These projections suggest that fisheries within EUS will experience increased vulnerability due to elevated variability in space and time as a result of climate change (*low confidence*).

30.5.3. Semi-Enclosed Seas

Semi-Enclosed Seas (SES) represent a subset of ocean sub-regions that are largely land-locked and consequently heavily influenced by surrounding landscapes and climates [*Healy and Harada*, 1991]. In most cases, they support small but regionally significant fisheries (3.3% of global production; Table SM30-1, Figure 30-1b) and opportunities for other industries such as tourism. Five SES (all over 200,000 km² with single entrances ≤120 km wide) are considered here. This particular geography results in reduced circulation and exchange with ocean waters, and jurisdictions for these water bodies are shared by two or more neighboring states. In many cases, the small volume and disconnected nature of SES (relative to coastal and oceanic environments) makes them highly vulnerable to both local and global stressors, especially with respect to the much reduced options for the migration of organisms as conditions change.

30.5.3.1. Observed Changes and Potential Impacts

30.5.3.1.1. Arabian Gulf

The Arabian Gulf (also referred to as the Persian Gulf), along with Red Sea, is the world's warmest sea, with both extreme negative and positive temperature excursions (annual temperature range of 12–35°C). Like other SES, the Arabian Gulf is particularly vulnerable to changing environmental conditions as a result of its landlocked nature. Trends in SST were not significant over the period 1950–2009 (Table 30-1), which is probably due to long-term variability, and a consequence of regional and abrupt changes that occurred in the late 1980s [*Conversi et al.*, 2010]. In keeping with this, recent (1985–2002) localized analyses (e.g., Kuwait Bay) show strong and significant warming trends (based in this case on AVHRR (NOAA) satellite data) of 0.6°C $decade^{-1}$ [*Al-Rashidi et al.*, 2009]. There is *limited evidence* and *low agreement* as to how this variability influences marine ecosystems and human activities within the Arabian Gulf, although impacts on some ecosystem components (e.g., coral reefs) have been defined to some extent. The mass coral bleaching and mortality that occurred in 1996 and 1998 were a direct result of the sensitivity of reef-building corals to elevated sea temperatures (*high confidence*) ([*Riegl*, 2002; 2003]; Box CC-CR). These changes to coral reefs have resulted in a loss of fish species that feed on coral-associated invertebrates while herbivores and planktivorous fish abundances have increased (*medium confidence*) [*Riegl*, 2002]. Despite coral ecosystems in this sub-region being adapted to some of the highest temperatures in shallow seas on earth, anthropogenic climate change is driving higher frequencies and intensities of mass coral bleaching and mortality [*Riegl et al.*, 2011]. Other biological changes (e.g., harmful algal blooms and fish kills, [*Heil et al.*, 2001]) have been associated with the increasing sea temperatures of the Arabian Gulf, although attribution to increasing temperatures as opposed to other factors (e.g., water quality) is limited [*Bauman et al.*, 2010].

30.5.3.1.2. Red Sea

Few studies have focused on attributing recent changes in the Red Sea ecosystems to climate change (including ocean acidification). The Red Sea warmed by 0.74°C from 1982–2006 [*Belkin*, 2009], although trends in the average SST, however, are not significant from 1950–2009 (p-value>0.05, Table 30-1) due to a high degree of variability when longer periods were examined (supplementary material in [*Belkin*, 2009]). The temperature of the warmest month of the year, however, showed a significant increase over the 60-year period (0.05°C decade^{-1}; Table 30-1). Regional trends within the Red Sea may also differ, with at least one other study reporting higher rates of warming for the central Red Sea (1.46°C, relative to 1950–1997 NOAA Extended Reconstructed SST (ERSST) v3b climatology [*Cantin et al.*, 2010]).

Long-term monitoring of coral community structure and size over 20 years shows that average colony size of corals has declined (*high confidence*) and species' latitudinal limits may have changed (*medium confidence*). The decline in average colony size is ascribed to heat-mediated bleaching as well as increases in coral diseases and Crown of Thorns Starfish (*Acanthaster* sp.) predation [*Riegl et al.*, 2012]. The patterns of this decline correlate well with the pattern of recent heating in the Red Sea [*Raitsos et al.*, 2011] with the biggest changes being seen in the southern part of the Red Sea. Skeletal growth of the long-lived massive coral *Diploastrea heliopora* has declined significantly, *very likely* due to warming temperatures (*medium confidence*) (p-value≤0.05; [*Cantin et al.*, 2010].

Cantin et al. [2010] proposed that the massive coral *Diploastrea helipora* will cease to grow in the central Red Sea by 2070 under SRES A1B and A2 (*medium confidence*), although this may not hold for other coral species. For example, an increase in linear extension of *Porites* corals, beginning in the 1980s, was recorded in the northern Red Sea [*Heiss*, 1996], where temperatures have increased by 0.74ºC from 1982-2006 [*Belkin*, 2009] suggesting that these corals were living in sub-optimal conditions (cooler waters). They may therefore benefit from elevated temperature before reaching their thermal threshold, at which point growth rates would be predicted to decline, as they are doing in other oceans. *Riegl and Piller* [2003] concluded that coral habitats at moderate depths in the Red Sea might provide important refugia from some aspects of climate change in the future (*limited evidence*). *Silverman et al.* [2007] quantified the sensitivity of net coral reef ecosystem calcification to changes in carbonate chemistry (pH, aragonite saturation). Their results demonstrate a strong negative effect of ocean acidification on ecosystem-scale calcification and decalcification, and show that small changes in carbonate dissolution could have large-scale implications for the long-term persistence of carbonate coral reef systems within the Red Sea [*Silverman et al.*, 2007; *Silverman et al.*, 2009].

30.5.3.1.3. Black Sea

The temperature of the surface waters of the Black Sea increased by 0.96ºC from 1982–2006 [*Belkin*, 2009], which is consistent with other studies (*high confidence*) [*Buongiorno Nardelli et al.*, 2010; *Bozkurt and Sen*, 2011]. As with other SES (i.e., Arabian Gulf and Baltic, Mediterranean, and Red Seas), longer data sets do not reveal a significant trend due to large-scale variability prior to 1982, which may be due to the influence of AMO, NAO, and other long-term sources of variability (Table 30-1; supplementary material in *Belkin, 2009*). *Buongiorno Nardelli et al.* [2010] observed that short-term SST variability (week-month) is strongly influenced by interactions with the overlying atmosphere, which itself is strongly influenced by the surrounding land temperatures. As with the Mediterranean and Red Seas, however, a significant upward trend in the temperature is recorded in the warmest month of the year over the period 1950–2009 (Table 30-1). Freshwater discharge from rivers draining into the Black Sea has remained more or less constant since the early 1960s [*Ludwig et al.*, 2009]. Increasing water temperature has steadily eliminated the Cold Intermediate Layer (CIL; temperatures below 8°C) throughout the Black Sea basin over 1991–2003 (*high confidence*)[*Oguz et al.*, 2003]. Reduced water column mixing and upwelling during warmer winter periods has reduced the supply of nutrients to the upper layers of the Black Sea [*Oguz et al.*, 2003] and expanded areas of low O_2 in the deeper parts of the Black Sea, which is the world's largest anoxic marine basin (*high confidence*) [*Murray et al.*, 1989]. These changes coincided with the collapse of fish stocks and the invasion by the ctenophore *Mnemiopsis leidyi* in the 1980s [*Oguz et al.*, 2008], while inputs of nutrients such as phosphate from the Danube River decreased strongly since 1992–1993 [*Oguz and Velikova*, 2010]. Environmental perturbations explain the declining levels of primary productivity, phytoplankton, bacterioplankton, and fish stocks in the Black Sea from the mid-1990s [*Yunev et al.*, 2007; *Oguz and Velikova*, 2010]. The Black Sea system is very dynamic and is strongly affected by non-climate stressors in addition to climate change, making attribution of detected trends to climate change difficult.

30.5.3.1.4. Baltic Sea

Temperatures in the highly dynamic Baltic Sea increased substantially since the early 1980s [*Aleksandrov et al.*, 2009; *Belkin*, 2009], with increases of 1.35°C (1982–2006) being among the highest for any SES [*Belkin*, 2009]. Increases of this magnitude are not seen in longer records throughout the Baltic Sea (1861–2001, [*MacKenzie et al.*, 2007; *MacKenzie and Schiedek*, 2007b; a]; 1900–1998, [*Madsen and Højerslev*, 2009]). The salinity of the surface and near bottom waters of the Baltic Sea (e.g., Gdansk Basin, [*Aleksandrov et al.*, 2009]; central Baltic [*Fonselius and Valderrama*, 2003; *Möllmann et al.*, 2003] decreased from 1975–2000, due to changing rainfall and river run-off, and a reduction in the pulses of sea water (vital for oxygenation and related chemical changes) from the North Sea through its opening via the Kattegat (*high confidence*) [*Samuelsson*, 1996; *Conley et al.*, 2009; *Hänninen and Vuorinen*, 2011]. There is a strong vertical zonation within the Baltic Sea in terms of the availability of O_2. The shallow sub-regions of the Baltic are relatively well oxygenated. However, O_2 levels are low in the deeper basins, producing conditions where organisms and ecosystems are exposed to prolonged hypoxia.

The annual biomass of phytoplankton has declined almost threefold in the Baltic Transition Zone (Kattegat, Belt Sea) and Western Baltic Sea since 1979 [*Henriksen*, 2009], reputedly due to changing nitrogen loads in the Danish Straits (*medium confidence)* in addition to increasing sea temperature (*very likely*) [*Madsen and Højerslev*, 2009]. Reduced phytoplankton production may have reduced the productivity of fisheries in the western Baltic Sea and the Transition Zone (*low to medium confidence*) [*Chassot et al.*, 2007]. Decreasing salinity in the Baltic deep basins may also affect zooplankton reproduction, especially that of the copepod *Pseudocalanus acuspes,* contributing to density-dependent decrease in growth of the commercially important herring and sprat stocks (*high confidence*) [*Möllmann et al.*, 2003; *Möllmann et al.*, 2005; *Casini et al.*, 2011]. The strong relationship between phytoplankton and fish production, and increasing sea temperature, decreasing salinity and other environmental factors, suggests that major changes in fisheries production will occur as sea temperatures increase and the hydrological cycle in the Baltic region changes (*high confidence*) [*MacKenzie et al.*, 2012]. A combination of climate change-induced oceanographic changes (i.e., decreased salinity and increased temperatures), eutrophication, and overfishing have resulted in major changes in trophic structure in the deep basins of the Baltic Sea [*Möllmann et al.*, 2009]. This had important implications for cod, a commercially important top-predator (*medium confidence*)[*Lindegren et al.*, 2010].

30.5.3.1.5. Mediterranean Sea

The Mediterranean Sea is strongly linked to the climates of North Africa and Central Europe. SST within the Mediterranean increased by 0.43℃ from 1957–2008 (supplementary material, *[Belkin, 2009]*), although analysis of data from 1950–2009 only detected a significant trend in summer temperature (0.11℃ decade^{-1}, p-value$\leq$0.05, Table 30-1) due to large fluctuations in SST prior to the 1980s. Surface temperatures increased in the Mediterranean Sea consistent with significant increases in SST at a number of monitoring sites (*high agreement*, *robust evidence*) (e.g.

[*Coma et al.*, 2009; *Conversi et al.*, 2010; *Calvo et al.*, 2011]). It is *likely* that temperatures, along with salinity, have also increased at depth (400 m or more) in the western Mediterranean Sea over the past 30-40 years which, when analyzed in the context of heat budget and water flux of the Mediterranean, is consistent with anthropogenic greenhouse warming [*Bethoux et al.*, 1990; *Rixen et al.*, 2005; *Vargas-Yáñez et al.*, 2010]. Large scale variability such as the AMO and NAO can obscure or accentuate the overall warming trend ([*Marullo et al.*, 2011]; WGI 14.5.1, 14.7.6). Relatively warm episodes in the 1870s, 1930–1970s and since the mid-1990s, for example, exhibit an influence of the AMO [*Kerr*, 2000; *Moron*, 2003]. Reported temperature anomalies in the Mediterranean, often locally manifesting themselves as periods of low wind, increased water column stratification, and a deepening thermocline, are associated with positive phases of the NAO index [*Molinero et al.*, 2005; *Lejeusne et al.*, 2010].

Sea levels have increased rapidly in some areas over recent decades and are also strongly influenced by NAO phases. The rate has been approximately 3.4 mm yr^{-1} (1990–2009) in the North-west Mediterranean (*high confidence*) [*Calvo et al.*, 2011]. These influences are reduced when measurements are pooled over longer time-scales, resulting in a lower rate of sea level rise [*Massuti et al.*, 2008]. If the positive phase of the NAO is more frequent in the future ([*Terray et al.*, 2004; *Kuzmina et al.*, 2005]; WGI 14.4.2), then future sea level rise may be slightly suppressed due to atmospheric influences (*medium confidence*) [*Jordà et al.*, 2012]. As temperatures have increased, the Mediterranean has become more saline (+0.035–0.040 psu from 1950–2000, [*Rixen et al.*, 2005]) and the length of the thermal stratification period persisted twice as long in 2006 as it did in 1974 [*Coma et al.*, 2009].

Conditions within the Mediterranean Sea changed abruptly and synchronously with similar changes across the North, Baltic, and Black Seas in the late 1980s [*Conversi et al.*, 2010], which possibly explains the lack of trend in SES SST when examined from 1950–2009 (Table 30-1). These changes in physical conditions (increased temperature, higher sea level pressure, positive NAO index) also coincided with step-changes in the diversity and abundance of zooplankton, decreases in stock abundance of anchovies, decreases in the frequency of “red tides”, and increases in mucilage outbreaks [*Conversi et al.*, 2010]. Mucilage outbreaks are strongly associated with warmer and more stratified water columns (*high confidence*), and lead to a greater abundance and diversity of marine microbes and potentially disease-causing organisms (*likely*) [*Danovaro et al.*, 2009]. Increasing temperatures are also driving the northward spread of warm-water species (*medium confidence*) such as the sardine *Sardinella aurita* [*Sabatés et al.*, 2006; *Tsikliras*, 2008], and have contributed to the fast spread of the invading Atlantic coral *Oculina patagonia* [*Serrano et al.*, 2013]. The recent spread of warm-water species that have invaded through the Straits of Gibraltar and the Suez Canal into cooler northern areas is leading to the ‘tropicalisation’ of Mediterranean fauna (*high confidence*) [*Bianchi*, 2007; *Ben Rais Lasram and Mouillot*, 2008; *CIESM*, 2008; *Galil*, 2008; 2011]. Warming since the end of the 1990s has accelerated the spread of tropical invasive species from the eastern Mediterranean basin ([*Raitsos et al.*, 2010]; 23.6.5).

In addition to general patterns of warming, periods of extreme temperatures have had large-scale and negative consequences for Mediterranean marine ecosystems. Unprecedented mass mortality events, that affected at least 25 prominent invertebrate species, occurred during the summers of 1999, 2003, and 2006 across hundreds of kilometers of coastline in the North-west Mediterranean Sea (*very high confidence*) [*Cerrano et al.*, 2000; *Garrabou et al.*, 2009; *Calvo et al.*, 2011; *Crisci et al.*, 2011]. Events coincided with either short periods (2–5 days: 2003, 2006) of high sea temperatures (27°C) or longer periods (30–40 days) of modestly high temperatures (24°C: 1999; [*Bensoussan et al.*, 2010; *Crisci et al.*, 2011]). Impacts on marine organisms have been reported in response to the extreme conditions during these events (e.g., gorgonian coral mortality [*Coma et al.*, 2009], shoot mortality, and anomalous flowering of seagrasses (*high confidence*) [*Diaz-Almela et al.*, 2007; *Marbà and Duarte*, 2010]. The frequency and intensity of these types of heat stress events are expected to increase as sea temperatures increase (*high confidence*).

Longer-term data series (over several decades) of changes in relative acidity of the Mediterranean Sea are scarce [*Calvo et al.*, 2011; *MerMex-Group*, 2011]. Recent re-analysis, however, has concluded that the pH of Mediterranean waters has decreased by 0.05–0.14 pH units since the pre-industrial period (*medium confidence*) [*Luchetta et al.*, 2010; *Touratier and Goyet*, 2011]. Anthropogenic CO_2 has penetrated the entire Mediterranean water column, with the western basin being more contaminated than the eastern basin [*Touratier and Goyet*, 2011]. Studies that have explored the consequences of ocean acidification for the biology and ecology of the Mediterranean Sea are rare [*Martin and Gatusso*, 2009; *Rodolfo-Metalpa et al.*, 2010; *Movilla et al.*, 2012], although insights have been gained by studying natural CO_2 seeps at Mediterranean sites such as Ischia in Italy, where biodiversity decreases with decreasing pH towards the vents, with a notable decline in calcifiers. [*Hall-Spencer et al.*, 2008]. Transplants of corals, mollusks, and bryozoans along the acidification gradients around seeps reveal a low level of vulnerability to CO_2 levels expected over the next 100 years *(low confidence*) [*Rodolfo-Metalpa et al.*, 2010 ; *Rodolfo-Metalpa et al.*, 2011]. However, periods of high temperature can increase vulnerability to ocean acidification, thereby increasing the long-term risk posed to Mediterranean organisms and ecosystems as temperatures warm. Significantly, some organisms such as seagrasses and some macroalgae appeared to benefit from local ocean acidification [*Hall-Spencer et al.*, 2008].

30.5.3.2. Key Risks and Vulnerabilities

SES are highly vulnerable to changes in global temperature on account of their small volume and landlocked nature. Consequently, SES will respond faster than most other parts of the Ocean (*high confidence*). Risks to ecosystems within SES are *likely* to increase as water columns become further stratified under increased warming, promoting hypoxia at depth and reducing nutrient supply to the upper water column (*medium evidence*, *high agreement*). The impact of rising temperatures on SES is exacerbated by their vulnerability to other human influences such as overexploitation, pollution, and enhanced run-off from modified coastlines. Due to a mixture of global and local human stressors, key fisheries have undergone fundamental changes in their abundance and distribution over the past 50 years (*medium confidence*). A major risk exists for SES from projected increases in the frequency of temperature extremes that drive mass mortality events, increasing water column stabilization leading to reduced mixing, and changes to the distribution and abundance of marine organisms. The vulnerability of marine ecosystems, fisheries, and human communities associated with the SES will continue to increase as global temperatures increase.

Sea temperatures are *very likely* to increase in the five SES under moderate (RCP6.0) to high (RCP8.5) future scenarios. Under BAU (RCP8.5; Table SM30-3), sea temperatures in the SES are projected to increase by 0.93–1.24°C over 2010–2039 (Table SM30-4). Increases of 3.45–4.37°C are projected over 2010–2099, with the greatest increases projected for the surface waters of the Baltic Sea (4.37°C) and Arabian Gulf (4.26°C), and lower yet substantial amounts of warming in the Red Sea (3.45°C) (Table SM30-4). The heat content added to these small ocean regions is *very likely* to increase stratification, which will reduce the nutrient supply to the upper layers of the water column, reducing primary productivity and driving major changes to the structure and productivity of fisheries. Reduced mixing and ventilation, along with increased microbial metabolism, will *very likely* increase hypoxia and expand the number and extent of ‘dead zones’. Changing rainfall intensity (23.3, WGI 12.4.) can exert a strong influence on the physical and chemical conditions within SES, and in some cases will combine with other climatic changes to transform these areas. These changes are *likely* to increase the risk of reduced bottom-water O_2 levels to Baltic and Black Sea ecosystems (due to reduced solubility, increased stratification, and microbial respiration), which is *very likely* to affect fisheries. These changes will increase the frequency and intensity of impacts arising from heat stress, based on responses to temperature extremes seen over the past 30 years, such as the mass mortality of benthic organisms that occurred in the Mediterranean Sea during the summers of 1999, 2003, and 2006, and the Arabian Gulf in 1996 and 1998. Extreme temperature events such as heat waves are projected to increase (*high confidence*) (23.2, [*IPCC*, 2012]). Similar projections to those outlined in 30.5.4.2 can be applied to the coral reefs of the Arabian Gulf and the Red Sea, where temperatures are *very likely* to increase above established thresholds for mass coral bleaching and mortality (*very high confidence*) (Figure 30-10).

30.5.4. Coastal Boundary Systems

The Coastal Boundary Systems (CBS) are highly productive regions, comprising 10.6% of primary production and 28.0% of global fisheries production (Table SM30-1, Figure 30-1b). The CBS include the marginal seas of the North-west Pacific, Indian, and Atlantic Oceans, encompassing: the Bohai/Yellow Sea, East China Sea, South China Sea, and South-east Asian Seas (e.g., the Timor, Arafura, and Sulu Seas, and the northern coast of Australia) in the Pacific; the Arabian Sea, Somali Current system, East Africa coast, Mozambique Channel, and Madagascar in the Indian Ocean; and the Caribbean Sea and Gulf of Mexico in the Atlantic Ocean). Some CBS are dominated by powerful currents such as the Kuroshio (Pacific), or are strongly influenced by monsoons (e.g., Asian-Australian and African monsoons).

30.5.4.1. Observed Changes and Potential Impacts

Many ecosystems within the CBS are strongly affected by the local activities of often-dense coastal human populations. Activities such as the overexploitation of fisheries, unsustainable coastal development, and pollution have resulted in the wide-spread degradation of CBS ecosystems [*Burke et al.*, 2002; *Burke et al.*, 2011]. These influences have combined with steadily increasing ocean temperature and acidification to drive major changes to a range of important ecosystems over the past 50 years. Understanding the interactions between climate change and non-climate change drivers is a central part of the detection and attribution process within the CBS.

Overall, the CBS warmed by 0.14–0.80°C from 1950–2009 (Table 30-1), although changes within the Gulf of Mexico/Caribbean Sea sub-region were not significant (p-value>0.05) over this period. Key sub-regions within the CBS such as the Coral Triangle and Western Indian Ocean warmed by 0.79 and 0.60°C, respectively, from 1950–2009 (Table 30-1). Rates of sea level rise vary from decreasing sea levels (-5 to -10 mm yr^{-1}) to low (2–3 mm yr^{-1}, Caribbean) to very high (10 mm yr^{-1}, South-east Asia; Figure 30-5) rates of increase. Ocean acidification also varies from region to region (Figure SM30-2), and is influenced by oceanographic and coastal processes, which often have a large human component.

30.4.4.1.1. Bohai/Yellow Sea/East China Sea

The Bohai Sea, Yellow Sea and the East China Sea (ECS) are shallow marginal seas along the edge of the North-west Pacific that are strongly influenced by the Kuroshio Current [*Matsuno et al.*, 2009], the East Asian Monsoon (EAM), and major rivers such as the Yellow (Huang He) River and Yangtze (Changjiang) River. Upwelling of the Kuroshio sub-surface waters provides abundant nutrients that support high levels of primary productivity [*Wong et al.*, 2000; *Wong et al.*, 2001]. The ecosystems of the ECS are heavily affected by human activities (e.g., overfishing and pollution), which tend to compound the influence and consequences of climate change.

SST within the ECS has increased rapidly since the early 1980s (*high confidence*) [*Lin et al.*, 2005; *Jung*, 2008; *Cai et al.*, 2011; *Tian et al.*, 2012]. The largest increases in SST have occurred in the ECS in winter (1.96℃, 1955–2005) and in the Yellow Sea in summer (1.10℃, 1971–2006, [*Cai et al.*, 2011]). These changes in SST are closely linked to a weakening of the EAM (e.g., [*Cai et al.*, 2006; *Tang et al.*, 2009; *Cai et al.*, 2011]) and increasing warmth of the Kuroshio Current [*Qi et al.*, 2010; *Zhang et al.*, 2011; *Wu et al.*, 2012]. At the same time, dissolved O_2 has decreased [*Lin et al.*, 2005; *Jung*, 2008; *Qi et al.*, 2010], with an associated increase in the extent of the hypoxic areas in coastal areas of the Yellow Sea/ECS [*Jung*, 2008; *Tang*, 2009; *Ning et al.*, 2011].

Primary productivity, biomass yields, and fish capture rates have experienced large changes within the ECS over the past decades (*limited evidence*, *medium agreement*, *low confidence)* [*Tang et al.*, 2003; *Lin et al.*, 2005; *Tang*, 2009]. Fluctuations in herring abundance appear to closely track SST shifts within the Yellow Sea [*Tang*, 2009]. For plankton and fish species, the proportions of warm-water species relative to warm-temperate species in the Changjiang River Estuary (extending to the southern Taiwan Strait) have changed in past decades [*Zhang et al.*, 2005; *Ma et al.*, 2009; *Lin and Yang*, 2011]. Northward shifts in catch distribution for some pelagic fish species in Korean waters were driven, in part, by warming SST (*medium confidence*, [*Jung et al.*, 2013]. The frequency of harmful algal blooms (HAB) and blooms of the giant jellyfish *Nemopilema nomurai* in the offshore area of the ECS have increased and have been associated with ocean warming and other factors such as eutrophication [*Ye and Huang*, 2003; *Tang*, 2009; *Cai and Tan*, 2010]. While attribution of these changes to anthropogenic climate change is complicated by the increasing influence of non-climate related human activities, many of these changes are consistent with those expected as SST increases.

30.5.4.1.2. South China Sea

The South China Sea (SCS) is surrounded by continental areas and a large number of islands, and is connected to the Pacific, ECS, and Sulu Sea by straits such as the Luzon and Taiwan Strait. The region is greatly influenced by cyclones/typhoons, and by the Pearl, Red, and Mekong Rivers. The region has a distinct seasonal circulation and is greatly influenced by the southwest monsoon (in summer), the Kuroshio Current and northeast monsoon (in winter). The SCS includes significant commercial fisheries areas and includes coral reefs, mangroves, and seagrasses.

The surface waters of the SCS have been warming steadily from 1945–1999 with the annual mean SST in the central SCS increasing by 0.92℃ (1950–2006, [*Cai et al.*, 2009]), a rate similar to that observed for the entire Indo-Pacific/SE Asian CBS from 1950–2009 (0.80°C, Table 30-1). Significant freshening in the SCS intermediate layer since the 1960s has been observed [*Liu et al.*, 2007]. The temperature change of the upper layers of the SCS has made a significant contribution to sea level variation, which is spatially non-homogeneous and varies in time [*Li et al.*, 2002; *Cheng and Qi*, 2007; *Liu et al.*, 2007].

Identifying the extent to which climate change is influencing the SCS is difficult due to confounding non-climate change factors and their interactions (e.g., local human pollution, over-exploitation together with 'natural' climate variability such as EAM, ENSO, and PDO). Changing sea temperatures have influenced the abundance of phytoplankton, benthic biomass, cephalopod fisheries, and the size of demersal trawl catches in the northern SCS observed over the period 1976–2004 (*limited evidence, medium agreement*) [*Ning et al.*, 2009]. Coral reefs and mangroves are degrading rapidly as a result of both climate change and non-climate change related factors (*very likely*) (Box CC-CR, [*Chen et al.*, 2009; *China-SNAP*, 2011; *Zhao et al.*, 2012]). Mass coral bleaching and mortality of coral reefs within the SCS were triggered by elevated temperatures in 1998 and 2007 [*Yu et al.*, 2006; *Li et al.*, 2011]. Conversely, warming enabled the establishment of a high latitude, non-carbonate, coral community in Daya Bay in the northern SCS, although this community has recently degraded due to increasing anthropogenic stresses [*Chen et al.*, 2009; *Qiu et al.*, 2010].

30.5.4.1.3. South-east Asian Seas

The South-east Asian Seas (SAS) include an archipelago of diverse islands that interact with the westward flow of the North Equatorial Current and the Indonesian Throughflow (Figure 30-1a). A large part of this region is referred to as the 'Coral Triangle' [*Veron et al.*, 2009]. The world's most biologically diverse marine area, it includes parts of Malaysia, Indonesia, the Philippines, Timor Leste, the Solomon Islands, and Papua New Guinea. SST increased significantly from 1985–2006 [*Peñaflor et al.*, 2009; *McLeod et al.*, 2010], although with considerable spatial variation. Trends examined over longer periods (1950–2009) show significant warming (+0.80°C, p-value$\leq$0.05, Table 30-1). The sea level is rising by up to 10 mm yr^{-1} in much of this region [*Church et al.*, 2004; *Church et al.*, 2006; *Green et al.*, 2010]. Like other tropical areas in the world, coral reefs within SAS have experienced periods of elevated temperature, which has driven several mass coral bleaching and mortality events since the early 1980s (*high confidence*) [*Hoegh-Guldberg et al.*, 2009; *McLeod et al.*, 2010] (Figure 30-10a). The most recent occurred during warm conditions in 2010 [*Krishnan et al.*, 2011]. These changes are the result of increasing ocean temperatures and are *very likely* to be a consequence of anthropogenic climate change (*high confidence*) (Box CC-CR, WGI 10.4.1). Although calcification rates of some key organisms (e.g., reef-building corals; [*Tanzil et al.*, 2009]) have slowed over the past two decades, it is not possible to conclude that the changes are due to ocean acidification. While a large part of the decline in coral reefs has been due to increasing local stresses (principally destructive fishing, declining water quality, and overexploitation of key reef species), projected increases in SST represent a major challenge for these valuable ecosystems (*high agreement*) [*Burke et al.*, 2002; *Burke and Maidens*, 2004].

30.5.4.1.4. Arabian Sea and Somali Current

The Arabian Sea and Somali Current are relatively productive ocean areas, being strongly influenced by upwelling and the monsoonal system. Wind-generated upwelling enhances primary production in the western Arabian Sea

[*Prakash and Ramesh*, 2007]. Several key fisheries within this region are under escalating pressure from both fishing and climate change. Sea surface temperature increased by 0.18℃ and 0.26℃ in the Arabian Sea and Somali Current, respectively, from 1982–2006 (HadSST2, [*Rayner et al.*, 2003; *Belkin*, 2009]), which is consistent with the overall warming of the Western Indian Ocean portion of the CBS from 1950–2009 (0.60℃, Table 30-1). Salinity of surface waters in the Arabian Sea increased by 0.5–1.0% over the past 60 years (Figure 30-6c), due to increased evaporation from warming seas and contributions from the outflows of the saline Red Sea and Arabian Gulf. As in other tropical sub-regions, increasing sea temperatures have increased the frequency of mass coral bleaching and mortality within this region [*Wilkinson and Hodgson*, 1999; *Goreau et al.*, 2000; *Wilkinson*, 2004].

The aragonite saturation horizon in both the Arabian Sea and Bay of Bengal is now 100–200 m shallower than in pre-industrial times as a result of ocean acidification (*medium confidence*) [*Feely et al.*, 2004]. Shoaling of the aragonite saturation horizon is *likely* to affect a range of organisms and processes, such as the depth distribution of pteropods (zooplankton) in the western Arabian Sea (*medium confidence*) [*Hitchcock et al.*, 2002; *Mohan et al.*, 2006]. More than 50% of the area of oxygen minimum zones (OMZs) in the world's oceans occur in the Arabian Sea and Bay of Bengal and long-term measurements reveal that O_2 concentrations are declining in this region (*high confidence*) [*Helly and Levin*, 2004; *Karstensen et al.*, 2008; *Stramma et al.*, 2010] (30.3.2.3). The information regarding the consequences of climate change within this region is undeveloped and suggests that important physical, chemical, and biological responses to climate change need to be the focus of further investigation.

30.5.4.1.5. East Africa coast and Madagascar

The Western Indian Ocean strongly influences the coastal conditions associated with Kenya, Mozambique, Tanzania, Madagascar, La Réunion, Mayotte, and three archipelagos (Comoros, Mauritius, and the Seychelles). Sea temperatures in the Western Indian Ocean have increased by 0.60℃ over 1950–2009 (*high confidence*) (p-value$\leq$0.05; Table 30-1), increasing the frequency of positive thermal anomalies which have triggered mass coral bleaching and mortality events across the region over the past two decades (*high confidence*,[*Baker et al.*, 2008; *Nakamura et al.*, 2011](CC-HS). Trends in changes in SST and surface salinity vary with location along the East African coastline, with faster rates at higher latitudes (Figure 30-2). Periods of heat stress over the past 20 years have triggered mass coral bleaching and mortality on coral reef ecosystems within this region [*McClanahan et al.*, 2007; *McClanahan et al.*, 2009a; *McClanahan et al.*, 2009c; *McClanahan et al.*, 2009b; *Ateweberhan and McClanahan*, 2010; *Ateweberhan et al.*, 2011]. Steadily increasing sea temperatures have also produced anomalous growth rates in long-lived corals such as *Porites* (*high confidence*) [*McClanahan et al.*, 2009b]. Differences in the susceptibility of reef-building corals to stress from rising sea temperatures has also resulted in changes to the composition of coral (*high confidence*) (p-value$\leq$0.05; [*McClanahan et al.*, 2007]) and benthic fish communities (*high confidence*) (p-value$\leq$0.05; [*Graham et al.*, 2008; *Pratchett et al.*, 2011a]). These changes are *very likely* to alter species composition and potentially the productivity of coastal fisheries (*robust evidence, high agreement, high confidence*) [*Jury et al.*, 2010], although there may be a significant lag between the loss of coral communities and the subsequent changes in the abundance and community structure of fish (p-value$\leq$0.05, [*Graham et al.*, 2007]). Some of these potential changes can be adverted or reduced by interventions such as the establishment of marine protected areas and changes to fishing management [*McClanahan et al.*, 2008; *Cinner et al.*, 2009; *Jury et al.*, 2010; *MacNeil et al.*, 2010].

30.5.4.1.6. Gulf of Mexico and Caribbean Sea

The Gulf of Mexico and Caribbean Sea form a semi-contained maritime province within the Western Atlantic. These areas are dominated by a range of activities including mineral extraction, fishing, and tourism, which provide employment and opportunity for almost 75 million people who live in coastal areas of the US, Mexico, and a range of other Caribbean nations [*Adams et al.*, 2004]. The Gulf of Mexico and Caribbean Sea have warmed by 0.31°C and 0.50°C and respectively from 1982–2006 (*very likely*) [*Belkin*, 2009]. Warming trends are not significant from 1950–2009 (Table 30-1), which may be partly due to spatial variability in warming patterns (30.5.3.1). The Caribbean region has experienced a sustained decrease in aragonite saturation state from 1996–2006 (*very likely*)

[*Gledhill et al.*, 2008]. Sea levels within the Gulf of Mexico and Caribbean Sea have increased at the rate of 2–3 mm y^{-1} from 1950–2000 [*Church et al.*, 2004; *Zervas*, 2009].

Understanding influences of climate change on ocean ecosystems in this region is complicated by the confounding influence of growing human populations and activities. The recent expansion of the seasonal hypoxic zone, and the associated 'dead zone', in the Gulf of Mexico has been attributed to nitrogen inputs driven by land management [*Turner and Rabalais*, 1994; *Donner et al.*, 2004] and changes to river flows, wind patterns, and thermal stratification of Gulf waters (*high confidence*) [*Justić et al.*, 1996; *Justić et al.*, 2007; *Levin et al.*, 2009; *Rabalais et al.*, 2009; *Rabalais et al.*, 2010]. The increases in coastal pollution and fishing have potentially interacted with climate change to exacerbate impacts on marine ecosystems within this region (5.3.4, 29.3). These changes have often been abrupt and non-linear [*Taylor et al.*, 2012].

A combination of local and global disturbances has driven a large-scale loss of reef-building corals across the Caribbean Sea since the late 1970s (*high confidence*) [*Hughes*, 1994; *Gardner et al.*, 2003]. Record thermal stress in 2005 triggered the largest mass coral bleaching and mortality event on record for the region, damaging coral reefs across hundreds of km^2 in the eastern Caribbean Sea (*high confidence*) [*Donner et al.*, 2007; *Eakin et al.*, 2010]. Although conditions in 2010 were milder than 2005, elevated temperatures still occurred in some parts of the Caribbean [*Smith et al.*, 2013]. Increasing temperatures in the Caribbean have also been implicated in the spread of marine diseases [*Harvell et al.*, 1999; *Harvell et al.*, 2002; *Harvell et al.*, 2004] and some introduced species (*likely*) [*Firth et al.*, 2011]. As in other sub-regions, pelagic fish species are sensitive to changes in sea temperature and modify their distribution and abundance [*Muhling et al.*, 2011]. Fish and invertebrate assemblages in the Gulf of Mexico have shifted deeper in response to SST warming over 1970s-2011 (*medium confidence*) [*Pinsky et al.*, 2013].

Coral ecosystems in the Caribbean Sea are at risk from ocean acidification (*very likely*) [*Albright et al.*, 2010; *Albright and Langdon*, 2011], although impacts are yet to be observed under field conditions. Ocean acidification may also be altering patterns of fish recruitment to coral reefs, although direct evidence for how this has affected Caribbean species is lacking (*low confidence*) [*Dixson et al.*, 2008; *Munday et al.*, 2009; *Dixson et al.*, 2010].

30.5.4.2. Key Risks and Vulnerabilities

Worldwide, 850 million people live within 100 km of tropical coastal ecosystems such as coral reefs and mangroves deriving multiple benefits including food, coastal protection, cultural services, and income from industries such as fishing and tourism [*Burke et al.*, 2011]. Marine ecosystems within the CBS are sensitive to increasing sea temperatures (Figure 30-10), although detection and attribution is complicated by the significant influence and interaction with non-climate change stressors (water quality, over-exploitation of fisheries, coastal degradation; Box CC-CR). Warming is *likely* to have changed the primary productivity of ocean waters, placing valuable ecosystems and fisheries within the ECS at risk (*low to medium confidence*). Other risks include the expansion of hypoxic conditions and associated dead zones in many parts of the CBS. Given the consequences for coastal ecosystems and fisheries, these changes are *very likely* to increase the vulnerability of coastal communities throughout the CBS.

Sea temperatures are increasing within many parts of the CBS ecosystems (1950–2009, Table 30-1), and will continue to do so over the next few decades and century. Sea temperatures are projected to change by 0.34–0.50°C over the near-term (2010–2039) and by 0.23–0.74°C over the long-term (2010–2099) under the lowest RCP scenario (RCP2.6). Under BAU (RCP8.5), CBS sea temperatures are projected to increase by 0.62–0.85°C over tne near-term and 2.44–3.32°C over the long-term (Table SM30-4). Given the large-scale impacts (e.g., mass coral bleaching and mortality events) that have occurred in response to much smaller changes in the past over the CBS regions (0.14–0.80°C from 1950–2009, Table 30-1), the projected changes of 2.44–3.32°C over 2010-2099 are *very likely* to have large-scale and negative consequences for the structure and function of many CBS ecosystems (*virtually certain*), especially given the sensitivity of coral reefs to relatively small increases in temperature over the past three decades [*Hoegh-Guldberg*, 1999; *Eakin et al.*, 2010; *Lough*, 2012].

It is *very likely* that coral-dominated reef ecosystems within the CBS (and elsewhere) will continue to decline and will consequently provide significantly less ecosystem goods and services for coastal communities if sea temperatures increase by more than 1°C above current temperatures (Box CC-CR, Figure 30-10). Combining the known sensitivity of coral reefs within the Caribbean and Coral Triangle sub-regions [*Strong et al.*, 1997; *Hoegh-Guldberg*, 1999; *Strong et al.*, 2011], with the exposure to higher temperatures that are projected under medium (RCP4.5) to high (RCP8.5) scenarios, reveals that both coral reef-rich regions are *virtually certain* to experience levels of thermal stress (DHM≥1) that cause coral bleaching every 1–2 years by the mid to late part of this century (*robust evidence, high levels of agreement, very high confidence*) (Figure 30-4b, c; Figure 30-10, Figure 30-12, Figure SM30-3; [*van Hooidonk et al.*, 2013]). The frequency of mass mortality events (DHM≥5, Figure 30-10a-c) also climbs towards events that occur every 1–2 years by the mid to late part of this century under low to high climate change scenarios (*robust evidence, high agreement, very high confidence*) [*Hoegh-Guldberg*, 1999; *Donner et al.*, 2005; *Frieler et al.*, 2012]. Mass mortality events that affect coral reefs will result in changes to community composition in the near-term (2010–2039) [*Berumen and Pratchett*, 2006; *Adjeroud et al.*, 2009] and a continuing downward trend in reef-building coral stocks in the longer term [*Gardner et al.*, 2003; *Bruno and Selig*, 2007; *Baker et al.*, 2008].

It is *virtually certain* that composition of fisheries catches [*Graham et al.*, 2007; *Pratchett et al.*, 2011a] [*Pratchett et al.*, 2008; *Pratchett et al.*, 2011b] will change. The productivity of many fisheries will decrease (*limited evidence, medium agreement*) as waters warm, acidify, and stratify, and as crucial habitat such as coral reefs degrades (*low confidence*). These changes are *very likely* to increase the vulnerability of millions of people who live in coastal communities and depend directly on fisheries and other ecological goods and services [*Hoegh-Guldberg et al.*, 2009; *McLeod et al.*, 2010].

[INSERT FIGURE 30-10 HERE
Figure 30-10: Annual maximum proportions of reef pixels with Degree Heating Months [*Donner et al.*, 2007]; DHM)≥1 (used for projecting coral bleaching; [*Strong et al.*, 1997; *Strong et al.*, 2011]) and DHM≥5 (associated with bleaching across 100% of affected areas with significant mortality, [*Eakin et al.*, 2010] for the period 1870–2009 for each of the six coral regions (Figure 30-4d) using the HadISST1.1 data set. The black line on each graph is the maximum annual area value for each decade over the period 1870–2009. This value is continued through 2010–2099 using CMIP5 data and splits into the four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, and 8.5). DHM were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHM, the annual percentage of grid cells with DHM≥1 and DHM≥5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010–2099 are the average of these maximum proportion values for each RCP. Monthly SST anomalies were derived using a 1985–2000 maximum monthly mean (MMM) climatology derived in the calculations for Figure 30-4. This was done separately for HadISST1.1, the CMIP5 models, and each of the four RCPs, at each grid cell for every region. DHMs were then derived by adding up the monthly anomalies using a 4-month rolling sum. Figure SM30-3 presents past and future sea temperatures for the six major coral reef provinces under historic, un-forced, RCP4.5 and RCP8.5 scenarios.]

30.5.5. Eastern Boundary Upwelling Ecosystems

The Eastern Boundary Upwelling Ecosystems (EBUE) include the California, Peru/Humboldt, Canary/North-west Africa, and Benguela Currents. They are highly productive sub-regions with rates of primary productivity that may exceed 1000 g C m^{-2} yr^{-1}. Although these provinces comprise less than 2% of the Ocean area, they contribute nearly 7% of marine primary production (Figure 30-1b) and more than 20% of the world's marine capture fisheries [*Pauly and Christensen*, 1995]. Catches in the EBUE are dominated by planktivorous sardine, anchovy, and horse/jack mackerel, and piscivorous benthic fish such as hake. Nutrient input from upwelling of cooler waters stimulates primary production that is transferred to mid and upper trophic levels, resulting in substantial fish, seabird, and marine mammal populations. As a result, the EBUE are considered 'hotspots' of productivity and biodiversity [*Block et al.*, 2011]. The high level of productivity is a result of large-scale atmospheric pressure gradients and wind systems that advect surface waters offshore leading to the upwelling of cold, nutrient-rich waters from depth (Box CC-UP) [*Chavez and Messie*, 2009; *Chavez et al.*, 2011]. Upwelling waters are typically low in pH and high in CO_2, and are *likely* to continue to enhance changes in pH and CO_2 resulting from rising atmospheric CO_2 [*Feely et al.*, 2008; *Gruber*, 2011].

30.5.5.1. Observed Changes and Potential Impacts

There are extensive studies of the coupled climate-ecosystem dynamics of individual EBUE (e.g., California Current). Decadal variability poses challenges to the detection and attribution of changes within the EBUE to climate change, although there are a number of long-term studies that have been able to provide insight into the patterns of change and their causes. Like other ocean sub-regions, EBUE are projected to warm under climate change, with increased stratification and intensified winds as westerly winds shift poleward (*likely*). However, cooling has also been predicted for some EBUE, resulting from the intensification of wind-driven upwelling [*Bakun*, 1990]. The California and Canary Currents have warmed by 0.73 and 0.53°C (*very likely*) (p-value≤0.05, 1950-2009, Table 30-1), respectively, while no significant trend was detected in the sea surface temperatures of the Benguela (p-value = 0.44) and Humboldt Currents (p-value = 0.21) from 1950–2009 (Table 30-1). These trends match shorter-term trends for various EBUE using Pathfinder version 5 data [*Demarcq*, 2009]. These differences are *likely* to be the result of differences in the influence of long-term variability and the specific responses of coastal wind systems to warming, although an analysis of wind data over the same period did not pick up clear trends (*low confidence*, with respect to long-term wind trends) [*Demarcq*, 2009; *Barton et al.*, 2013].

How climate change will influence ocean upwelling is central to resolving ecosystem and fishery responses within each EBUE. There is considerable debate, however, as to whether or not climate change will drive an intensification of upwelling (e.g., [*Bakun et al.*, 2010; *Narayan et al.*, 2010; *Barton et al.*, 2013] in all regions. This debate is outlined in Box CC-UP. EBUE are also areas of naturally low pH and high CO_2 concentrations due to upwelling, and consequently may be vulnerable to ocean acidification and its synergistic impacts [*Barton et al.*, 2012]. A full understanding of the consequences of ocean acidification for marine organisms and ecosystems is discussed elsewhere (Box CC-OA, Box CC-UP, 6.2, 6.3.2, [*Kroeker et al.*, 2013], WGI 6.4).

30.5.5.1.1. Canary Current

Part of the North Atlantic STG, the Canary Current extends from northern Morocco southwestward to the North Atlantic Equatorial Current. It is linked with the Portugal Current (which is sometimes considered part of the Canary Current) upstream and extends downstream to the Atlantic Equatorial Current. The coastal upwelling system, however, is limited to a narrow belt along the Saharan west coast to the coast of Guinea, with the most intense upwelling occurring centrally, along the coasts of Mauritania (15–20º N) and Morocco (21–26° N). Total fish catches, comprising mainly coastal pelagic sardines, sardinellas, anchovies, and mackerel, have fluctuated around 2 million tons yr^{-1} since the 1970s (http://www.seaaroundus.org/lme/27.aspx). Contrasting with the other EBUE, fishing productivity is modest, probably due to the legacy of uncontrolled fishing in the 1960s [*Arístegui et al.*, 2009].

Most observations suggest that the Canary Current has warmed since the early 1980s [*Arístegui et al.*, 2009; *Belkin*, 2009; *Demarcq*, 2009; *Barton et al.*, 2013], with analysis of HadISST1.1 data from 1950–2009 indicating warming of 0.53°C from 1950–2009 (p-value≤0.05, Table 30-1). *Gómez-Gesteira et al.* [2008] suggest a 20% and 45% decrease in the strength of upwelling in winter and summer, respectively, from 1967–2006, consistent with a decrease in wind strength and direction over the past 60 years. More recently, [*Barton et al.*, 2013] show no clear increasing or decreasing trend in wind strength over the past 60 years, and a lack of agreement among wind trends and variability from different wind products, (e.g. PFEL, ICOADS, WASWind). This study presents no evidence for changes in upwelling intensity, with the exception of upwelling off North-west Spain, where winds are becoming slightly less favorable. Alteration of wind direction and strength influences upwelling and hence nutrient concentrations, howevernutrient levels can also change in response to other variables such as the supply of iron-laden dust from the Sahara [*Alonso-Pérez et al.*, 2011]. There is *medium evidence* and *medium agreement* that primary production in the Canary Current has decreased over the past two decades [*Arístegui et al.*, 2009; *Demarcq*, 2009], in contrast to the nearby upwelling region off North-west Spain, where no significant trend was observed

[*Bode et al.*, 2011]. Satellite chlorophyll records (SeaWiFS, MODIS) are relatively short, making it difficult to distinguish the influence of warming oceans from longer-term patterns of variability [*Arístegui et al.*, 2009; *Henson et al.*, 2010]. Changing temperature has resulted in changes to important fisheries species. For example, Mauritanian waters have become more suitable as feeding and spawning areas for some fisheries species (e.g., *Sardinella aurita*) as temperatures increased [*Zeeberg et al.*, 2008]. Clear attribution of these changes depends on the linkage between the Azores High and global temperature, and on longer records for both physical and biological systems as pointed out for data sets in general [*Arístegui et al.*, 2009; *Henson et al.*, 2010].

30.5.5.1.2. Benguela Current

The Benguela Current originates from the eastward-flowing, cold South Atlantic Current, flows northward along the southwest coast of Africa, and is bounded north and south by the warm-water Angola and Agulhas Currents, respectively. Upwelling is strongest and most persistent toward the center of the system in the Lüderitz-Orange River upwelling cell [*Hutchings et al.*, 2009]. Fish catch reached a peak in the late 1970s of 2.8 million tons yr^{-1} (http://www.seaaroundus.org/lme/29/1.aspx), before declines in the northern Benguela, due to overfishing and interdecadal environmental variability, resulted in a reduced catch of around 1 million tons yr^{-1} (present) [*Cury and Shannon*, 2004; *Heymans et al.*, 2004; *Hutchings et al.*, 2009]. Offshore commercial fisheries currently comprise sardine, anchovy, horse mackerel, and hake, while the inshore artisanal and recreational fisheries comprise a variety of fish species mostly caught by hook and line.

Most research on the Benguela Current has focused on fisheries and oceanography, with little emphasis on climate change. As with the other EBUE, strong interannual and interdecadal variability in physical oceanography make the detection and attribution of biophysical trends to climate change difficult. Nevertheless, the physical conditions of the Benguela Current are highly sensitive to climate variability over a range of scales, especially to atmospheric teleconnections that alter local wind stress [*Hutchings et al.*, 2009; *Leduc et al.*, 2010; *Richter et al.*, 2010; *Rouault et al.*, 2010]. Consequently, there is *medium agreement*, despite *limited evidence* [*Demarcq*, 2009], that upwelling intensity and associated variables (e.g., temperature, nutrient, and O_2 concentrations) from the Benguela system will change as a result of climate change (Box CC-UP).

The temperature of the surface waters of the Benguela Current did not increase from 1950 to 2009 (p-value>0.05, Table 30-1), although shorter records show an decrease in the south-central Benguela Current (0.35–0.55 ºC $decade^{-1}$ [*Rouault et al.*, 2010] or an increase for the whole Benguela region (0.24ºC, *Belkin* [2009]). These differences between short versus long records indicate the substantial influence of long-term variability on the Benguela system [*Belkin*, 2009]. Information on other potential consequences of climate-change within the Benguela system is sparse. Sea-level rise is similar to the global mean, although it has not been measured rigorously within the Benguela [*Brundrit*, 1995; *Veitch*, 2007]. Although upwelling water in the northern and southern portions of the Benguela Current exhibits elevated and suppressed pCO_2, respectively [*Santana-Casiano et al.*, 2009]), the consequences of changing upwelling intensity remain poorly explored with respect to ocean acidification. Finally, while periodic hypoxic events in the Benguela system are largely driven by natural advective processes, these may be exacerbated by future climate change [*Monteiro et al.*, 2008; *Bakun et al.*, 2010].

Despite its apparent sensitivity to environmental variability, there is *limited evidence* of ecological changes in the Benguela Current EBUE due to climate change [*Poloczanska et al.*, 2013]. For example, pelagic fish [*Roy et al.*, 2007], benthic crustaceans [*Cockcroft et al.*, 2008], and seabirds [*Crawford et al.*, 2008] have demonstrated general eastward range shifts around the Cape of Good Hope. Although these may be associated with increased upwelling along the South African south coast, specific studies that attribute these changes to anthropogenic climate change are lacking. Trawl surveys of demersal fish and cephalopod species showed consistently predictable 'hotspots' of species richness over a 20–30 year study period (the earliest surveys since 1984 off South Africa) that were associated with greater depths and cooler bottom waters [*Kirkman et al.*, 2013]. However, major changes in the structure and function of the demersal community have been shown in some parts of the Benguela in response to environmental change e.g., due to predominately fishing pressure in the 1960s and environmental forcing in the early 2000s in the southern Benguela [*Howard et al.*, 2007], therefore changes driven by climate change may eventually affect the persistence of these biodiversity hotspots [*Kirkman et al.*, 2013].

30.5.5.1.3. California Current

The California Current spans ~23° of latitude from central Baja California, Mexico, to central British Columbia, Canada, linking the North Pacific Current (Westwind Drift) with the North Equatorial and Kuroshio Currents to form the North Pacific Gyre. High productivity driven by advective transport and upwelling [*Hickey*, 1979; *Chelton et al.*, 1982; *Checkley and Barth,* 2009; *Auad et al.*, 2011] supports well-studied ecosystems and fisheries. Fish catches from the California Current have been approximately 0.6 million tonnes yr^{-1} since 1950 (http://www.seaaroundus.org/lme/3.aspx), which makes it the lowest catch of the four EBUE. The ecosystem supports the foraging and reproductive activities of 2–6 million seabirds from around 100 species [*Tyler et al.*, 1993]. Marine mammals are diverse and relatively abundant, including recovering populations of humpback whales, among others [*Barlow et al.*, 2008].

The average temperature of the California Current warmed by 0.73°C from 1950–2009 (p-value $\leq$0.05, Table 30-1) and by 0.14–0.80°C from 1985–2007 [*Demarcq*, 2009]. Like other EBUE, the California Current is characterized by large-scale interannual and interdecadal climate-ecosystem variability [*McGowan et al.*, 1998; *Hare and Mantua*, 2000; *Chavez et al.*, 2003; *Checkley and Barth*, 2009]. During an El Niño, coastally-trapped Kelvin waves from the tropics deepen the thermocline, thereby severely reducing upwelling and increasing ocean temperatures from California to Washington [*Peterson and Schwing*, 2003; *King et al.*, 2011]. Atmospheric teleconnections to the tropical Pacific alter wind stress and coastal upwelling. Therefore, the ENSO is intimately linked with Bakun's (1990) upwelling intensification hypothesis (Box CC-UP). Interdecadal variability in the California Current stems from variability in the Pacific-North America pattern [*Overland et al.*, 2010], which is influenced by the PDO [*Mantua et al.*, 1997; *Peterson and Schwing*, 2003] and the NPGO [*Di Lorenzo et al.*, 2008]. The major effects of the PDO and NPGO appear north of 39°N [*Di Lorenzo et al.*, 2008; *Menge et al.*, 2009].

There is *robust evidence* and *medium agreement* that the California Current has experienced a decrease in the number of upwelling events (23–40%), but an increase duration of individual events resulting in an increase of the overall magnitude of upwelling events from 1967–2010 (*high confidence*) [*Demarcq*, 2009; *Iles et al.*, 2012]. This is consistent with changes expected under climate change yet remains complicated by the influence of decadal-scale variability (*low confidence*) [*Iles et al.*, 2012]. Oxygen concentrations have also undergone large and consistent decreases from 1984–2006 throughout the California Current, with the largest relative decreases occurring below the thermocline (21% at 300 m). The hypoxic boundary layer (<60 µmol kg^{-1}) has also shoaled by up to 90 m in some regions [*Bograd et al.*, 2008]. These changes are consistent with the increased input of organic carbon into deeper layers from enhanced upwelling and productivity, which stimulates microbial activity and results in the drawdown of O_2 (*likely*), [*Bakun et al.*, 2010] but see also [*McClatchie et al.*, 2010; *Koslow et al.*, 2011]; WGI 3.8.3). These changes are *likely* to have reduced the available habitat for key benthic communities as well as fish and other mobile species [*Stramma et al.*, 2010]. Increasing microbial activity will also increase the partial pressure of CO_2, decreasing pH and the carbonate chemistry of seawater. Together with the shoaling of the saturation horizon, these changes have increased the incidence of low O_2 and low pH water flowing onto the continental shelf (*high confidence*) (40–120 m, [*Feely et al.*, 2008]), causing problems for industries such as the shellfish aquaculture industry [*Barton et al.*, 2012].

30.5.5.1.4. Humboldt Current

The Humboldt Current is the largest of the four EBUE, covering an area larger than the other three combined. It comprises the eastern edge of South Pacific Gyre, linking the northern part of the Antarctic Circumpolar Current with the Pacific South Equatorial Current. Although the primary productivity per unit area is modest compared to that of the other EBUE, the Humboldt Current system has very high levels of fish production. Current catches are in line with a long-term average (since the 1960s) of 8 million tons yr^{-1} (http://www.seaaroundus.org/lme/13/1.aspx), although decadal-scale variations range from 2.5–13 million tons yr^{-1}. While the anchovies currently contribute 80% of the total catch, they alternate with sardines on a multi-decadal scale, with their dynamics mediated by the approach and retreat of sub-tropical waters to and from the coast [*Alheit and Bakun*, 2010]. This variability does not appear to be altering due to anthropogenic climate change. Thus, from the late 1970s to the early 1990s, sardines were more important [*Chavez et al.*, 2003]. The other major commercial fish species are jack mackerel among the pelagic fish, and hake among the demersal fish.

The Humboldt Current EBUE did not show an overall warming trend in SST over the last 60 years (p-value>0.05, Table 30-1), which is consistent with other data sets (1982–2006, HadISST1.1, [*Belkin*, 2009]; 1985-2007, Pathfinder, [*Demarcq*, 2009]). Wind speed has increased in the central portions of the Humboldt Current, although wind has decreased in its southern and northern sections [*Demarcq*, 2009]. The lack of a consistent warming signal may be due to the strong influence of adjacent ENSO activity exerting opposing drivers on upwelling and which, if they intensify, would decrease temperatures (*limited evidence*, *medium agreement*). Similar to the Canary Current EBUE, however, there was a significant increase in the temperatures of the warmest month of the year over the period 1950–2009 ($p\text{-value} \leq 0.05$, Table 30-1).

Primary production is suppressed during warm El Niño events and amplified during cooler La Niña phases, these changes then propagate through to higher trophic levels [*Chavez et al.*, 2003; *Tam et al.*, 2008; *Taylor et al.*, 2008]. However, in addition to trophic changes, there is also a direct thermal impact on organisms, which varies depending on the thermal adaptation window for each species (*high confidence*). A 37-year zooplankton time series for the coast of Peru showed no persistent trend in abundance and diversity [*Ayón et al.*, 2004], although observed shifts coincided with the shifts in the regional SST. As for other EBUE, there is lack of studies that have rigorously attempted to detect and attribute changes to anthropogenic climate change, although at least two studies [*Mendelssohn and Schwing*, 2002; *Gutierrez et al.*, 2011] provide additional evidence that the northern Humboldt Current has cooled (due to upwelling intensification) since the 1950s, a trend matched by increasing primary production. This is not entirely consistent with the lack of significant change over the period 1950–2009 (p-value>0.05, Table 30-1). Nevertheless, these relationships are *likely* to be complex in their origin, especially in their sensitivity to the long-term changes associated with ENSO and PDO, and the fact that areas within the Humboldt Current EBUE may be showing different behaviors.

30.5.5.2. Key Risks and Vulnerabilities

EBUE are vulnerable to changes that influence the intensity of currents, upwelling, and mixing (and hence changes in SST, wind strength and direction), as well as O_2 content, carbonate chemistry, nutrient content, and the supply of organic carbon to deep offshore locations (*robust evidence*, *high agreement*, *high confidence*). The extent to which any particular EBUE is vulnerable to these factors depends on location (Figure 3 from *Gruber* [2011] and other factors such as alternative sources of nutrient input and fishing pressure [*Bakun et al.*, 2010]. This complex interplay between regional and global drivers means that our understanding of how factors such as upwelling within the EBUE will to respond to further climate change is uncertain (Box CC-UP, [*Rykaczewski and Dunne*, 2010]).

In the GCM ensembles examined (Table SM30-3), modest rates of warming (0.22–0.93°C) occur within the four EBUEs in the near-term. Over 2010-2099, however, EBUE SSTs warm by 0.07–1.02ºC under RCP2.6, and 2.52–3.51ºC under RCP8.5 (Table SM30-4). These high temperatures have the potential to increase stratification of the water column and substantially reduce overall mixing in some areas. In contrast, the potential strengthening of coastal wind systems would intensify upwelling and stimulate primary productivity through the increased injection of nutrients into the photic zone of the EBUE (Box CC-UP). *Garreaud and Falvey* [2009] explored how wind stress along the South American coast would change by 2100 under B2 and A2 IPCC scenarios. Using an ensemble of 15 GCMs, southerly wind systems favoring upwelling increased along the sub-tropical coast of South America, extending and strengthening conditions for upwelling.

Changes in the intensity of upwelling within the EBUE will drive fundamental changes to the abundance, distribution, and viability of resident organisms, although an understanding of their nature and direction is limited. In some cases, large-scale decreases in primary productivity and dependent fisheries are projected to occur for EBUE ecosystems [*Blanchard et al.*, 2012], while other projections question the strong connection between primary productivity and fisheries production [*Arístegui et al.*, 2009]. Increased upwelling intensity also has potential disadvantages. Elevated primary productivity may lead to decreasing trophic transfer efficiency, thus increasing the amount of organic carbon exported to the seabed, where it is *virtually certain* to increase microbial respiration and hence increase O_2 stress [*Weeks et al.*, 2002; *Bakun et al.*, 2010]. Increased wind stress may also increase turbulence, breaking up food concentrations (affecting trophic transfer), or causing excessive offshore advection, which could remove plankton from shelf habitats. The central issue for the EBUE is therefore whether or not upwelling will intensify and, if so, whether the negative consequences (e.g., reduced O_2 and elevated CO_2) associated with upwelling intensification will outweigh potential benefits from increased primary production and fisheries catch.

30.5.6. Sub-Tropical Gyres

Sub-Tropical Gyres (STG) dominate the Pacific, Atlantic, and Indian Oceans (Figure 30-1a), and consist of large stable water masses that circulate clockwise (northern hemisphere) and anticlockwise (southern hemisphere) due to the Coriolis Effect. The oligotrophic areas at the core of the STG represent one of the largest habitats on Earth, contributing 21.2% of ocean primary productivity and 8.3% of the global fish catch (Figure 30-1b, Table SM30-1). A number of small island nations are found within this region. While many of the observed changes within these nations have been described in previous chapters (e.g., 5.3-4, 29.3–5), region-wide issues and consequences are discussed here due to the strong linkages between ocean and coastal issues.

30.5.6.1. Observed Changes and Potential Impacts

The central portions of the STG are oligotrophic (Figure SM30-1. Temperatures within the STG of the North Pacific (NPAC), South Pacific (SPAC), Indian Ocean (IOCE), North Atlantic (NATL), and South Atlantic (SATL) have increased at rates of 0.020, 0.024, 0.032, 0.025, and 0.027°C yr^{-1} from 1998–2010, respectively ([*Signorini and McClain*, 2012]. This is consistent with increases observed from 1950–2009 (0.25–0.67ºC, Table 30-1). However differences among studies done over differing time-periods emphasize the importance of long-term patterns of variability. Salinity has decreased across the North and South Pacific STG (Figure 30-6c, WGI 3.3.3.1), consistent with warmer sea temperatures and an intensification of the hydrological cycle [*Boyer*, 2005].

The North and South Pacific STGs have expanded since 1993 (*high confidence*), with these changes *likely* being the consequence of a combination of wind forcing and long-term variability ([*Parrish et al.*, 2000]; (WGI 3.6.3). Chlorophyll levels, as determined by remote-sensing of ocean color (Box CC-UP), have decreased in the NPAC, IOCE, and NATL by 9%, 12%, and 11%, respectively ($p\text{-value}\leq 0.5$; [*Signorini and McClain*, 2012]) over and above the inherent seasonal and interannual variability from 1998–2010 [*Vantrepotte and Mélin*, 2011]. Chlorophyll levels did not change in the remaining two gyres (SPAC and SATL, and confirmed for SPAC by [*Lee and McPhaden*, 2010; *Lee et al.*, 2010]). Furthermore, over the period 1998–2007, median cell diameter of key phytoplankton species exhibited statistically significant linear declines of about 2% in the North and South Pacific, and 4% in the North Atlantic Ocean [*Polovina and Woodworth*, 2012]. Changes in chlorophyll and primary productivity in these sub-regions have been noted before [*McClain et al.*, 2004; *Gregg et al.*, 2005; *Polovina et al.*, 2008] and are influenced by seasonal and longer-term sources of variability (e.g., ENSO, PDO, 6.3.4, Figure 6.9). These changes represent a significant expansion of the world's most unproductive waters, although caution must be exercised given the limitations of satellite detection methods (Box CC-PP) and the shortness of records relative to longer-term patterns of climate variability. There is *high confidence* that changes that reduce the vertical transport of nutrients into the euphotic zone (e.g., decreased wind speed, increasing surface temperatures, and stratification) will reduce the rate of primary productivity and hence fisheries.

30.5.6.1.1. Pacific Ocean STG

Pacific climate is heavily influenced by the position of the Intertropical Convergence Zone (ITCZ) and the South Pacific Convergence Zone (SPCZ), which are part of the ascending branch of the Hadley circulation (WGI 14.3.1). These features are also strongly influenced by interannual to interdecadal climate patterns of variability including ENSO and PDO. The current understanding of how ENSO and PDO will change as average global temperatures increase is not clear (*low confidence*) ([*Collins et al.*, 2010], WGI 12.4.4.2). The position of both the ITCZ and

SPCZ vary seasonally and with ENSO [*Lough et al.*, 2011], with a northward migration during the northern hemisphere summer and a southward migration during the southern hemisphere summer. These changes, along with the West Pacific Monsoon, determine the timing and extent of the wet and dry seasons in SPAC and NPAC sub-regions [*Ganachaud et al.*, 2011]. Tropical cyclones are prominent in the Pacific (particularly the western Pacific), and CBS sub-regions between 10°–30° north and south of the equator, although the associated storm systems may occasionally reach higher latitudes. Spatial patterns of cyclones vary with ENSO, spreading out from the Coral Sea to the Marquesas Islands during El Niño and contracting back to the Coral Sea, New Caledonia, and Vanuatu during La Niña [*Lough et al.*, 2011]. Historically, there have been almost twice as many land-falling tropical cyclones in La Niña as opposed to El Niño years off the east coast of Australia, with a declining trend in the number of severe tropical cyclones from 0.45 per year in the early 1870s to 0.17 per year in recent times [*Callaghan and Power*, 2011].

The Pacific Ocean underwent an abrupt shift to warmer sea temperatures in the mid-1970s as a result of both natural (e.g., Interdecadal Pacific Oscillation (IPO) and climate forcing (*high confidence*)[*Meehl et al.*, 2009]. This change coincided with changes to total rainfall, rain days, and dry spells across the Pacific, with the direction of change depending on the location relative to the SPCZ. Countries such as the Cook Islands, Tonga, Samoa and American Samoa, and Fiji tend to experience drought conditions as the SPCZ (with cooler sea temperatures) moves toward the northeast during El Niño (*high confidence*). The opposite is true during La Niña conditions. The consequences of changing rainfall on the countries of the Pacific STG are discussed in greater detail elsewhere (5.4, 29.3, Table 29.1). While these changes are due to different phases of long-term variability in the Pacific, they illustrate the ramifications and sensitivity of the Pacific to changes in climate change.

Elevated sea temperatures within the Pacific Ocean have increased the frequency of widespread mass coral bleaching and mortality since the early 1980s (*very high confidence*, [*Hoegh-Guldberg and Salvat*, 1995; *Hoegh-Guldberg*, 1999; *Mumby et al.*, 2001; *Baker et al.*, 2008; *Donner et al.*, 2010]. There are few, if any, scientific records of mass coral bleaching and mortality prior to this period (*high confidence* [*Hoegh-Guldberg*, 1999]. Rates of decline in coral cover on coastal coral reef ecosystems range between 0.5–2.0% per year depending on the location within the Indo-Pacific region (*high confidence*, [*Bruno and Selig*, 2007; *Hughes et al.*, 2011; *Sweatman et al.*, 2011; *De'ath et al.*, 2012]. The reasons for this decline are complex and involve non-climate change related factors (e.g., coastal pollution and overfishing) as well as global warming and possibly acidification. A recent comprehensive analysis of the ecological consequences of coral bleaching and mortality concluded that "bleaching episodes have resulted in catastrophic loss of coral reefs in some locations, and have changed coral community structure in many others, with a potentially critical influence on the maintenance of biodiversity in the marine tropics" (*high confidence*, [*Baker et al.*, 2008]. Increasing sea levels have also caused changes in seagrass and mangrove systems. *Gilman et al.* [2007] found a reduction in mangrove area with sea level rise, with the observed mean landward recession of three mangrove areas over four decades being 25, 64, and 72 mm yr^{-1}, 12–37 times faster than the observed rate of sea level rise. Significant interactions exist between climate change and coastal development, where migration shoreward depends on the extent to which coastlines have been modified or barriers to successful migration have been established.

Changes in sea temperature also lead to changes in the distribution of key pelagic fisheries such as skipjack tuna (*Katsuwonus pelamis*), yellowfin tuna (*Thunnus albacares*), big-eye tuna (*T. obesus*) and South Pacific albacore tuna (*T. alalunga*), which make up the majority of key fisheries in the Pacific Ocean. Changes in distribution and recruitment in response to changes in sea temperature as result of ENSO demonstrate the close association of pelagic fish stocks and water temperature. The shift in habitat for top predators in the northeast Pacific was examined by *Hazen et al.* [2012], who used tracking data from 23 marine species and associated environmental variables to predict changes of up to 35% in core habitat for these species within the north Pacific. Potential habitats are predicted to contract for the blue whale, salmon shark, loggerhead turtle, and blue and mako sharks, while potential habitats for the sooty shearwater, black -footed albatross, leatherback turtle, white shark, elephant seal, and albacore, bluefin and yellowfin tuna are predicted to expand [*Hazen et al.*, 2012]. However, expansion of OMZs in the Pacific STG is predicted to compress habitat (depth) for hypoxia-intolerant species such as tuna [*Stramma et al.*, 2010; *Stramma et al.*, 2012].

Reduction of ocean productivity of the STG [*Sarmiento et al.*, 2004; *Signorini and McClain*, 2012] reduces the flow of energy to higher trophic levels such as those of pelagic fish [*Le Borgne et al.*, 2011]. The distribution and abundance of fisheries stocks such as tuna are also sensitive to changes in sea temperature, and hence long-term variability such as ENSO and PDO. The redistribution of tuna in the western central equatorial region has been related to the position of the oceanic convergence zones, where the warm pool meets the cold tongue of the Pacific. These changes have been reliably reproduced by population models that use temperature as a driver of the distribution and abundance of tuna [*Lehodey et al.*, 1997; *Lehodey et al.*, 2006]. Projections of big-eye tuna (*T. obesus*) distributions under SRES A2 show an improvement in spawning and feeding habitats to 2100 in the eastern tropical Pacific and declines in the western tropical Pacific leading to an eastern displacement of tuna stocks [*Lehodey et al.*, 2008; *Lehodey et al.*, 2010b].

30.5.6.1.2. Indian Ocean STG

Like the Pacific Ocean, the Indian Ocean plays a crucial role in global weather patterns, with teleconnections throughout Africa, Australasia, Asia, and the Americas (e.g., [*Clark et al.*, 2000; *Manhique et al.*, 2011; *Meehl and Arblaster*, 2011; *Nakamura et al.*, 2011]. Increasing sea level, temperature, storm distribution and intensity, and changing carbonate chemistry all influence the broad range of physical, chemical, and biological aspects of the Indian Ocean. Coral reef ecosystems in the Indian Ocean gyre system were heavily affected by record positive sea temperature anomalies seen in the southern hemisphere between February–April 1998 (*robust evidence, high agreement, high confidence*) [*Ateweberhan et al.*, 2011]. Coral cover across the Western Indian Ocean declined by an average of 37.7% after the 1998 heat stress event [*Ateweberhan et al.*, 2011]. Responses to the anomalously hot conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases in coral cover directly after the 1998 event (from 40–53% coral cover in 1977–1997 to 7% in 1999–2000) (*high confidence*) [*Ateweberhan et al.*, 2011]. Coral reefs lining the islands of southern India and Sri Lanka experienced similar decreases in coral cover (45%, 1977–1997 to 12%, 1999–2000). Corals in the southwestern Indian Ocean (Comoros, Madagascar, Mauritius, Mayotte, Réunion and Rodrigues) showed less impact (44%, 1977–1997 to 40%, 1999–2000). Recovery from these increases in mortality has been variable, with sites such as those around the central Indian Ocean islands exhibiting fairly slow recovery (13% by 2001–2005) while those around southern India and Sri Lanka are showing much higher rates (achieving a mean coral cover of 37% by 2001–2005, [*Ateweberhan et al.*, 2011]). These changes to the population size of key reef-building species will drive major changes in the abundance and composition of fish populations in coastal areas, and affect other ecosystem services that are important for underpinning tourism and coastal protection (*medium confidence*, Box CC-CR).

Fisheries that exploit tuna and other large pelagic species are very valuable to many small island states within the Indian Ocean). As with Pacific fisheries, the distribution and abundance of large pelagic fish in the Indian Ocean is greatly influenced by sea temperature. The anomalously high sea temperatures of 1997–98 (leading to a deepening of the mixed layer in the west and a shoaling in the east) coincided with anomalously low primary production in the western Indian Ocean and a major shift in tuna stocks (*high confidence*) ([*Menard et al.*, 2007; *Robinson et al.*, 2010]. Fishing grounds in the Western Indian Ocean were deserted and fishing fleets underwent a massive shift toward the eastern basin, which was unprecedented for the tuna fishery (*high confidence*). As a result of these changes, many countries throughout the Indian Ocean lost significant tuna-related revenue [*Robinson et al.*, 2010]. In 2007, tuna fishing revenue was again reduced by strong surface warming and deepening of the mixed layer, and associated with a modest reduction in primary productivity in the west. These trends highlight the overall vulnerability of tuna fishing countries in the Indian Ocean to climate variability, a situation similar to the other major oceans of the world.

30.5.6.1.3. Atlantic Ocean STG

SST has increased within the two STG of the Atlantic Ocean over the last two decades [Belkin, 2009; Signorini and McClain, 2012]. Over longer periods of time (1950–2009), trends in average temperature are not significant for the North Atlantic STG (p-value>0.05) while they remain so for the South Atlantic STG (*very likely*) (0.08°C decade^{-1}, p-value≤0.05, Table 30-1). In both cases, however, temperatures in the coolest and warmest months increased significantly (Table 30-1). The difference between these studies (i.e., over 10–30 years versus 60 years) emphasizes the importance of long-term patterns of variability in the North Atlantic region. Variability in SST at a period of about 60–80 years is associated with the Atlantic Multi-decadal Oscillation (AMO) [*Trenberth and Shea*, 2006]. Sea surface temperatures influence hurricane activity (*very likely*) with recent record SST associated with record hurricane activity in 2005 in the Atlantic [*Trenberth and Shea*, 2006] and mass coral bleaching and mortality in the eastern Caribbean (*high confidence*, [*Eakin et al.*, 2010]. In the former case, analysis concluded that 0.1°C of the SST anomaly was attributable to the state of the AMO while 0.45°C was due to ocean warming as a result of anthropogenic influences [*Trenberth and Shea*, 2006].

These changes have influenced the distribution of key fishery species as well the ecology of coral reefs in Bermuda [*Wilkinson and Hodgson*, 1999; *Baker et al.*, 2008] and in the eastern Caribbean [*Eakin et al.*, 2010]. Small island nations such as Bermuda depend on coral reefs for fisheries and tourism and are vulnerable to further increases in sea temperature that cause mass coral bleaching and mortality (*high confidence*, Box CC-CR, Figure 30-10). As with the other STG, phytoplankton communities and pelagic fish stocks are sensitive to temperature changes that have occurred over the past several decades. Observation of these changes has enabled development of models that have a high degree of accuracy in projecting the distribution and abundance of these elements within the Atlantic region in general [*Cheung et al.*, 2011].

30.5.6.2. Key Risks and Vulnerabilities

Sea surface temperatures of the vast STG of the Atlantic, Pacific, and Indian Oceans are increasing, which is *very likely* to increase stratification of the water column. In turn, this is *likely* to reduce surface concentrations of nutrients and, consequently, primary productivity (*medium confidence*) (Box CC-PP). Warming is projected to continue (Table SM30-4), with substantial increases in the vulnerability and risk associated with systems that have been observed to change so far (*high confidence*) (Figure 30-12). Under RCP2.6, the temperatures of the STG are projected to increase by 0.17–0.56°C in the near-term (over 2010–2039) and between -0.03–0.90°C in the long-term (over 2010-2099) (Table SM30-4). Under RCP8.5, however, surface temperatures of the world's STG are projected to be 0.45–0.91°C warmer in the near-term and 1.90–3.44°C warmer in the long-term (Table SM30-4). These changes in temperature are *very likely* to increase water column stability, reduce the depth of the mixed layer, and influence key parameters such as nutrient availability and O_2 concentrations. It is not clear as to how longer-term sources of variability such as ENSO and PDO will change (WGI 14.4, 14.7.6) and ultimately influence these trends.

The world's most oligotrophic ocean sub-regions are *likely* to continue to expand over coming decades, with consequences for ecosystem services such as gas exchange, fisheries, and carbon sequestration. *Polovina et al.* [2011] explored this question for the North Pacific using a climate model that included a coupled ocean biogeochemical component to investigate potential changes under an SRES A2 scenario (~RCP6.0–8.5; Figure 1.5 [*Rogelj et al.*, 2012]). Model projections indicated the STG expanding by approximately 30% by 2100, driven by the northward drift of the mid-latitude westerlies and enhanced stratification of the water column. The expansion of the STG occurred at the expense of the equatorial upwelling and other regions within the North Pacific. In the North Pacific STG, the total primary production is projected to decrease by 10-20% and large fish catch by 19–29% by 2100 under SRES A2 [*Howell et al.*, 2013; *Woodworth-Jefcoats et al.*, 2013]. However, our understanding of how large-scale eddy systems will change in a warming world is incomplete, as are the implications for primary productivity of these large and important systems (Box CC-PP, Box CC-UP).

Understanding how storm frequency and intensity will change represents a key question for many countries and territories within the various STG. Projections of increasing sea temperature are *likely* to change the behavior of tropical cyclones. At the same time, the maximum wind speed and rainfall associated with cyclones is *likely* to increase, although future trends in cyclones and severe storms are *very likely* to vary from region to region (WGI 14.6). Patterns such as 'temporal clustering' can have a strong influence on the impact of tropical cyclones on ecosystems such as coral reefs [*Mumby et al.*, 2011], although how these patterns will change within all STG is uncertain at this point. However, an intensifying hydrological cycle is expected to increase precipitation in many areas (*high confidence* WGI 2.5, 14.2), although longer droughts are also expected in other STG (*medium* *confidence*). Changes in the hydrological cycle impact on coastal ecosystems, increasing damage through coastal flooding and physical damage from storm waves [*Mumby et al.*, 2011]. Improving our understanding of how weather systems associated with features such as the SPCZ (WGI 14.3.1) will vary is critical to climate change adaptation of a large number of nations associated with the STG. Developing an understanding of how ocean temperature, climate systems such as the SPCZ and ITCZ, and climate change and variability (e.g., ENSO, PDO) interact will be essential in this regard. For example, variability in the latitude of the SPCZ is projected to increase, possibly leading to more extreme events in Pacific island countries [*Cai et al.*, 2012].

The consequences of projected sea temperatures on the frequency of coral bleaching and mortality within key sub-regions of the STG are outlined in Box CC-CR, Figures 30.10 and Figure SM30-3. As with other sub-regions (particularly CBS, STG, and SES) dominated by coral reefs, mass coral bleaching and mortality becomes an annual risk under all scenarios, with mass mortality events beginning to occur every 1–2 years by 2100 (*virtually certain,* Box CC-CR, Figure 30-10, Figure SM30-3). Coral-dominated reef ecosystems (areas with more than 30% coral cover) are *very likely* to disappear under these circumstances by the mid part of this century [*van Hooidonk et al.*, 2013]. The loss of substantial coral communities has implications for the three-dimensional structure of coral reefs (Box CC-CR) and the role of the latter as habitat for organisms such as fish [*Hoegh-Guldberg*, 2011; *Hoegh-Guldberg et al.*, 2011a; *Pratchett et al.*, 2011a; *Bell et al.*, 2013b]. The consequences of increasing sea temperature can be exacerbated by increasing ocean acidification, with potential implications for reef calcification ([*Kleypas et al.*, 1999; *Hoegh-Guldberg et al.*, 2007; *Doney et al.*, 2009], *medium confidence*), reef metabolism and community calcification [*Dove et al.*, 2013], and other key ecological processes ([*Pörtner et al.*, 2001; *Pörtner et al.*, 2007; *Munday et al.*, 2009]. Ocean pH within the STG will continue to decrease as atmospheric CO_2 increases, bringing pH within the STG to 7.9 and 7.7 at atmospheric concentrations of 450 ppm and 800 ppm, respectively (Figure SM30-2a, Box CC-OA). Aragonite saturation states will decrease to around 1.6 (800 ppm) and 3.3 (450 ppm; Figure SM30-2b). Decreasing carbonate ion concentrations and saturation states pose serious risks to other marine calcifiers such as encrusting coralline algae, coccolithophores (phytoplankton), and a range of benthic invertebrates [*Doney et al.*, 2009; *Feely et al.*, 2009]. Increasing sea temperatures and sea level are also *likely* to influence other coastal ecosystems (e.g., mangroves, seagrass meadows) in the Pacific, although significant gaps and uncertainties exist (29.3.4 [*Waycott et al.*, 2007; *Waycott et al.*, 2011]. Many of the negative consequences for coral reefs, mangroves, and seagrass meadows are *likely* to have negative consequences for dependent coastal fisheries (through destruction of habitat) and tourism industries (*medium confidence*) ([*Bell et al.*, 2011b; *Pratchett et al.*, 2011a; *Pratchett et al.*, 2011b; *Bell et al.*, 2013a].

Populations of key large pelagic fish are projected to move many hundreds of kilometers east of where they are today in the Pacific STG (*high confidence*) [*Lehodey et al.*, 2008; *Lehodey et al.*, 2010a; *Lehodey et al.*, 2011; *Lehodey et al.*, 2013], with implications for income, industry, and food security across multiple Pacific Island nations (*high confidence*)[*Cheung et al.*, 2010; *McIlgorm et al.*, 2010; *Bell et al.*, 2011b; *Bell et al.*, 2013a], 7.4.2, Table 29.2-29.3). These predictions of species range displacements, contractions, and expansions in response to anticipated changes in the Ocean (Box CC-MB) present both a challenge and an opportunity for the development of large-scale management strategies to preserve these valuable species. Our understanding of the consequences of reduced O_2 for pelagic fish populations is not clear, although there is *high agreement* on the potential physiological outcomes (6.3.3). Those species that are intolerant to hypoxia, such as skipjack and yellowfin tuna [*Lehodey et al.*, 2011], will have their depth range compressed in the Pacific STG, which will increase their vulnerability to fisheries and reduce overall fisheries habitat and productivity (*medium confidence*) [*Stramma et al.*, 2010; *Stramma et al.*, 2011]. Despite the importance of these potential changes, our understanding of the full range of consequences is *limited* at this point.

30.5.7. Deep Sea (>1000 m)

Assessments of the influence of climate change on the Deep Sea (DS) are challenging due to difficulty of access and scarcity of long-term, comprehensive observations [*Smith et al.*, 2009]. The size of this habitat is also vast, covering well over 54% of the earth's surface and stretching from the top of the mid-oceanic ridges to the bottom of deep ocean trenches [*Smith et al.*, 2009]. The fossil record in marine sediments reveals that the DS has undergone large changes in response to climate change in the past [*Knoll and Fischer*, 2011]. The paleo-skeletal record shows it is the rate, not just the magnitude, of climate change (temperature, O_2, and CO_2) that is critical to marine life in DS. The current rate of change in key parameters *very likely* exceeds that of other major events in Earth history. Two primary time scales are of interest. The first is the slow rate (century-scale) of ocean circulation and mixing, and consequently the slow rate at which DS ecosystems experience physical climate change. The second is the rapid rate at which organic matter enters the deep ocean from primary productivity generated at surface of the Ocean, which represents a critical food supply to DS animals [*Smith and Kaufmann*, 1999; *Smith et al.*, 2009]. It can also represent a potential risk in some circumstances where the flux of organic carbon into the deep ocean, coupled with increased sea temperatures, can lead to anoxic areas (dead zones) as metabolism is increased and O_2 decreased [*Chan et al.*, 2008; *Stramma et al.*, 2010].

30.5.7.1. Observed Changes and Potential Impacts

The greatest rate of change of temperature is occurring in the upper 700 m of the Ocean (WGI 3.2, *very high confidence*), although smaller yet significant changes are occurring at depth. The DS environment is typically cold (~-0.5–3°C; [*Smith et al.*, 2008]), although abyssal temperatures in the SES can be higher (e.g., Mediterranean DS ~12°C, [*Danovaro et al.*, 2010]. In the latter case, DS organisms can thrive in these environments as well, illustrating the variety of temperature conditions that differing species of abyssal life have adapted to. Individual species, however, are typically constrained within a narrow thermal and O_2-demand window of tolerance [*Pörtner*, 2010] and therefore it is *likely* that shifts in the distribution of DS species and regional extinctions will occur. Warming over multiple decades has been observed below 700 m [*Levitus et al.*, 2005; *Levitus et al.*, 2009], with warming being minimal at mid-range depths (2000–3000 m), and increasing towards the sea floor in some sub-regions (e.g., Southern Ocean, WGI Chapter 3). For the deep Atlantic Ocean, the mean age of deep waters (mean time since last exposure to the atmosphere) is ~250 years; the oldest deep waters of the Pacific Ocean are >1000 years old. The patterns of ocean circulation are clearly revealed by the penetration of tracers and the signal of CO_2 released from burning fossil-fuel penetrating into the abyss [*Sabine et al.*, 2004]. It will take many centuries for full equilibration of deep ocean waters and their ecosystems with recent planetary warming and CO_2 levels [*Wunsch and Heimbach*, 2008].

Temperature accounts for ~86% of the variance in the export of organic matter to the DS (*medium confidence*) [*Laws et al.*, 2000]. Consequently, upper ocean warming will reduce the export of organic matter to the DS (*medium confidence*), potentially changing the distribution and abundance of DS organisms and associated food webs, and ecosystem processes [*Smith and Kaufmann*, 1999]. Most organic matter entering the DS is recycled by microbial systems at relatively shallow depths [*Buesseler et al.*, 2007], at rates that are temperature dependent. Upper ocean warming will increase the rate of sub-surface decomposition of organic matter (*high confidence)*, thus intensifying the intermediate depth oxygen minimum zones [*Stramma et al.*, 2008; *Stramma et al.*, 2010] and reducing food supply to the abyssal ocean.

Particulate organic carbon is exported from the surface to deeper layers of the Ocean (>500m) with an efficiency of between 20–50% [*Buesseler et al.*, 2007], much of it being recycled by microbes before it reaches 1000m [*Smith et al.*, 2009]. The export of organic carbon is dependent on surface net primary productivity, which is likely to vary (Box CC-PP), influencing the supply of food to DS [*Laws et al.*, 2000; *Smith et al.*, 2008]. Warming of intermediate waters will also increase respiration at mid-water depths, reducing the flux of organic carbon. Our understanding of other components of DS ecosystems is also relatively poor. For example, there is *limited evidence* and *limited agreement* as to how ocean warming and acidification are *likely* to affect ecosystems such as those associated with hydrothermal vents [*Van Dover*, 2012].

Oxygen concentrations are decreasing in the DS [*Stramma et al.*, 2008; *Helm et al.*, 2011a]. Although, the largest signals occur at intermediate water depths < 1000 m [*Nakanowatari et al.*, 2007; *Whitney et al.*, 2007; *Falkowski et al.*, 2011], some waters >1000 m depth are also experiencing a decline [*Jenkins*, 2008]. The quantity of dissolved O_2 throughout the Ocean will be reduced with warming due to direct effects on solubility (*high confidence*), with these effects being widely distributed [*Shaffer et al.*, 2009]. It is also *virtually certain* that metabolic rates of all animals and microbial respiration rates will increase with temperature [*Brown et al.*, 2004]. Thus, increased microbial activity and reduced O_2 solubility at higher temperatures will have additive consequences for the decline of O_2 (*high* *confidence*) even in the DS. The DS waters are relatively well-oxygenated due to the higher solubility of O_2 in colder waters and the low supply rate of organic matter to great depths. The availability of oxygen to marine animals is governed by a combination of concentration, temperature, pressure, and related properties such as diffusivity. Analysis by [*Hofmann et al.*, 2013] reveals that the supply potential of oxygen to marine animals in cold deep waters is similar to that at much shallower depths *(very high confidence)*.

Anthropogenic CO_2 has penetrated to at least 1000 m in all three ocean basins (particularly the Atlantic; [*Doney et al.*, 2009]. Further declines of calcite and aragonite in already under-saturated DS water will presumably decrease biological carbonate structure formation and increase dissolution, as has happened many times in Earth's past (*high confidence*) [*Zeebe and Ridgwell*, 2011]. Some cold-water corals (reported down to 3500m) already exist in waters under-saturated with respect to aragonite [*Lundsten et al.*, 2009]. While initial investigations suggested that ocean acidification (reduced by 0.15 and 0.30 pH units) would result in a reduction in the calcification rate of deep water corals (30% and 6%, respectively [*Maier et al.*, 2009]), there is accumulating evidence that ocean acidification may have far less impact than previously anticipated on the calcification of some deep water corals (*limited evidence, medium agreement, low confidence*) although it may reduce important habitats given that dead unprotected coral mounds are *likely* to dissolve in under-saturated waters [*Thresher et al.*, 2011; *Form and Riebesell*, 2012; *Maier et al.*, 2013].

30.5.7.2. Key Risks and Vulnerabilities

Rising atmospheric CO_2 poses a risk to DS communities through increasing temperature, and decreasing O_2, carbonate chemistry and pH (*high confidence*) [*Keeling et al.*, 2010]. Risks associated with the DS have implications for the Ocean and planet given the high degree of inherent dependency and connectivity. The resulting changes to the flow of organic carbon to some parts of the DS (e.g., STG) are *very likely* to affect DS ecosystems (*medium confidence*) [*Smith et al.*, 2008]. As with the Ocean generally, there is a need to fill in the substantial gaps that exist in our knowledge and understanding of the world's largest habitat and its responses to rapid anthropogenic climate change.

30.5.8. Detection and Attribution of Climate Change Impacts with Confidence Levels

The analysis in Chapter 30 and elsewhere in AR5 has identified a wide range of physical, chemical, and ecological components that have changed over the last century (Box CC-MB). Figure 30-11 summarizes a number of examples from the Ocean as a region together with the degree of confidence in both the detection and attribution steps. For ocean warming and acidification, confidence is *very high* that changes are being detected and that they are due to changes to the atmospheric greenhouse gas content. There is considerable confidence in both the detection (*very high confidence*) and attribution (*high confidence*) of mass coral bleaching and mortality (Figure 30-11b), given the well-developed understanding of environmental processes and physiological responses driving these events (Box CC-CR, 6.3.1). For other changes, confidence is lower, either because detection of changes has been difficult, or monitoring programs are not long-established (e.g., field evidence of declining calcification) or because detection has been possible but models are in conflict (e.g., wind-driven upwelling). The detection and attribution of recent changes is discussed in further detail in (18.3.3–4).

[INSERT FIGURE 30-11 HERE
Figure 30-11: Expert assessment of degree of confidence in detection and attribution of physical and chemical changes (a) and ecological changes (b) across sub-regions, as designated in Figure 30-1a, and processes in the Ocean (based on evidence explored throughout Chapter 30 and elsewhere in AR5). Further explanation of this figure is given in 18.3.3–4 and 18.6.]

30.6. Sectorial Impacts, Adaptation, and Mitigation Responses

Human welfare is highly dependent on ecosystem services provided by the Ocean. Many of these services are provided by coastal and shelf areas, and are consequently addressed in other chapters (e.g., 5.4.3, 7.3.2.4, 22.3.2.3) Oceans contribute provisioning (e.g., food, raw materials; see 30.6.4.1), regulating (e.g., gas exchange, nutrient recycling, carbon storage, climate regulation, water flux), supporting (e.g., habitat, genetic diversity) and cultural (e.g., recreational, cultural) services [*Millennium-Ecosystem-Assessment*, 2005; *Tallis et al.*, 2013]. The accumulating evidence indicating that fundamental ecosystem services within the Ocean are shifting rapidly should be of major concern, especially with respect to the ability of regulating and supporting ecosystem services to underpin current and future human population demands [*Rockström et al.*, 2009; *Ruckelshaus et al.*, 2013].

Discussion here is restricted to environmental, economic, and social sectors that have direct relevance to the Ocean, namely natural ecosystems, fisheries and aquaculture, tourism, shipping, oil and gas, human health, maritime security, and renewable energy. The influences of climate change on Ocean sectors will be mediated through simultaneous changes in multiple environmental and ecological variables (Figure 30-12), and the extent to which changes can be adapted to and/or risks mitigated (Table 30-3). Both short-term and longer-term adaptation is necessary to address impacts arising from warming, even under the lowest stabilization scenarios assessed.

[INSERT FIGURE 30-12 HERE
Figure 30-12: (a) Examples of projected impacts and vulnerabilities associated with climate change in Ocean sub-regions. (b) Examples of risks to fisheries from observed and projected impacts across Ocean sub-regions. Letters indicate level of confidence: (vL): Very low, (L): Low, (M): Medium, (H): High and (vH): Very high. Details of sub-regions are given in Table 30-1a and 30.1.1.

Sectorial approaches dominate resource management in the Ocean (e.g., shipping tends to be treated in isolation from fishing within an area), yet cumulative and interactive effects of individual stressors are known to be ubiquitous and substantial [*Crain et al.*, 2008]. Climate change consistently emerges as a dominant stressor in regional to global-scale assessments, although land-based pollution, commercial fishing, invasive species, coastal habitat modification, and commercial activities such as shipping all rank high in many places around the world (e.g., 30.5.3, 30.5.4, 5.3.4) [*Halpern et al.*, 2009; *Halpern et al.*, 2010]. Such cumulative effects pose challenges to managing for the full suite of stressors to marine systems, but also present opportunities where mitigating a few key stressors can potentially improve overall ecosystem condition (e.g., [*Halpern et al.*, 2010; *Kelly et al.*, 2011]. The latter has often been seen as a potential strategy for reducing negative consequences of climate impacts on marine ecosystems by boosting ecosystem resilience, thus buying time while the core issue of reducing greenhouse gas emissions is tackled [*West et al.*, 2009].

30.6.1. Natural Ecosystems

Adaptation in natural ecosystems may occur autonomously, such as shifts in species' composition and distributions [*Poloczanska et al.*, 2013] or engineered by human intervention, such as assisted dispersal (4.4, [*Hoegh-Guldberg et al.*, 2008]. Currently, adaptation strategies for marine ecosystems included reducing additional stressors (e.g. maintaining water quality, adapting fisheries management) and maintaining resilience ecosystems (e.g., Marine Protected Areas) and are moving towards whole-of-ecosystem management approaches. Coral reefs, for example, will recover faster from mass coral bleaching and mortality if healthy populations of herbivorous fish are maintained (*medium confidence*, [*Hughes et al.*, 2003], indicating that reducing overfishing will help maintain coral-dominated reef systems while the international community reduces the emissions of greenhouse gases to stabilize global temperature and ocean chemistry.

Approaches such as providing a formal valuation of ecological services from the Ocean have the potential to facilitate adaptation by underpinning more effective governance, regulation, and ocean policy while at the same time potentially improving the management of these often vulnerable services through the development of market mechanisms and incentives [*Beaudoin and Pendleton*, 2012]. Supporting, regulating, and cultural ecosystem services tend to transcend the immediate demands placed on provisioning services and are difficult to value in formal economic terms due to their complexity, problems such as double counting, and the value of non-market goods and services arising from marine ecosystems generally [*Fu et al.*, 2011; *Beaudoin and Pendleton*, 2012].

'Blue Carbon' is defined as the organic carbon sequestered by marine ecosystems such as phytoplankton, mangrove, seagrass, and salt marsh ecosystems [*Laffoley and Grimsditch*, 2009; *Nellemann and Corcoran*, 2009]. In this respect, Blue Carbon will provide opportunities for both adaptation to, and mitigation of, climate change if key uncertainties in inventories, methodologies, and policies for measuring, valuing, and implementing Blue Carbon strategies are resolved [*McLeod et al.*, 2011]. Sediment surface levels in vegetated coastal habitats can rise several meters over thousands of years, building carbon-rich deposits [*Brevik and Homburg*, 2004; *Lo Iacono et al.*, 2008]. The degradation of coastal habitats not only liberates much of the carbon associated with vegetation loss, but can release and oxidize buried organic carbon through erosion of cleared coastlines (*high confidence*) [*Duarte et al.*, 2005]. Combining data on global area, land-use conversion rates, and near-surface carbon stocks for marshes, mangroves, and seagrass meadows, *Pendleton et al.* [2012] revealed that the CO_2 emissions arising from destruction of these three ecosystems was equivalent to 3–19% of the emissions generated by deforestation globally, with economic damages estimated to be US$6–42 billion annually. Similarly, *Luisetti et al.* [2013] estimate the carbon stock of seagrass and salt marshes in Europe, representing <4% of global carbon stocks in coastal vegetation, was valued at US$180 million, at EU Allowance price of €8/tCO_2 in June 2012. A reversal of EU Environmental Protection Directives could result in economic losses of US$1 billion by 2060. Blue Carbon strategies can also be justified in light of the numerous ecosystem services these ecosystems provide, such as protection against coastal erosion and storm damage, and provision of habitats for fisheries species (17.4).

30.6.2. Economic Sectors

30.6.2.1. Fisheries and Aquaculture

The Ocean provided 64% of the production (in tonnes) supplied by world fisheries (capture and aquaculture) in 2010, amounting to 148.5 million tonnes of fish and shellfish [*FAO*, 2012]. This production, valued at US$217.5 billion, and supplied, on average, 18.6 kg of protein-rich food per person to an estimated population of 6.9 billion [*FAO*, 2012]. Marine capture fisheries supplied 77.4 million tonnes with highest production from the northwest Pacific (27%), west-central Pacific (15%), northeast Atlantic (11%) and southeast Pacific (10%)[*FAO*, 2012]. World aquaculture production (59.9 million tonnes in 2010) is dominated by freshwater fishes, nevertheless marine aquaculture supplied 18.1 million tonnes (30%)[*FAO*, 2012].

Marine capture fisheries production increased from 16.8 million tonnes in 1950 to a peak of 86.4 million tonnes in 1996, then declined before stabilising around 80 million tonnes [*FAO*, 2012]. The stagnation of marine capture fisheries production is attributed to full exploitation of around 60% of the world's marine fisheries and overexploitation of 30% (estimates for 2009) [*FAO*, 2012]. Major issues for industrial fisheries include illegal, unreported and unregulated fishing, ineffective implementation of monitoring, control and surveillance, and overcapacity in fishing fleets [*Bank and FAO*, 2008; *FAO*, 2012]. Such problems are being progressively addressed in several developed and developing countries [*Hilborn*, 2007; *Pitcher et al.*, 2009; *Worm et al.*, 2009], where investments have been made in stock assessment, strong management, and application of the FAO Code of Conduct for Responsible Fisheries and the FAO Ecosystem Approach to Fisheries Management.

The significance of marine capture fisheries is illustrated powerfully by the number of people engaged in marine small-scale fisheries (SSF) in developing countries. SSF account for around half of the fish harvested from the Ocean, and provide jobs for more than 47 million people – about 12.5 million fishers and another 34.5 million people engaged in post-harvest activities [*Mills et al.*, 2011]. SSF are often characterized by large numbers of politically-weak fishers operating from decentralized localities, with poor governance, and insufficient data to monitor catches effectively [*Kurien and Willmann*, 2009; *Cochrane et al.*, 2011; *Pomeroy and Andrew*, 2011]. For these SSF, management that aims to avoid further depletion of overfished stocks may be more appropriate in the short-term than management aimed at maximizing sustainable production. These aims are achieved through adaptive management by: (1) introduction of harvest controls (e.g., size limits, closed seasons and areas, gear restrictions, and protection of spawning aggregations) to avoid irreversible damage to stocks in the face of uncertainty [*Cochrane et* *al.*, 2011]; (2) flexible modification of these controls through monitoring [*Plagányi et al.*, 2013]; and (3) investing in the social capital and institutions needed for communities and governments to manage SSF [*Makino et al.*, 2009; *Pomeroy and Andrew*, 2011].

Changes to ocean temperature, chemistry, and other factors are generating new challenges for fisheries resulting in loss of coastal and oceanic habitat [*Hazen et al.*, 2012; *Stramma et al.*, 2012], the movement of species [*Cheung et al.*, 2011], the spread and increase of disease and invading species [*Ling*, 2008; *Raitsos et al.*, 2010; *Chan et al.*, 2011], and changes in primary production[*Chassot et al.*, 2010]. There is *medium evidence* and *medium agreement* that these changes will change both the nature of fisheries and their ability to provide food and protein for hundreds of millions of people (7.2.1.2). The risks to ecosystems and fisheries vary from region to region (7.3.2.4). Dynamic bioclimatic envelope models under SRES A1B project potential increases in fisheries production high latitudes, and potential decreases at lower latitudes by the mid-21st century [*Cheung et al.*, 2010] (6.5). Overall, warming temperatures are projected to shift optimal environments for individual species polewards and redistribute production, however changes will be region specific [*Cheung et al.*, 2010; *Merino et al.*, 2012].

Fisheries, in particular shellfish, are also vulnerable to declining pH and carbonate ion concentrations. As a result, the global production of shellfish fisheries is *likely* to decrease, [*Cooley and Doney*, 2009; *Pickering et al.*, 2011]) with further ocean acidification (*medium confidence*) (6.3.2, 6.3.5, 6.4.1.1, Box CC-OA). Impacts may be first observed in EBUE where upwelled water is already relatively low in O_2 and undersaturated with aragonite (30.5.5). Seasonal upwelling of acidified waters onto the continental shelf in the California Current region, has recently affected oyster hatcheries along the coast of Washington and Oregon (30.5.5.1.1[*Barton et al.*, 2012]). Whether declining pH and aragonite saturation due to climate change played a role is unclear, however future declines will increase the risk of such events occurring.

Most marine aquaculture species are sensitive to changing ocean temperature (6.3.1.4, exposed through pens, cages and racks placed directly in the sea, utilization of seawater in land-based tanks or collection of wild spat) and, for mollusks particularly, changes in carbonate chemistry (6.3.2.4 [*Turley et al.*, 2011; *Barton et al.*, 2012]). Environmental changes can therefore impact farm profitability, depending on target species and farm location. For example, a 1°C rise in SST is projected to shift production of Norwegian salmonids further north but may increase production overall [*Hermansen and Heen*, 2012]. Industries for non-food products, which can be important for regional livelihoods such as Black Pearl in Polynesia, are also affected by rising SST. Higher temperatures are known to affect the quality of pearl nacre, and can increase levels of disease in adult oysters [*Bell et al.*, 2011a; *Pickering et al.*, 2011; *Bell et al.*, 2013b]. Aquaculture production is also vulnerable to extreme events such as storms and floods (e.g., [*Chang et al.*, 2013]). Flooding and inundation by seawater may be a problem to shore facilities on low-lying coasts. For example, shrimp farming operations in the tropics will be challenged by rising sea levels, which will be exacerbated by mangrove encroachment and reduce the ability for thorough-drying of ponds between crops [*Della Patrona et al.*, 2011].

The impacts of climate change on marine fish stocks are expected to affect the economics of fishing and livelihoods in fishing nations through changes in the price and value of catches, fishing costs, income to fishers and fishing companies, national labor markets, and industry re-organization [*Sumaila et al.*, 2011] (6.4.1). A study of the potential vulnerabilities of national economies to the effects of climate change on fisheries, in terms of exposure to warming, relative importance of fisheries to national economies and diets, and limited societal capacity to adapt, concluded that a number countries including Malawi, Guinea, Senegal, Uganda, Sierra Leone, Mozambique, Tanzania, Peru, Columbia, Venezuela, Mauritania, Morocco, Bangladesh, Cambodia, Pakistan, Yemen, and Ukraine are most vulnerable [*Allison et al.*, 2009].

Aquaculture production is expanding rapidly [*Bostock et al.*, 2010] and will play an important role in food production and livelihoods as the human demand for protein grows. This may also add pressure on capture fisheries (7.3.2.6) [*FAO*, 2012; *Merino et al.*, 2012]. Two-thirds of farmed food fish production (marine and freshwater) is achieved with the use of feed derived from wild-harvested, small, pelagic fish and shellfish. Fluctuations in the availability and price of fishmeal and fish oil for feeds, as well as their availability, pose challenges for the growth of sustainable aquaculture production, particularly given uncertainties in changes in EBUE upwelling dynamics to climate change (30.5.5). Technological advances and management change such as increasing feed efficiencies, using alternatives to fishmeal and fish oil, and farming of herbivorous finfish, coupled with economic and regulatory incentives will reduce the vulnerability of aquaculture to the impacts of climate change on small, pelagic fish abundance [*Naylor et al.*, 2009; *Merino et al.*, 2010; *FAO*, 2012].

The challenges of optimizing the economic and social benefits of both industrial fisheries, SSF and aquaculture operations, which often already include strategies to adapt to climatic variability [*Salinger et al*., 2013], are now made more complex by climate change [*Cochrane et al*., 2009; *Brander*, 2010; 2013]. Nevertheless, adaptation options include establishment of early-warning systems to aid decision-making, diversification of enterprises and development of adaptable management systems [*Chang et al.*, 2013]. Vulnerability assessments that link oceanographic, biological, and socio-economic systems can be applied to identify practical adaptations to assist enterprises, communities, and households to reduce the risks from climate change and capitalize on the opportunists [*Pecl et al.*, 2009; *Bell et al.*, 2013b; *Norman-López et al.*, 2013]. The diversity of these adaptation options, and the policies needed to support them, are illustrated by the following examples.

30.6.2.1.1. Tropical fisheries based on large pelagic fish

Fisheries for skipjack, yellowfin, big-eye, and albacore tuna provide substantial economic and social benefits to the people of Small Island Developing States (SIDS). For example, tuna fishing license fees contribute substantially (up to 40%) to the government revenue of several Pacific Island nations [*Gillett*, 2009; *Bell et al.*, 2013b]. Tuna fishing and processing operations also contribute up to 25% of gross domestic product in some of these nations and employ over 12,000 people [*Gillett*, 2009; *Bell et al.*, 2013b]. Considerable economic benefits are also derived from fisheries for top pelagic predators in the Indian and Atlantic Oceans [*FAO*, 2012; *Bell et al.*, 2013a]. Increasing sea temperatures and changing patterns of upwelling are projected to cause shifts in the distribution and abundance of pelagic top predator fish stocks (30.5.2, 30.5.5, 30.5.6), with potential to create ‘winners’ and ‘losers’ among island economies as catches of the trans-boundary tuna stocks change among and within their exclusive economic zones (EEZs;[*Bell et al.*, 2013b; *Bell et al.*, 2013a].

A number of practical adaptation options and supporting policies have been identified to minimize the risks and maximize the opportunities associated with the projected changes in distribution of the abundant skipjack tuna in the tropical Pacific ([*Bell et al.*, 2011; *Bell et al*., 2013a], Table 30-2). These adaptation and policy options include: (1) full implementation of the regional ‘vessel day scheme’, designed to distribute the economic benefits from the resource in the face of climatic variability, and other schemes to control fishing effort in subtropical areas; (2) strategies for diversifying the supply of fish for canneries in the west of the region as tuna move progressively east; (3) continued effective fisheries management of all tuna species; (4) energy efficiency programs to assist domestic fleets to cope with increasing fuel costs and the possible need to fish further from port; and (5) the eventual restructuring of regional fisheries management organizations to help coordinate management measures across the entire tropical Pacific. Provision of operational-level catch and effort data from all industrial fishing operations to improve models for projecting redistribution of tuna stocks and quotas under climate change [*Salinger et al*. 2013][*Nicol et al.*, 2013]. Similar adaptation options and policy responses are expected to be relevant to the challenges faced by tuna fisheries in the tropical and sub-tropical Indian and Atlantic Oceans.

[INSERT TABLE 30-2 HERE
Table 30-2: Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from pelagic and coastal fisheries and aquaculture, and to maximize the opportunities. These measures are classified as ‘win-win’ (W-W) adaptations, which address other drivers of the sector in the short-term and climate change in the long-term, or ‘lose-win’ (L-W) adaptations, where benefits exceed costs in the short-term but accrue under longer-term climate change (modified from [*Bell et al.*, 2013b]).

30.6.2.1.2. Small-scale fisheries

Small-scale fisheries (SSF) account for 56% of catch and 91% of people working in fisheries in developing countries [*Mills et al.*, 2011]. SSF are fisheries that tend to operate at family or community level, have low levels of capitalization, and make an important contribution to food security and livelihoods. They are often dependent on coastal ecosystems, such as coral reefs, that provide habitats for a wide range of harvested fish and invertebrate species. Despite their importance to many developing countries, such ecosystems are under serious pressure from human activities including deteriorating coastal water quality, sedimentation, ocean warming, overfishing, and acidification (7.2.1.2, 30.3, 30.5, Box CC-CR). These pressures are translating into a steady decline in live coral cover, which is *very likely* to continue over the coming decades, even where integrated coastal zone management is in place (30.5.4, 30.5.6. For example, coral losses around Pacific Islands are projected to be as high as 75% by 2050 [*Hoegh-Guldberg et al.*, 2011a]. Even under the most optimistic projections (a 50% loss of coral by 2050), changes to state of coral reefs (Box CC-CR, Figure 30-10, Figure 30-12) are *very likely* to reduce the availability of associated fish and invertebrates that support many of the SSF in the tropics (*high confidence*). In the Pacific, the productivity of SSF on coral reefs has been projected to decrease by at least 20% by 2050 [*Pratchett et al.*, 2011b], which is also *likely* to occur in other coral reef areas globally given the similar and growing stresses in these other regions (Table SM30-1, 30.5.4).

Adaptation options and policies for building the resilience of coral reef fisheries to climate change suggested for the tropical Pacific include: (1) strengthening the management of catchment vegetation to improve water quality along coastlines; (2) reducing direct damage to coral reefs; (3) maintaining connectivity of coral reefs with mangrove and seagrass habitats; (4) sustaining and diversifying the catch of coral reef fish to maintain their replenishment potential; and (5) transferring fishing effort from coral reefs to skipjack and yellowfin tuna resources by installing anchored fish-aggregating devices (FADs) close to shore [*Bell et al.*, 2011b; *Bell et al.*, 2013b; *Bell et al.*, 2013a], Table 30-2). These adaptation options and policies represent a ‘no regrets’ strategy in that they provide benefits for coral reef fisheries and fishers irrespective of climate change and ocean acidification.

30.6.2.1.3. Northern Hemisphere HLSBS fisheries

The high latitude fisheries in the northern hemisphere span from around 30/35°N to 60°N in the North Pacific and 80°N in the North Atlantic, covering a wide range of thermal habitats supporting subtropical/temperate species to boreal/arctic species. The characteristics of these HLSBS environments, as well as warming trends, are outlined in 30.5.1 and Table 30-1. In part, as a result of 30 years of increase in temperature [*Belkin*, 2009; *Sherman et al.*, 2009], there has been an increase in the size of fish stocks associated with high latitude fisheries in the northern hemisphere. This is particularly the case for the Norwegian spring-spawning herring, which has recovered from near-extinction as a result of overfishing and a cooler climate during the 1960s [*Toresen and Østvedt*, 2000]. The major components of both pelagic and demersal high latitude fish stocks are boreal species located north of 50°N. Climate change is projected to increase high latitude plankton production and displace zooplankton and fish species poleward. As a combined result of these future changes, the abundance of fish (particularly boreal species) may increase in the northernmost part of the high latitude region [*Cheung et al.*, 2011], although increases will only be moderate in some areas.

The changes in distribution and migration of the pelagic fishes shows considerable spatial and temporal variability, which can increase tensions among fishing nations. In this regard, tension over the Atlantic mackerel fisheries has led to what many consider the first climate-change related conflict between fishing nations ([*Cheung et al.*, 2012], 30.6.5), and which has emphasized the importance of developing international collaboration and frameworks for decision making [*Miller et al.*, 2013](30.6.7, 15.4.3.3). The Atlantic mackerel has over the recent decades been a shared stock between the EU and Norway. However, the recent advancement of the Atlantic mackerel into the Icelandic EEZ during summer has resulted in Icelandic fishers operating outside the agreement between the EU and Norway. Earlier records of mackerel from the first half of the 20th and second half of the 19th century show, however, that mackerel was present in Icelandic waters during the earlier warm periods [*Astthorsson et al.*, 2012]. In the Barents Sea, the North-east Arctic cod, *Gadus morhua*, reached record-high abundance during 2012 and also reached its northernmost-recorded distribution (82°N)[*ICES*, 2012]. A further northward migration is impossible since this would be into the Deep Sea Polar Basin, beyond the habitat of shelf species. A further advancement eastwards to the Siberian shelf is, however, possible. The North-east Arctic cod stock is shared exclusively by Norway and Russia, and to date there has been a good agreement between those two nations on the management of the stock. These examples highlight the importance of international agreements and cooperation (Table 30-4).

The HLSBS fisheries constitute a large-scale high-tech industry, with large investments in highly mobile fishing vessels, equipment, and land-based industries with capacity for adapting fisheries management and industries for climate change [*Frontiers-Economics-Ltd*, 2013]. Knowledge of how climate fluctuations and change affect the growth, recruitment, and distribution of fish stocks is presently not incorporated into fisheries management strategies [*Perry et al.*, 2010]. These strategies are vital for fisheries that hope to cope with the challenges of a changing ocean environment, and are centrally important to any attempt to develop ecosystem-based management and sustainable fisheries under climate change. The large pelagic stocks, with their climate-dependent migration pattern, are shared among several nations. Developing equitable sharing of fish quotas through international treaties (Table 30-4) is a necessary adaptation for a sustainable fishery. Factors presently taken into account in determining the shares of quotas are the historical fishery, bilateral exchanges of quotas for various species, and occupation time of the stocks in the various EEZs.

30.6.2.2. Tourism

Tourism recreation represents one of the world's largest industries, accounting for 9% (>US$6 trillion) of global GDP and employing over 255 million people. It is expected to grow by an average of 4% annually and reach 10% of global GDP within the next 10 years [*WTTC*, 2012]. As with all tourism, that which is associated with the Ocean is heavily influenced by climate change, global economic and socio-political conditions, and their interactions ([*Scott et al.*, 2012b]; 10.6.1). Climate change, through impacts on ecosystems (e.g., coral reef bleaching), can reduce the appeal of destinations, increase operating costs, and/or increase uncertainty in a highly sensitive business environment [*Scott et al.*, 2012b].

Several facets of the influence of climate change on the Ocean directly impact tourism (10.6.1, 10.6.2). Tourism is susceptible to extreme events such as violent storms, long periods of drought, and/or extreme precipitation events (5.3.3, 10.6.1, [*IPCC*, 2012]). Sea level rise through its influence on coastal erosion and submergence, salinization of water supplies, and changes to storm surge, increases the vulnerability of coastal tourism infrastructure, tourist safety, and iconic ecosystems (*high confidence*) (5.3.3.2 10.6.1, [*IPCC*, 2012], Table SPM.1). For example, approximately 29% of resorts in the Caribbean are within 1 m of the high tide mark and 60% are at risk of beach erosion from rapid sea level rise [*Scott et al.*, 2012a].

Increasing sea temperatures (30.3.1.1) can change the attractiveness of locations and the opportunities for tourism through their influence on the movement of organisms and the state of ecosystems such as coral reefs (10.6.2, Box CC-CR, [*UNWTO and UNEP*, 2008]). Mass coral bleaching and mortality (triggered by elevated sea temperatures, *high confidence*) can decrease the appeal of destinations for diving-related tourism, although the level of awareness of tourists of impacts (e.g., <50% of tourists were concerned about coral bleaching during 1998) and expected economic impacts have been found to be uncertain [*Scott et al.*, 2012b]. Some studies, however, have noted reduced tourist satisfaction and identified 'dead coral' as one of the reasons for disappointment at the end of the holiday [*Westmacott et al.*, 2001]. Tourists respond to changes in factors such as weather and opportunity by expressing different preferences. For example, preferred conditions and hence tourism are projected to shift towards higher latitudes with climate change, or from summer to cooler seasons [*Amelung et al.*, 2007] (10.6.2).

Options for adaptation by the marine tourism sector include: (1) identifying and responding to inundation risks with current infrastructure, and planning for projected sea level rise when building new tourism infrastructure (5.5, [*Scott et al.*, 2012a]); (2) promoting shoreline stability and natural barriers by preserving ecosystems such as mangroves, salt marshes and coral reefs (5.5, [*Scott et al.*, 2012b]); (3) deploying forecasting and early-warning systems in order to anticipate challenges to tourism and natural ecosystems [*Strong et al.*, 2011; *IPCC*, 2012]; (4) preparation of risk management and disaster preparation plans in order to respond to extreme events; (5) reducing the effect of other stressors on ecosystems and building resilience in iconic tourism features such as coral reefs and mangroves; and (6) educating tourists to improve understanding the negative consequences of climate change over those stemming from local stresses [*Scott et al.*, 2012b; *Scott et al.*, 2012a]. Adaptation plans for tourism industries need to address specific operators and regions. For example, some operators may have costly infrastructure at risk while others may have few assets but are dependent on the integrity of natural environments [*Turton et al.*, 2010].

30.6.2.3. Shipping

International shipping accounts for >80% of world trade by volume [*UNCTAD*, 2009a; b] and ~3% of global CO_2 emissions from fuel combustion although CO_2 emissions are expected to increase 2-3 fold by 2050 [*Heitmann and Khalilian*, 2010], WGIII 8.1, 8.2). Changes in shipping routes [*Borgerson*, 2008], variation in the transport network due to shifts in grain production and global markets, as well as new fuel and weather-monitoring technology, may alter these emission patterns (WGIII 8.3, 8.5). Extreme weather events, intensified by climate change, may interrupt ports and transport routes more frequently, damaging infrastructure and introducing additional dangers to ships, crews, and the environment [*UNCTAD*, 2009a; b; *Pinnegar et al.*, 2012](10.4.4). These issues have been assessed by some countries which have raised concerns over the potential for costly delays and cancellation of services, and the implications for insurance premiums as storminess and other factors change increase risks [*Thornes et al.*, 2012].

Climate change may benefit maritime transport by reducing Arctic sea ice and consequently shorten travel distances between key ports [*Borgerson*, 2008] thus also decreasing total GHG emissions from ships (WGIII 8.5.2). Currently, reliability of this route limits its use [*Schøyen and Bråthen*, 2011], and the potential full operation of the Northwest Passage and Northern Sea Route would require a transit management regime, regulation (e.g., navigation, environmental, safety, and security), and a clear legal framework to address potential territorial claims that may arise, with a number of countries having direct interest in the Arctic. Further discussion of issues around melting Arctic sea ice and the Northern Sea Route are given in Chapter 28 (28.2.5, 28.3.4).

30.6.2.4. Offshore Energy and Mineral Resource Extraction and Supply

The marine oil and gas industry face potential impacts from climate change on its ocean-based activities. Over 100 oil and gas platforms were destroyed in the Gulf of Mexico by the unusually strong hurricanes Katrina and Rita in 2005. Other consequences for oil pipelines and production facilities ultimately reduced US refining capacity by 20% [*IPCC*, 2012]. The increasing demand for oil and gas has pushed operations to waters 2000 m deep or more, far beyond continental shelves. The very large-scale moored developments required are exposed to greater hazards and higher risks, most of which are not well understood by existing climate/weather projections. Although there is a strong trend towards seafloor well completions with a complex of wells, manifolds, and pipes that are not exposed to surface forcing, these systems face different hazards from instability and scouring of the unconsolidated sediments by DS currents [*Randolph et al.*, 2010]. The influence of warming oceans on sea floor stability is widely debated due largely to uncertainties about the effects of methane and methane hydrates [*Sultan et al.*, 2004; *Archer et al.*, 2009; *Geresi et al.*, 2009]. Declining sea ice is also opening up the Arctic to further oil and gas extraction., Discussion of the potential expansion of oil and mineral production in the Arctic is made in Chapter 28 (28.2.5, 28.2.6, 28.3.4).

The principal threat to oil and gas extraction and infrastructure in maritime settings is the impact of extreme weather [*Kessler et al.*, 2011], which is *likely* to increase given that future storm systems are expected to have greater energy [*Emanuel*, 2005; *Trenberth and Shea*, 2006; *Knutson et al.*, 2010]. Events such as Hurricane Katrina have illustrated challenges which will arise for this industry with projected increases in storm intensity [*Cruz and Krausmann*, 2008]. In this regard, early warning systems and integrated planning offer some potential to reduce the effect of extreme events [*IPCC*, 2012].

30.6.3. Human Health

The major threats to public health due to climate change include diminished security of water and food supplies, extreme weather events, and changes in the distribution and severity of diseases, including those due to marine biotoxins ([*Costello et al.*, 2009], 5.4.3.5, 6.4.2.3, 11.2). The predominately negative impacts of disease for human communities are expected to be more serious in low-income areas such as South-east Asia, southern and east Africa, and various sub-regions of South America [*Patz et al.*, 2005], which also have under-resourced health systems [*Costello et al.*, 2009]. Many of the influences are directly or indirectly related to basin-scale changes in the Ocean (e.g., temperature, rainfall, plankton populations, sea level rise, and ocean circulation [*McMichael et al.*, 2006]). Climate change in the Ocean may influence the distribution of diseases like cholera (11.5.2.1), and the distribution and occurrence of harmful algal blooms (HAB). The frequency of cholera outbreaks induced by *Vibrio cholerae* and other enteric pathogens are correlated with sea surface temperatures, multidecadal fluctuations of ENSO, and plankton blooms, which may provide insight into how this disease may change with projected rates of ocean warming [*Colwell*, 1996; *Pascual et al.*, 2000; *Rodó et al.*, 2002; *Patz et al.*, 2005; *Myers and Patz*, 2009; *Baker-Austin et al.*, 2012]. The incidence of diseases such as ciguatera also shows a link to ENSO, with ciguatera becoming more prominent after periods of elevated sea temperature. This indicates that ciguatera may become more frequent in a warmer climate [*Llewellyn*, 2010], particularly given the higher prevalence of ciguatera in areas with degraded coral reefs (*low confidence*) [*Pratchett et al.*, 2011a].

30.6.4. Ocean-based Mitigation

30.6.4.1 Deep Sea Carbon Sequestration

Carbon dioxide capture and storage into the deep sea and geologic structures are also discussed in WGIII Chapter 7 (7.5.5, 7.8.2, 7.10, 7.12) The economic impact of deliberate CO_2 sequestration beneath the sea floor has previously been reviewed [*IPCC*, 2005]. Active CO_2 sequestration from co-produced CO_2 into sub-sea geologic formations is being instigated in the North Sea and in the Santos Basin offshore from Brazil. These activities will increase as offshore oil and gas production increasingly exploits fields with high CO_2 in the source gas and oil. Significant risks from the injection of high levels of CO_2 into deep ocean waters have been identified for DS organisms and ecosystems although chronic effects have not yet been studied. These risks are similar to those discussed previously with respect to ocean acidification and could further exacerbate declining O_2 levels and changing trophic networks in deep water areas [*Seibel and Walsh,* 2001] (6.4.2.2).

There are significant issues within the decision frameworks regulating these activities. Dumping of any waste or other matter in the sea, including the seabed and its subsoil, is strictly prohibited under the 1996 London Protocol (LP) except for those few materials listed in Annex I. Annex 1 was amended in 2006 to permit storage of CO_2 under the seabed. “Specific Guidelines for Assessment of Carbon Dioxide Streams for Disposal into Sub-Seabed Geological Formations” were adopted by the parties to the LP in 2007. The Guidelines take a precautionary approach to the process, requiring Contracting Parties under whose jurisdiction or control such activities are conducted to issue a permit for the disposal subject to stringent conditions being fulfilled [*Rayfuse and Warner*, 2012].

30.6.4.2 Offshore renewable energy

Renewable energy supply from the Ocean includes ocean energy and offshore wind turbines. The global technical potential for ocean and wind energy is not as high as solar energy although considerable potential still remains. Detailed discussion of the potential of renewable energy sources are given in WGIII Chapter 7 (7.4.2, 7.5.3, 7.8.2). There is an increasing trend in the renewable energy sector to offshore wind turbines (10.2.2). At present, there is *high uncertainty* about how changes in wind intensity and patterns, and extreme events, will impact the offshore wind energy sector. Given the design and engineering solutions available to combat climate change impacts (Table 10.1, Table 10.7), it is *unlikely* that this sector will face insurmountable challenges from climate change.

30.6.5. Maritime Security and Related Operations

Climate change and its influence on the Ocean has become an area of increasing concern in terms of the maintenance of national security and the protection of citizens. These concerns have arisen as Nation States increasingly engage in operations ranging from humanitarian assistance in climate-related disasters to territorial issues exacerbated by changing coastlines, human communities, resource access, and new seaways [*Kaye*, 2012; *Rahman*, 2012], 12.6.1). In this regard, increasing sea levels along gently sloping coastlines can have the seemingly perverse outcome that the territorial limits to the maritime jurisdiction of the State might be open to question as the distance from national baselines to the outer limits of the EEZ increases beyond 200 nm over time [*Schofield and Arsana*, 2012].

Changes in coastal resources may also be coupled with decreasing food security to compound coastal poverty and lead, in some cases, to increased criminal activities such as piracy, IUU fishing, and human, arms and drug trafficking [*Kaye*, 2012]. While the linkages have not been clearly defined in all cases, it is possible that changes in the Ocean as result of climate change will increase pressure on resources aimed at maintaining maritime security and countering criminal activity, disaster relief operations, and freedom of navigation (12.6.2). National maritime security capacity and infrastructure may also require rethinking as new challenges present themselves as a result of climate change and ocean acidification (12.6.1-2) [*Allen and Bergin*, 2009; *Rahman*, 2012]. Opportunities may also arise from changes to international geography such as formation of new ice-free seaways through the Arctic, which may benefit some countries in terms of maintaining maritime security and access (28.2.6). Conversely, such new features may also lead to increasing international tensions as States perceive new vulnerabilities from these changes to geography.

Like commercial shipping (30.6.2.3), naval operations in many countries result in significant greenhouse emissions (e.g., the US Navy emits around 2% of the national greenhouse gas emissions, [*Mabus*, 2010]). As a result, there are a number of programs being implemented by navies around the world to try and reduce their carbon footprint and air pollution such as improving engine efficiency, reducing fouling of vessels, increasing the use of biofuels, and using nuclear technology for power generation, amongst other initiatives.

30.7. Synthesis and Conclusions

Evidence that human activities are fundamentally changing the Ocean is *virtually certain*. Sea temperatures have increased rapidly over the past 60 years at the same time as pH has declined, consistent with the expected influence of rising atmospheric concentrations of CO_2 and other greenhouse gases (*very high confidence*). The rapid rate at which these fundamental physical and chemical parameters of the Ocean are changing is unprecedented within the last 65 Ma (*high confidence*) and possibly 300 Ma (*medium confidence*). As the heat content of the Ocean has increased, the Ocean has become more stratified (*very likely*), although there is considerable regional variability. In some cases, changing surface wind has influenced the extent of mixing and upwelling, although our understanding of where and why these differences occur regionally is uncertain. The changing structure and function of the Ocean has led to changes in parameters such as O_2, carbonate ions, and inorganic nutrients concentrations (*high confidence*). Not surprisingly, these fundamental changes have resulted in responses by key marine organisms, ecosystems and ecological processes, with negative implications for hundreds of millions of people that depend on the ecosystem goods and services provided by the Ocean (*very likely*). Marine organisms are migrating at rapid rates towards higher latitudes, fisheries are transforming, and many organisms are shifting their reproductive and migratory activity in concert with the changes in temperature and other parameters. Ecosystems such as coral reefs are declining rapidly (*high confidence*). An extensive discussion of these changes is provided in previous sections and in other chapters of AR5.

[INSERT TABLE 30-3 HERE
Table 30-3 Key risks to ocean and coastal issues from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels

are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

30.7.1. Key Risks and Vulnerabilities

The rapid changes in the physical, chemical, and biological state of the Ocean pose a number of key risks and vulnerabilities for ecosystems, communities, and nations worldwide. Table 30-3 and Figure 30-12 summarize risks and vulnerabilities from climate change and ocean acidification, along with adaptation issues and prospects, and a summary of expert opinion on how these risks will change under further changes in environmental conditions.

Rising ocean temperatures are changing the distribution, abundance, and phenology of many marine species and ecosystems, and consequently represent a key risk to food resources, coastal livelihoods, and industries such as tourism and fishing, especially for HLSBS, CBS, STG, and EBUE (Table 30-3, Figure 30-12a-b, 30.5, Box CC-MB, 6.3.1 6.3.4, 7.3.2.4). Key risks involve changes in the distribution and abundance of key fishery species (Figure 30-12a 2, 4; Figure 30-12b *2*; *high confidence*) as well as the spread of disease and invading organisms, each of which has the potential to impact ecosystems as well as aquaculture and fishing (Table 30-3, 6.3.5, 6.4.1.1, 6.5.3, 7.3.2.4, 7.4.2, 29.5.3, 29.5.4). Adaptation to these changes may be possible in the short-term through dynamic fisheries policy and management (i.e., relocation of fishing effort, Table 30-3), as well as monitoring and responding to potential invading species in coastal settings. The increasing frequency of thermal extremes (Box CC-HS) will also increase the risk that the thermal threshold of corals and other organisms is exceeded on a more frequent basis (especially in CBS, STG, SES, HLSBS, and EUS ocean regions; 30.5, Box CC-CR, 6.2). These changes pose a key risk to vulnerable ecosystems such as mangroves and coral reefs, with potential to have a series of serious impacts on fisheries, tourism, and coastal ecosystem services such as coastal protection (Table 30-3, 30.5, Box CC-CR, 5.4.2.4, 6.3.2. 6.3.5, 6.4.1.3, 7.2.1.2, 29.3.1.2). Genetic adaptation of species to increasing levels of stress may not occur fast enough given fairly long generation times of organisms such as reef building corals and many other invertebrates and fish (Table 30-3). In this case, risks may be reduced by addressing non-climate change related stresses (e.g., pollution, overfishing), although this strategy could have minimal impact if further increases in sea temperature occur (*high confidence*). The loss of these important coastal ecosystems is associated with the emerging risks associated with the collapse of some coastal fisheries along with livelihoods, food, and regional security (*medium confidence*). These changes are *likely* to be exacerbated by other key risks such as coastal inundation and habitat loss due to sea level rise, as well is intensified precipitation events (*high confidence*) (5.4, Box CC-CR). Adaptation options in this case include engineered coastal defences, re-establishing coastal vegetation such as mangroves, protecting water supplies from salination, and developing strategies for coastal communities to withdraw to less vulnerable locations over time (5.5).

The recent decline in O_2 concentrations has been ascribed to warming through the effect on ocean mixing and ventilation, as well as the solubility of O_2 and its consumption by marine microbes (30.3.2.3, 30.5.7, 6.1.1.3, 6.3.3). This represents a key risk to ocean ecosystems (Figure 30-12a *6*, Figure 30-12b *3; medium confidence*). These changes increase the vulnerability of marine communities, especially those below the euphotic zone, to hypoxia and ultimately lead to a restriction of suitable habitat (Figure 30-12a *7*, *high confidence*). In the more extreme case, often exacerbated by the contribution of organic carbon from land-based sources, 'dead zones' may form . Decreasing oxygen, consequently, is *very likely* to increase the vulnerability of fisheries and aquaculture (Figure 30-12b *1, 3; medium confidence*), and consequently puts livelihoods at risk, particularly in EBUE (e.g., California and Humboldt Current ecosystems; 30.5.5), SES (e.g., Baltic and Black Seas; 30.5.3) and CBS (e.g., Gulf of Mexico, NE Indian Ocean; 30.5.4, 30.3.2.3). It is *very likely* that the warming of surface waters has also increased the stratification of the upper ocean by about 4% between 0 and 200 m from 1971–2010 in all oceans north of about 40°S. In many cases, there is significant adaptation opportunity to reduce hypoxia locally by reducing the flow of organic carbon and hence microbial activity within these coastal systems (30.5.4). Relocating fishing effort, and modifying procedures associated with industries like aquaculture, may offer some opportunity to adapt to these changes (*likely*). Declining O_2 concentrations is likely to have significant impacts on DS habitats, where organisms are relatively sensitive to environmental changes of this nature due to the very constant conditions under which they have evolved (30.5.7).

Ocean acidification has increased the vulnerability of ocean ecosystems by affecting key aspects of the physiology and ecology of marine organisms (particularly in CBS, STG, and SES regions; Table 30-3; 6.3.2, Box CC-OA). Decreasing pH and carbonate ion concentrations reduce the ability of marine organisms to produce shells and skeletons, and may interfere with a broad range of important processes such as reproduction, navigation, and neural function in a broad range of marine organisms which show minor to major influences of ocean acidification on their biology (30.3.2.2, 6.3.2, Box CC-OA). Natural variability in ocean pH can interact with ocean acidification to create damaging periods of extremes (i.e., high CO_2, low O_2 and pH), which can have a strong effect on coastal activities such as aquaculture (*medium confidence* Figure 30-12b *1*; Box CC-UP, 6.2). There may be opportunity to adapt aquaculture to increasingly acidic conditions by monitoring natural variability and restricting water intake to periods of optimal conditions. Reducing other non-climate change or ocean acidification associated stresses also represents an opportunity to build greater ecological resilience against the impacts of changing ocean carbonate chemistry. Ocean acidification is also an emerging risk for DS habitats as CO_2 continues to penetrate the Ocean, although the impacts and adaptation options are poorly understood and explored. Ocean acidification has heightened importance for some groups of organisms and ecosystems (Box CC-OA). In ecosystems that are heavily dependent on the accumulation of calcium carbonate over time (e.g., coral reefs, *Halimeda* beds), increasing ocean acidification puts at risk ecosystems services which are critical for hundreds of thousands of marine species, plus people and industries, particularly within CBS, STG and SES (*high confidence)*. Further risks may emerge from the non-linear interaction of different factors (e.g., increasing ocean temperature may amplify effects of ocean acidification, and *vice versa*) and via the interaction of local stressors with climate change (e.g., interacting changes may lead to greater ecosystems disturbances than each impact on its own). There is an urgent need to understand these types of interactions and impacts, especially given the long time it will take to return ocean ecosystems to pre-industrial pH and carbonate chemistry (i.e., tens of thousands of years, FAQ 30.1, should CO_2 emissions continue at the current rate).

It is *very likely* that surface warming has increased stratification of the upper ocean is contributing to the decrease in O_2 along with the temperature related decreases in oxygen solubility (WGI 3.8.3). Changes to wind speed, wave height, and storm intensity influence the location and rate of mixing within the upper layers of the Ocean and hence the concentration of inorganic nutrients (e.g., in EBUE, EUS; Figure 30-12a *1, 3*). These changes to ocean structure increase the risks and vulnerability of food webs within the Ocean. However, our understanding of how primary productivity is going to change in a warming and more acidified ocean is limited, as is our understanding of how upwelling will respond to changing surface wind as the world continues to warm (Box CC-PP, Box CC-UP). As already discussed, these types of changes can have implications for the supply of O_2 into the Ocean and the upward transport of inorganic nutrients to the euphotic zone. While our understanding is limited, there is significant potential for regional increases in wind speed to result in greater rates of upwelling and the supply of inorganic nutrients to the photic zone. While this may increase productivity of phytoplankton communities and associated fisheries, greater rates of upwelling can increase the risk of hypoxic conditions developing at depth as excess primary production sinks into the Ocean and stimulates microbial activity at depth (Table 30-3, 30.3.2.3, 30.5.5, 6.1.1.3). Changes in storm intensity can increase the risk of damage to shipping and industrial infrastructure, which increases the risk of accidents and delays to the transport of products between countries, security operations, and the extraction of minerals from coastal and oceanic areas (30.6.2, [*IPCC*, 2012].

The proliferation of key risks and vulnerabilities to the goods and services provided by ocean ecosystems as a result of ocean warming and acidification generate a number of key risks for the citizens of almost every nation. Risks to food security and livelihoods are expected to increase over time, aggravating poverty and inequity (Table 30-3). As these problems increase, regional security is likely to deteriorate as disputes over resources increase, along with increasing insecurity of food and nutrition (Table 30-3, [*IPCC*, 2012], 30.6.5, 12.4-12.6, 29.3).

30.7.2. Global Frameworks for Decision-Making

Global frameworks for decision-making are central to management of vulnerability and risk at the scale and complexity of the world's oceans. General frameworks and conventions for policy development and decision-making within oceanic and coastal regions are important in terms of the management of stressors not directly due to ocean warming or acidification, but which may influence the outcome of these two factors. Table 30-3 and Table 30-4 outlines a further set of challenges arising from multiple interacting stressors, as well as potential risks and vulnerabilities, ramifications, and adaptation options. In the latter case, examples of potential global frameworks and initiatives for initiating and managing these adaptation options are described. These frameworks represent opportunities for global cooperation and the development of international, regional, and national policy responses to the challenges posed by the changing ocean [*Kenchington and Warner*, 2012; *Tsamenyi and Hanich*, 2012; *Warner and Schofield*, 2012].

[INSERT TABLE 30-4 HERE
Table 30-4: Ramifications, adaptation options and frameworks for decision-making for ocean regions. Symbols are as follows: T = sea temperature; UW = upwelling; OA = ocean acidification; NU = nutrient concentration; IC = ice cover; SS = storm strength; SLR = sea level rise (↑ = Increased; ↓ = decreased; italics = uncertain). Acronyms are: CBD (Convention on Biological Diversity); CTI (Coral Triangle Initiative); GEF (Global Environment Facility); IHO (International Hydrographic Organization); ILO (International Labor Organization); IOM (International Organization of Migration); ISPS (International Ship and Port Facility Security); MARPOL (International Convention for the Prevention of Pollution From Ships); PACC (Pacific Adaptation to Climate Change Project); PEMSEA (Partnerships in Environmental Management for the Seas of East Asia); RFMO (Regional Fisheries Management Organizations); SPREP (Secretariat of the Pacific Regional Environment Programme); UNCLOS (United Nations Convention on the Law of the Sea); UNHCR (United Nations High Commissioner for Refugees); UNSFSA (Straddling Fish Stocks Agreement); and WHO (World Health Organization).]

The United Nations Convention on the Law of the Sea (UNCLOS) was a major outcome of the third UN Conference on the Law of the Sea (UNCLOS III). The European Union and 164 countries have joined in the Convention. UNCLOS replaced earlier frameworks that were built around the 'freedom of the seas' concept and which limited territorial rights to 3 nm off a coastline. UNCLOS provides a comprehensive framework for the legitimate use of the Ocean and its resources, including maritime zones, navigational rights, protection and preservation of the marine environment, fishing activities, marine scientific research, and mineral resource extraction from the seabed beyond national jurisdiction. The relationship between climate change and UNCLOS is not clear and depends on interpretation of the key elements within the UNFCCC (United Nations Framework Convention for Climate Change) and Kyoto Protocol [*Boyle*, 2012]. However, UNCLOS provides mechanisms to help structural adaptation in response to challenges posed by climate change. In a similar way, there is a wide range of other policy and legal frameworks that structure and enable responses to the outcomes of rapid anthropogenic climate change in the Ocean.

There are many existing international conventions and agreements that explicitly recognize climate change (Table 30-4). The United Nations Straddling Fish Stocks Agreement (UNSFSA) aims at enhancing international cooperation of fisheries resources, with an explicit understanding under article 6 that management needs to take account "existing and predicted oceanic, environmental and socio-economic conditions" and to undertake "relevant research, including surveys of abundance, biomass surveys, hydro-acoustic surveys, research on environmental factors affecting stock abundance, and oceanographic and ecological studies" (Annex one, article 3). International conventions such as these will become increasingly important as changes to the distribution and abundance of fisheries are modified by climate change and ocean acidification.

Global frameworks for decision-making are increasingly important in the case of the Ocean, most of which falls outside national boundaries [*Elferink*, 2012; *Warner*, 2012]. Approximately 64% of the Ocean (40% of the Earth's surface) is outside EEZs and continental shelves of the world's nations (high seas and seabed beyond national jurisdiction). With rapidly increasing levels of exploitation, there are increasing calls for more effective decision frameworks aimed at regulating fishing and other activities (e.g., bio-prospecting) within these ocean 'commons'. These international frameworks will become increasingly valuable as nations respond to impacts on fisheries resources that stretch across national boundaries. One such example is the multilateral cooperation that was driven by President Yudhoyono of Indonesia in August 2007 and led to the Coral Triangle Initiative on Coral Reefs, Fisheries, and Food Security (CTI), which involves region-wide (involving 6.8 million km^2 including 132,800 km of coastline) cooperation between the governments of Indonesia, the Philippines, Malaysia, Papua New Guinea, the Solomon Islands, and Timor Leste on reversing the decline in coastal ecosystems such as coral reefs [*Clifton*, 2009; *Hoegh-Guldberg et al.*, 2009; *Veron et al.*, 2009]. Partnerships, such as the CTI, have the potential to provide key frameworks to address issues such as interaction between the over-exploitation of coastal fishing resources and the recovery of reefs from mass coral bleaching and mortality, and the implications of the movement of valuable fishery stocks beyond waters under national jurisdiction. An initiative called the Global Partnership for Oceans set out (www.globalpartnershipforoceans.org, March 28, 2012) to establish a global framework with which to share experience, resources and expertise, as well as to engage governments, industry, civil, and public sector interests in both understanding and finding solutions to key issues such as overfishing, pollution, and habitat destruction [*GPO*, 2012]. Similarly, the Areas Beyond National Jurisdiction (ABNJ, Global Environment Facility) Initiative has been established to promote the efficient, collaborative, and sustainable management of fisheries resources and biodiversity conservation across the Ocean.

Global partnerships are also essential for providing support to the many nations that often do not have the scientific or financial resources to solve the challenges that lie ahead [*Busby*, 2009; *Mertz et al.*, 2009]. In this regard, international networks and partnerships are particularly significant in terms of assisting nations in developing local adaptation solutions to their ocean resources. By sharing common experiences and strategies through global networks, nations have the chance to tap into a vast array of options with respect to responding to the negative consequences of climate change and ocean acidification on the world's ocean and coastal resources.

30.7.3. Emerging Issues, Data Gaps, and Research Needs

While there has been an increase in the number of studies being undertaken to understand the physical, chemical, and biological changes within the Ocean in response to climate change and ocean acidification, the number of marine studies still lag significantly behind terrestrial and atmospheric studies [*Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al.*, 2013]. Rectifying this gap should be a major international objective given the importance of the Ocean in terms of understanding and responding to future changes and consequences from ocean warming and acidification.

30.7.3.1. Changing Variability and Marine Impacts

Understanding the long-term variability of the Ocean is critically important in terms of the detection and attribution of changes to climate change (30.3, 30.5.8), but also in terms of the interaction between variability and anthropogenic climate change. Developing instrument systems that expand the spatial and temporal coverage of the Ocean and key processes will be critical to documenting and understanding its behavior under further increases in average global temperature and changes the atmospheric concentration of CO_2. International collaborations such as the Argo network of oceanographic floats are rapidly improving our understanding of the physical behavior of the Ocean and will provide important insight into its long-term subsurface variability [*Schofield et al.*, 2013].

30.7.3.2. Surface Wind, Storms, and Upwelling

Improving our understanding of the potential behavior of surface wind in a warming world is needed for improving our understanding of how upwelling will change in key regions (e.g., EUS, EBUE; Box CC-UP). Understanding these changes will provide important information for future fisheries management but will also illuminate the potential risks of intensified upwelling leading to hypoxia at depth and the potential expansion of 'dead zones' (30.3.2; 30.5.2-30.5.4). Understanding surface wind in a warming climate will also yield important information on surface mixing as well as how surface wave height might also vary, improving our understanding of potential interactions in coastal areas between wind, waves, and sea level rise (30.3.1). Given the importance of mixing and upwelling to the supply of inorganic nutrients to the surface layers of the ocean, understanding these important phenomena at the ocean-atmosphere interface will provide important insight into how ocean warming and acidification are likely to impact ecosystems, food webs and ultimately central important fisheries such as those found along the west coasts of Africa and the Americas.

30.7.3.3. Declining O_2 Concentrations

The declining level of O_2 in the Ocean is an emerging issue of major importance (30.3.2). Developing a better understanding of the role and temperature sensitivity of microbial systems in determining O_2 concentrations will enable a more coherent understanding of the changes and potential risks to marine ecosystems. Given the importance of microbial systems to the physical, chemical, and biological characteristics of the Ocean, it is extremely important that these systems receive greater focus, especially with regards to their response to ocean warming and acidification. This is particularly important for the DS (>1000 m), which is the most extensive habitat on the planet. In this respect, increasing our understanding of DS habitats and how they may be changing under the influence of climate change and ocean acidification is of great importance. Linkages between changes occurring in the surface layers and those associated with the DS are particularly important in light of our need to understand how rapidly changes are occurring and what the implications are for the metabolic activity and O_2 content of DS habitats.

30.7.3.4. Ocean Acidification

The rapid and largely unprecedented changes to ocean acidification represent an emerging issue given the central importance of pH and the concentration of ions such as carbonate in the biology of marine organisms (Box CC-OA). Despite the relatively short history of research on this issue, there are already a large number of laboratories and field studies that demonstrate a large range of effects across organisms, processes, and ecosystems. Key gaps [*Gattuso et al.*, 2011] remain in our understanding of how ocean acidification will interact with other changes in the Ocean, and whether or not biological responses to ocean acidification are necessarily linear. The vulnerability of fishery species (e.g., mollusks) to ocean acidification represents an emerging issue, with a need for research to understand and develop strategies for industry to minimize the impacts. Understanding of how carbonate structures like coral reefs and *Halimeda* beds, will respond to a rapidly acidifying ocean represents a key gap and research need, especially in understanding the rate at which consolidated carbonate structures and related habitats are likely to erode and dissolve. Interactions between ocean acidification, upwelling, and decreasing O_2 represent additional areas of concern and research. There is also a need to improve our understanding of the socio-economic ramifications of ocean acidification [*Turley et al.*, 2011; *Hilmi et al.*, 2013].

30.7.3.5. Net Primary Productivity

Oceanic phytoplankton are responsible for 50% of global net primary productivity. However, our understanding of how oceanic primary production is likely to change in a warmer and more acidified ocean is uncertain (Box CC-PP; Box CC-UP). Changes in net primary productivity will resonate through food webs and ultimately affect fish production. Given the central role that primary producers and their associated ecological processes play in ocean ecosystem functioning, it is crucial that we improve our understanding of how net primary productivity is likely to vary at global and regional levels (30.5.2, 30.5.5). At the same time, understanding how plankton communities will vary spatially and temporarily will be important in any attempt to understand how fish populations will fare in a warmer and more acidified ocean. The research challenge is to determine when and where net primary production is expected to change, coupled with research on adaptation strategies for changes to the global distribution of seafood procurement, management and food security.

30.7.3.6. Movement of Marine Organisms and Ecosystems

Marine organisms are moving, generally towards higher latitudes or deeper waters, consistent with the expectation of a warming ocean. Our current understanding of which organisms and ecosystems are moving, and the ramifications for reorganisation of ecosystems and communities, and the implications for nations is uncertain at best. Given the implications for fisheries, invasive species, and the spread of disease, it is an imperative that our understanding of the movement of ecosystems is improved. Documentation of species' responses and a deeper understanding of the processes that lead to persistent range shifts, and a focus on the ecosystem, social and economic implications of range shifts is a research need.

30.7.3.7. Understanding Cumulative and Synergistic Impacts

Understanding cumulative and synergistic impacts is poorly developed for ocean systems. Much of our understanding has been built on experimental approaches that are focused on single stressors that respond gradually without interaction or have impacts that accumulate over time (Table 30-3). Multifactorial experiments exploring the impact of combined variables (e.g., elevated temperature and acidification at the same time) will enable more realistic projections of the future to be established. Equally, developing a better understanding of how biological and ecological responses change in relation to key environmental variables should also be a goal of future research. In this regard, assumptions that responses are likely to be gradual and linear over time ultimately have little basis, yet are widespread within the scientific literature.

30.7.3.8. Reorganization of Ecosystems and Food Webs

The pervasive influence of ocean warming and acidification on the distribution, abundance, and function of organisms and processes has and will continue to drive the reorganization of ecosystems and food webs (*virtually certain*) ([*Hoegh-Guldberg and Bruno*, 2010; *Poloczanska et al.*, 2013], Box CC-MB). One of the inevitable outcomes of differing tolerances and responses to climate change and ocean acidification is the development of novel assemblages of organisms in the near future. Such communities are likely to have no past or contemporary counterparts, and will consequently require new strategies for managing coastal areas and fisheries. Changes to a wide array of factors related or not related to climate change have the potential to drive extremely complex changes in community structure and, consequently, food web dynamics. Developing a greater capability for detecting and understanding these changes will be critical for future management of ocean and coastal resources.

30.7.3.9. Socio-ecological Resilience

Many communities depend on marine ecosystems for food and income yet our understanding of the consequences of environmental degradation is poor. For example, while there is *high confidence* that coral reefs will continue to deteriorate at current rates of climate change and ocean acidification [*Gardner et al.*, 2003; *Bruno and Selig*, 2007; *De'ath et al.*, 2012], there is relatively poor understanding of the implications for the hundreds of millions of people who depend on these important coastal ecosystems for food and livelihoods. Improving our understanding of how to reinforce socio-ecological resilience in communities affected by the deterioration of key coastal and oceanic ecosystems is central to developing effective adaptation responses to these growing challenges (30.6 Table 30-3, Table 30-4).

Frequently Asked Questions

FAQ 30.1: Can we reverse the climate change impacts on the ocean? *[to be inserted after Section 30.3.2]*
In less than 150 years, greenhouse gas emissions have resulted in such major physical and chemical changes in our oceans that it will take thousands of years to reverse them. There are a number of reasons for this. Given its large mass and high heat capacity, the ability of the Ocean to absorb heat is 1000 times larger than that of the atmosphere. The Ocean has absorbed at least nine tenths of the Earth's heat gain between 1971 and 2010. To reverse that heating, the warmer upper layers of the Ocean have to mix with the colder deeper layers. That mixing can take up to 1000 years. This means it will take centuries to millennia for deep ocean temperatures to warm in response to today's surface conditions, and at least as long for ocean warming to reverse after atmospheric greenhouse gas

concentrations decrease (*virtually certain*). But climate change-caused alteration of basic conditions in the Ocean is not just about temperature. The Ocean becomes more acidic as more CO_2 enters it and will take tens of thousands of years to reverse these profound changes to the carbonate chemistry of the ocean (*virtually certain*). These enormous physical and chemical changes are producing sweeping and profound changes in marine ecosystems. Large and abrupt changes to these ecosystems are unlikely to be reversible in the short to medium term (*high confidence*).

FAQ30.2: Does slower warming mean less impact on plants and animals? *[to be inserted in Section 30.4]*
The greater thermal inertia of the Ocean means that temperature anomalies and extremes are lower than those seen on land. This does not necessarily mean that impacts of ocean warming are less for the ocean than for land. A large body of evidence reveals that small amounts of warming in the Ocean can have large effects on ocean ecosystems. For example, relatively small increases in sea temperature (as little as 1–2°C) can cause mass coral bleaching and mortality across hundreds of square kilometers of coral reef (*high confidence*). Other analyses have revealed that increased temperatures are spreading rapidly across the world's oceans (measured as the movement of bands of equal water temperature or isotherms). This rate of warming presents challenges to organisms and ecosystems as they try to migrate to cooler regions as the Ocean continues to warm. Rapid environmental change also poses steep challenges to evolutionary processes, especially where long-lived organisms such as corals and fish are concerned (*high confidence*).

FAQ30.3: How will marine primary productivity change? *[to be inserted after Section 30.5.2.2]*
Drifting microscopic plants known as phytoplankton are the dominant marine primary producers, at the base of the marine food chain. Their photosynthetic activity is critically important to life in general. It provides oxygen, supports marine food webs, and influences global biogeochemical cycles. Changes in marine primary productivity in response to climate change remain the single biggest uncertainty in predicting the magnitude and direction of future changes in fisheries and marine ecosystems (*low confidence*). Changes have been reported to a range of different ocean systems (e.g., High Latitude Spring Bloom Systems, Sub-tropical Gyre Systems, Equatorial Upwelling Systems, and Eastern Boundary Upwelling Ecosystems), some of which are consistent with changes in ocean temperature, mixing, and circulation. However, direct attribution of these changes to climate change is made difficult by long-term patterns of variability that influence productivity of different parts of the Ocean (e.g., Pacific Decadal Oscillation). Given the importance of this question for ocean ecosystems and fisheries, longer time series studies to understand how these systems are changing as a result of climate change are a priority (*high agreement*).

FAQ30.4: Will climate change cause 'dead zones' in the oceans? *[to be inserted after Section 30.5.5.2]*
Dissolved oxygen is a major determinant of the distribution and abundance of marine organisms. Dead zones are persistent hypoxic conditions where the water doesn't have enough dissolved oxygen to support oxygen-dependent marine species. These areas exist all over the world and are expanding, with impacts on coastal ecosystems and fisheries (*high confidence*). Dead zones are caused by several factors, particularly eutrophication where too many nutrients run off coastal cities and agricultural areas into rivers that carry these materials out to sea. This stimulates primary production leading to a greater supply of organic carbon, which can sink into the deeper layers of the ocean. As microbial activity is stimulated, there is a sharp reduction in dissolved oxygen levels and an increased risk of dead zones (*high confidence*). Climate change can influence the distribution of dead zones by increasing water temperature and hence microbial activity, as well as reducing mixing of the ocean (i.e., increasing layering or stratification) of the Ocean – which have different temperatures, densities, salinities – and reducing mixing of oxygen-rich surface layers into the deeper parts of the Ocean. In other areas, increased upwelling can lead to stimulated productivity, which can also lead to more organic carbon entering the deep ocean, where it is consumed, decreasing oxygen levels (*medium confidence*). Managing local factors such as the input of nutrients into coastal regions can play an important role in reducing the rate at which dead zones are spreading across the world's oceans (*high agreement).*

FAQ30.5: How can we use non-climate factors to manage climate change impacts on the oceans?
[to be inserted after Section 30.7.1]
Like most natural system, the Ocean is exposed to a range of stresses that may or may not be related to climate change. Human activities can result in pollution, eutrophication (too many nutrients), habitat destruction, invasive species, destructive fishing, and over-exploitation of marine resources. Sometimes, these activities can increase the impacts of climate change, although they can, in a few circumstances, dampen the effects as well. Understanding

how these factors interact with climate change and ocean acidification is important in its own right. However, reducing the impact of these non-climate factors may reduce the overall rate of change within ocean ecosystems. Building ecological resilience through ecosystem-based approaches to the management of the marine environment, for example, may pay dividends in terms of reducing and delaying the effects of climate change (*high confidence*).

Cross-Chapter Boxes

Box CC-CR. Coral Reefs

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

Coral reefs are shallow-water ecosystems that consist of reefs made of calcium carbonate which is mostly secreted by reef-building corals and encrusting macroalgae. They occupy less than 0.1% of the ocean floor yet play multiple important roles throughout the tropics, housing high levels of biological diversity as well as providing key ecosystem goods and services such as habitat for fisheries, coastal protection and appealing environments for tourism (Wild *et al*., 2011). About 275 million people live within 30 km of a coral reef (Burke *et al*., 2011) and derive some benefits from the ecosystem services that coral reefs provide (Hoegh-Guldberg, 2011) including provisioning (food, livelihoods, construction material, medicine), regulating (shoreline protection, water quality), supporting (primary production, nutrient cycling) and cultural (religion, tourism) services. This is especially true for the many coastal and small island nations in the world's tropical regions (29.3.3.1).

Coral reefs are one of the most vulnerable marine ecosystems (*high confidence*; 5.4.2.4, 6.3.1, 6.3.2, 6.3.5, 25.6.2, and 30.5) and more than half of the world's reefs are under medium or high risk of degradation (Burke *et al*., 2011). Most human-induced disturbances to coral reefs were local until the early 1980s (e.g., unsustainable coastal development, pollution, nutrient enrichment and overfishing) when disturbances from ocean warming (principally mass coral bleaching and mortality) began to become widespread (Glynn, 1984). Concern about the impact of ocean acidification on coral reefs developed over the same period, primarily over the implications of ocean acidification for the building and maintenance of the calcium carbonate reef framework (Box CC-OA).

[INSERT FIGURE CR-1 HERE
Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).]

A wide range of climatic and non-climatic drivers affect corals and coral reefs and negative impacts have already been observed (5.4.2.4, 6.3.1, 6.3.2, 25.6.2.1, 30.5.3, 30.5.6). Bleaching involves the breakdown and loss of endosymbiotic algae, which live in the coral tissues and play a key role in supplying the coral host with energy (see 6.3.1. for physiological details and 30.5 for a regional analysis). Mass coral bleaching and mortality, triggered by positive temperature anomalies (*high confidence*), is the most widespread and conspicuous impact of climate change (Figure CR-1A and B, Figure 5-3; 5.4.2.4, 6.3.1, 6.3.5, 25.6.2.1, 30.5 and 30.8.2). For example, the level of thermal stress at most of the 47 reef sites where bleaching occurred during 1997-98 was unmatched in the period 1903 to 1999 (Lough, 2000). Ocean acidification reduces biodiversity (Figure CR-1C and D) and the calcification rate of corals (*high confidence*; 5.4.2.4, 6.3.2, 6.3.5) while at the same time increasing the rate of dissolution of the reef framework (*medium confidence*; 5.2.2.4) through stimulation of biological erosion and chemical dissolution. Taken together, these changes will tip the calcium carbonate balance of coral reefs towards net dissolution (*medium confidence*; 5.4.2.4). Ocean warming and acidification have synergistic effects in several reef-builders (5.2.4.2, 6.3.5). Taken together, these changes will erode habitats for reef-based fisheries, increase the exposure of coastlines to waves and storms, as well as degrading environmental features important to industries such as tourism (*high confidence*; 6.4.1.3, 25.6.2, 30.5).

A growing number of studies have reported regional scale changes in coral calcification and mortality that are consistent with the scale and impact of ocean warming and acidification when compared to local factors such as declining water quality and overfishing (Hoegh-Guldberg *et al*., 2007). The abundance of reef building corals is in rapid decline in many Pacific and SE Asian regions (*very high confidence*, 1-2% per year for 1968-2004; Bruno and Selig, 2007). Similarly, the abundance of reef-building corals has decreased by over 80% on many Caribbean reefs (1977 to 2001; Gardner *et al*., 2003), with a dramatic phase shift from corals to seaweeds occurring on Jamaican reefs (Hughes, 1994). Tropical cyclones, coral predators and thermal stress-related coral bleaching and mortality have led to a decline in coral cover on the Great Barrier Reef by about 51% between 1985 and 2012 (Figure CR-1E and F). Although less well documented, benthic invertebrates other than corals are also at risk (Przeslawski *et al*., 2008). Fish biodiversity is threatened by the permanent degradation of coral reefs, including in a marine reserve (Jones *et al*., 2004).

Future impacts of climate-related drivers (ocean warming, acidification, sea level rise as well as more intense tropical cyclones and rainfall events) will exacerbate the impacts of non-climate related drivers (*high confidence*). Even under optimistic assumptions regarding corals being able to rapidly adapt to thermal stress, one-third (9 to 60%, 68% uncertainty range) of the world's coral reefs are projected to be subject to long-term degradation (next few decades) under the RCP3-PD scenario (Frieler *et al*., 2013). Under the RCP4.5 scenario, this fraction increases to two-thirds (30 to 88%, 68% uncertainty range). If present day corals have residual capacity to acclimate and/or adapt, half of the coral reefs may avoid high frequency bleaching through 2100 (*limited evidence, limited agreement*; Logan *et al*., 2013). Evidence of corals adapting rapidly, however, to climate change is missing or equivocal (Hoegh-Guldberg, 2012).

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

- *Resources*: Coral reefs account for 10 to 12% of the fish caught in tropical countries, and 20 to 25% of the fish caught by developing nations (Garcia and Moreno, 2003). Over half (55%) of the 49 island countries considered by Newton *et al*. (2007) are already exploiting their coral reef fisheries in an unsustainable way and the production of coral reef fish in the Pacific is projected to decrease 20% by 2050 under the SRES A2 emissions scenario (Bell *et al*., 2013).
- *Coastal* protection: Coral reefs contribute to protecting the shoreline from the destructive action of storm surges and cyclones (Sheppard *et al*., 2005), sheltering the only habitable land for several island nations, habitats suitable for the establishment and maintenance of mangroves and wetlands, as well as areas for recreational activities. This role is threatened by future sea level rise, the decrease in coral cover, reduced rates of calcification and higher rates of dissolution and bioerosion due to ocean warming and acidification (5.4.2.4, 6.4.1, 30.5).
- *Tourism*: More than 100 countries benefit from the recreational value provided by their coral reefs (Burke *et al*., 2011). For example, the Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generates A$ 5.4 billion to the Australian economy and 54,000 jobs (90% in the tourism sector; Biggs, 2011).

Coral reefs make a modest contribution to the Global Domestic Product but their economic importance can be high at the country and regional scales (Pratchett *et al*., 2008). For example, tourism and fisheries represent 5% of the GDP of South Pacific islands (average for 2001-2011; Laurans *et al*., 2013). At the local scale, these two services provided in 2009-2011 at least 25% of the annual income of villages in Vanuatu and Fiji (Pascal, 2011; Laurans *et al*., 2013).

Isolated reefs can recover from major disturbance, and the benefits of their isolation from chronic anthropogenic pressures can outweigh the costs of limited connectivity (Gilmour *et al*., 2013). Marine protected areas (MPAs) and fisheries management have the potential to increase ecosystem resilience and increase the recovery of coral reefs after climate change impacts such as mass coral bleaching (McLeod *et al*., 2009). Although they are key conservation and management tools, they are unable to protect corals directly from thermal stress (Selig *et al*., 2012) suggesting that they need to be complemented with additional and alternative strategies (Rau *et al*., 2012; Billé *et al*., 2013). While MPA networks are a critical management tool, they should be established considering other forms of resource management (e.g., fishery catch limits and gear restrictions) and integrated ocean and coastal management to control land-based threats such as pollution and sedimentation. There is *medium confidence* that networks of highly protected areas nested within a broader management framework can contribute to preserving coral reefs under increasing human pressure at local and global scales (Salm *et al*. 2006). Locally, controlling the input of nutrients and sediment from land is an important complementary management strategy (Mcleod *et al*., 2009) because nutrient enrichment can increase the susceptibility of corals to bleaching (Wiedenmann *et al*., 2012) and coastal pollutants enriched with fertilizers can increase acidification (Kelly *et al.*, 2011). In the long term, limiting the amount of ocean warming and acidification is central to ensuring the viability of coral reefs and dependent communities (*high confidence*; 5.2.4.4, 30.5).

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Box CC-HS. Heat Stress and Heat Waves

[Lennart Olsson (Sweden), Dave Chadee (Trinidad and Tobago), Ove Hoegh-Guldberg (Australia), John Porter (Denmark), Hans-O. Pörtner (Germany), Kirk Smith (USA), Maria Isabel Travasso (Argentina), Petra Tschakert (USA)]

Heat waves are periods of abnormally and uncomfortably hot weather during which the risk of heat stress on people and ecosystems is high. The number and intensity of hot days have increased markedly in the last three decades (Coumou et al., 2013) (*high confidence*). According to WG I, it is *likely* that the occurrence of heat waves has more than doubled in some locations due to human influence and it is *virtually certain* that there will be more frequent hot extremes over most land areas in the latter half of the 21st century. Coumou et al. (2013) predicted that, under a medium warming scenario, the number of monthly heat records will be over 12 times more common by the 2040s compared to a non-warming world. In a longer time perspective, if the global mean temperature increases to +10C or more, the habitability of large parts of the tropics and mid-latitudes will be at risk (Sherwood and Huber, 2010). Heat waves affect natural and human systems directly, often with severe losses of lives and assets as a result, and they may act as triggers for tipping points (Hughes et al., 2013). Consequently, heat waves play an important role in several key risks noted in Chapter 19 and CC-KR.

Economy and Society [Ch 10, 11, 12, 13]

Environmental heat stress has already reduced the global labor capacity to 90% in peak months with a further predicted reduction to 80% in peak months by 2050. Under a high warming scenario (RCP8.5), labor capacity is expected to be less than 40% of present day conditions in peak months by 2200 (Dunne et al., 2013). Adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial.

Heat waves are associated with social predicaments such as increasing violence (Anderson, 2012) as well as overall health and psychological distress and low life satisfaction (Tawatsupa et al., 2012). Impacts are highly differential with disproportional burdens on poor people, elderly people, and those who are marginalized (Wilhelmi et al., 2012). Urban areas are expected to suffer more due to the combined effect of climate and the urban heat island effect (Fischer et al., 2012). In LICs and MICs, adaptation to heat stress is severely restricted for most people in poverty and particularly those who are dependent on working outdoors in agriculture, fisheries, and construction. In small-scale agriculture, women and children are particularly at risk due to the gendered division of labor (Croppenstedt et al., 2013). The expected increase in wildfires as a result of heat waves (Pechony and Shindell, 2010) is a concern for human security, health, and ecosystems. Air pollution from wildfires already causes an estimated 339,000 premature deaths per year worldwide (Johnston et al., 2012).

Human Health [Ch 11]

Morbidity and mortality due to heat stress is now common all over the world (Barriopedro *et al.*, 2011; Rahmstorf and Coumou, 2011; Nitschke et al., 2011; Diboulo et al., 2012; Hansen et al., 2012). People in physical work are at particular risk as such work produces substantial heat within the body, which cannot be released if the outside temperature and humidity is above certain limits (Kjellstrom et al., 2009). The risk of non-melanoma skin cancer from exposure to UV radiation during summer months increases with temperature (van der Leun, Jan C et al., 2008). Increase in ozone concentrations due to high temperatures affects health (Smith et al., 2010), leading to premature mortality, e.g. cardiopulmonary mortality (Smith et al., 2010). High temperatures are also associated with an increase in air-borne allergens acting as a trigger for respiratory illnesses such as asthma, allergic rhinitis, conjunctivitis, and dermatitis (Beggs, 2010).

Ecosystems [Ch 4, 5, 6, 30]

Tree mortality is increasing globally (Williams et al., 2012) and can be linked to climate impacts, especially heat and drought (Reichstein et al., 2013), even though attribution to climate change is difficult due to lack of time series and confounding factors. In the Mediterranean region, higher fire risk, longer fire season, and more frequent large, severe fires are expected as a result of increasing heat waves in combination with drought (Duguy et al., 2013), Box 4.2.

Marine ecosystem shifts attributed to climate change are often caused by temperature extremes rather than changes in the average (Pörtner and Knust, 2007). During heat exposure near biogeographical limits, even small (<0.5°C) shifts in temperature extremes can have large effects, often exacerbated by concomitant exposures to hypoxia and/or elevated CO_2 levels and associated acidification (Hoegh-Guldberg et al., 2007), Figure 6-5, (*medium confidence*) [Ch 6.3.1, 6.3.5; 30.4; 30.5; CC-MB]

Most coral reefs have experienced heat stress sufficient to cause frequent mass coral bleaching events in the last 30 years, sometimes followed by mass mortality (Baker et al., 2008). The interaction of acidification and warming exacerbates coral bleaching and mortality (*very high confidence*).Temperate seagrass and kelp ecosystems will decline with the increased frequency of heat waves and through the impact of invasive subtropical species (*high confidence*). [Ch 5, 6, 30.4-30.5, CC-CR, CC-MB]

Agriculture [Ch 7]

Excessive heat interacts with key physiological processes in crops. Negative yield impacts for all crops past +3C of local warming without adaptation, even with benefits of higher CO_2 and rainfall, are expected even in cool environments (Teixeira et al., 2011). For tropical systems where moisture availability or extreme heat limits the length of the growing season, there is a high potential for a decline in the length of the growing season and

suitability for crops (*medium evidence, medium agreement*) (Jones and Thornton, 2009). For example, half of the wheat-growing area of the Indo-Gangetic Plains could become significantly heat-stressed by the 2050s.

There is *high confidence* that high temperatures reduce animal feeding and growth rates (Thornton et al., 2009). Heat stress reduces reproductive rates of livestock (Hansen, 2009), weakens their overall performance (Henry et al., 2012), and may cause mass mortality of animals in feedlots during heat waves (Polley et al., 2013). In the U.S., current economic losses due to heat stress of livestock are estimated at several billion USD annually (St-Pierre et al., 2003).

Box CC-HS References

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Box CC-MB. Observed Global Responses of Marine Biogeography, Abundance, and Phenology to Climate Change

[Elvira Poloczanska (Australia), Ove Hoegh-Guldberg (Australia), William Cheung (Canada), Hans O. Pörtner (Germany), Michael Burrows (UK)]

WGII AR4 presented detection and attribution of a global climate change fingerprint on natural systems (AR4, Ch 1, SPM Figure 1), but studies from marine systems were mostly absent. Since AR4, there has been a rapid increase in studies that focus on climate change impacts on marine species, which represents an opportunity to move from more anecdotal evidence to examining and potentially attributing detected changes within the Ocean to climate change (6.3, Figure MB-1). Recent changes in populations of marine species and the associated shifts in diversity patterns are resulting, at least partly, from climate change-mediated biological responses across ocean regions (6.2, Table 6.7, 30.5) (*robust evidence, high agreement, high confidence*).

Poloczanska *et al*. (2013) assess a potential pattern in responses of ocean life to recent climate change using a global database of 208 peer-reviewed papers. Observed responses (n=1735) were recorded from 857 species or assemblages across regions and taxonomic groups, from phytoplankton to marine reptiles and mammals (Figure MB-1). Observations were defined as those where the authors of a particular paper assessed the occurrence change in a biological parameter (including distribution, phenology, abundance, demography or community composition) and, if change occurs, the consistency of the change with that expected under climate change. Studies from the peer-reviewed literature were selected using three criteria: (1) authors inferred or directly tested for trends in biological and climatic variables; (2) included data after 1990; and (3) observations spanned at least 19 years, to reduce bias resulting from biological responses to short-term-climate variability.

[INSERT FIGURE MB-1 HERE
Figure MB-1: 1735 observed responses to climate change from 208 single- and multi-species studies. Changes attributed to climate change (blue), inconsistent with climate change (red) and are equivocal (yellow). Each circle

represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite or equivocal) observations within each region. Note: 57% of the studies included were published since AR4 (from Poloczanska *et al.*, 2013).]

The results of this meta-analysis show that climate change has already had widespread impacts on species' distribution, abundance, phenology, and subsequently, species richness and community composition across a broad range of taxonomic groups (plankton to top predators). Of the observations that showed a response in either direction, changes in phenology, distribution and abundance were overwhelmingly (81%) in a direction that was consistent with theoretical responses to climate change (6.2). Knowledge gaps exist, especially in equatorial sub-regions and the Southern Hemisphere (Figure MB-1).

The timing of many biological events (phenology) had an earlier onset. For example, over the last 50 years, spring events shifted earlier for many species with an average advancement of 4.4 ± 0.7 days decade^{-1} (mean ± SE) and summer events by 4.4 ± 1.1 days decade^{-1} (*robust evidence, high agreement, high confidence*) (Figure MB-2). Phenological observations included in the study, range from shifts in peak abundance of phytoplankton and zooplankton, to reproduction and migration of invertebrates, fishes and seabirds (6.3.2, 30.5).

The distributions of benthic, pelagic and demersal species and communities have shifted by 10s to 1000s of km, although the range shifts have not been uniform across taxonomic groups or ocean regions (6.3.2, 30.5) (*robust evidence, high agreement, high confidence*). Overall, leading range edges expanded in a poleward direction at 72.0 ± 13.5 km decade^{-1} and trailing edges contracted in a poleward direction at 15.8 ± 8.7 km decade^{-1} (Figure MB-2) revealing much higher current rates of migration than the potential maximum rates reported for terrestrial species (Figure 4.6) despite slower warming of the Ocean than land surface (WG1 3.2).

[INSERT FIGURE MB-2 HERE
Figure MB-2. Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations (from Poloczanska et al., 2013).]

Poleward distribution shifts have resulted in increased species richness in mid to high latitude regions (Hiddink and ter Hofstede, 2008) and changing community structure (Simpson *et al.,* 2011) (28.2.2). Increases in warm-water components of communities concurrent with regional warming have been observed in mid to high latitude ocean regions including the Bering Sea, Barents Sea, Nordic Sea, North Sea, and Tasman Sea (Box 6.1, 30.5). Observed changes in species composition of catches from 1970–2006 that is partly attributed to long-term ocean warming suggest increasing dominance of warmer water species in sub-tropical and higher latitude regions, and reduction in abundance of sub-tropical species in equatorial waters (Cheung *et al*., 2013), with implications for fisheries (6.5, 7.4.2, 30.6.2.1)

The magnitude and direction of distribution shifts can be related to temperature velocities (i.e., the speed and direction at which isotherms propagate across the Ocean's surface (30.3.1.1, Burrows *et al.* 2011). Pinsky *et al.* (2013) showed that shifts in both latitude and depth of benthic fish and crustaceans could be explained by climate velocity with remarkable accuracy, using a database of 128 million individuals across 360 marine taxa from surveys of North American coastal waters conducted over 1968 to 2011. Poloczanska *et al.* (2013) found that faster distribution shifts generally occur in regions of highest surface temperature velocity, such as the North Sea and sub-Arctic Pacific Ocean. Observed marine species shifts, since approximately 1950s, have generally been able to track observed velocities (Fig MB-3), with phyto- and zooplankton distribution shifts vastly exceeding climate velocities, but with considerable variability within and among taxonomic groups (Poloczanska *et al.* 2013).

Biogeographic shifts are also be influenced by other factors such as nutrient and stratification changes, species' interactions, habitat availability and fishing (6.3). Rate and pattern of biogeographic shifts in sedentary organisms and benthic macroalgae are complicated by the influence of local dynamics and topographic features (islands, channels, coastal lagoons, e.g., of the Mediterranean (Bianchi, 2007), coastal upwelling e.g., Lima *et al.* (2007)). Geographical barriers constrain range shifts and may cause a loss of endemic species (Ben Rais Lasram *et al.*, 2010), with associated niches filled by alien species, either naturally migrating or artificially introduced (Philippart *et al.*, 2011).

Whether marine species can continue to keep pace as warming rates, hence climate velocities, increase (Fig MB-3b) is a key uncertainty. Climate velocities on land are expected to outpace the ability of many terrestrial species to track climate velocities this century (4.3.2.5, Figure 4.6) For marine species, the observed rates of shift are generally much faster than those land for land species, particularly for primary producers and lower trophic levels (Poloczanska *et al. 2013*). Phyto- and zooplankton communities (excluding larval fish) have extended distributions at remarkable rates (Figure MB-3b), such as in the North-east Atlantic (30.5.1) with implications for marine food webs.

Geographical range shifts and depth distribution vary between coexisting marine species (Genner *et al*., 2004; Perry *et al*., 2005; Simpson *et al*., 2011) as a consequence of species-specific thermal window widths and associated vulnerabilities (Figure 6.5). Warming therefore causes differential changes in growth, reproductive success, larval output, early juvenile survival, and recruitment, implying shifts in the relative performance of animal species and, thus, their competitiveness (Pörtner and Farrell, 2008; Figure 6.7A). Such effects may underlie abundance losses or local extinctions, “regime shifts” between coexisting species, or critical mismatches between predator and prey organisms. Changes in local and regional species richness, abundance, community composition, productivity, energy flows and invasion resistance result. Even among Antarctic stenotherms such differences related to mode of life, phylogeny and associated metabolic capacities exist (6.3.1.4). As a consequence, marine ecosystem functions may be substantially reorganized at the regional scale, potentially triggering a range of cascading effects (Hoegh-Guldberg and Bruno, 2010). A focus on understanding the mechanisms underpinning the nature and magnitude of responses of marine organisms to climate change can help forecast impacts and the associated costs to society and facilitate adaptive management strategies effective in mitigating these impacts (6.3, 6.4).

[INSERT FIGURE MB-3 HERE
Figure MB-3. A. Rate of climate change for the Ocean (sea surface temperature (SST) °C); B. corresponding climate velocities for the Ocean and median velocity from land (adapted from Burrows et al., 2011); and C. observed rates of displacement of marine taxonomic groups over several decades until 2010. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.008 °C yr^{-1} correspond to ca. 2.4 km yr^{-1}median climate velocity in the Ocean. When compared to observed rates of displacement, many marine taxonomic groups have been able to track these velocities, except phyto- and zooplankton where rates of displacement greatly exceed climate velocity. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (A) Observed rates of climate change for Ocean SST (Black dotted line) are derived from HadISST1.1 data set, all other rates are calculated based on the average of the CMIP5 climate model ensembles (Table S30-3) for the historical period and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window. (B) Median climate velocity calculated from HadISST1.1 dataset over 1960–2010 using the methods of Burrows et al., 2011. The three axes represent estimated median climate velocities are representative of areas of slow velocities such as Pacific subtropical gyre (STG) system (Purple line), the global Ocean surface (excluding polar seas, Blue line), and areas of high velocities such as the Coral Triangle and North Sea (Orange line). Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2010. The Red line corresponds to the median rate over global land surface calculated using historical surface temperatures from the CMIP5 model ensemble (Table S30-3). (C) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. 2013 using published studies (Figure MB-2 Black data set). Note the displacement rates for phytoplankton exceed the axis, so values are given.]

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Box CC-OA. Ocean Acidification

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Anthropogenic ocean acidification and global warming share the same primary cause, which is the increase of atmospheric CO_2 (Figure OA-1A; WGI, 2.2.1). Eutrophication, loss of sea ice, upwelling and deposition of atmospheric nitrogen and sulphur all exacerbate ocean acidification locally (5.3.3.6, 6.1.1, 30.3.2.2).

[INSERT FIGURE OA-1 HERE
Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.]

Chemistry and Projections

The fundamental chemistry of ocean acidification is well understood (*robust evidence, high agreement*). Increasing atmospheric concentrations of CO_2 result in an increased flux of CO_2 into a mildly alkaline ocean, resulting in a reduction in pH, carbonate ion concentration, and the capacity of seawater to buffer changes in its chemistry (*very high confidence*). The changing chemistry of the surface layers of the open ocean can be projected at the global scale with high accuracy using projections of atmospheric CO_2 levels (Fig. CC-OA-1B). Observations of changing upper ocean CO_2 chemistry over time support this linkage (WGI Table 3.2 and Figure 3.18; Figures 30.8, 30.9). Projected changes in open ocean, surface water chemistry for year 2100 based on representative concentration pathways (WGI, Figure 6.28) compared to preindustrial values range from a pH change of -0.14 unit with RCP 2.6 (421 ppm CO_2, +1 ºC, 22% reduction of carbonate ion concentration) to a pH change of -0.43 unit with RCP 8.5 (936 ppm CO_2, +3.7 ºC, 56% reduction of carbonate ion concentration). Projections of regional changes, especially in the highly complex coastal systems (5.3.3.6, 30.3.2.2), in polar regions (WGI 6.4.4), and at depth are more difficult but generally follow similar trends.

Biological, Ecological, and Biogeochemical Impacts

Investigations of the effect of ocean acidification on marine organisms and ecosystems have a relatively short history, recently analyzed in several metaanalyses (6.3.2.1, 6.3.5.1). A wide range of sensitivities to projected rates of ocean acidification exists within and across diverse groups of organisms, with a trend for greater sensitivity in early life stages (*high confidence*; 5.4.2.2, 5.4.2.4, 6.3.2). A pattern of positive and negative impacts emerges (*high confidence*; Fig. OA-1C) but key uncertainties remain in our understanding of the impacts on organisms, life histories and ecosystems. Responses can be influenced, often exacerbated by other drivers, such as warming, hypoxia, nutrient concentration, and light availability (*high confidence*; 5.4.2.4, 6.3.5).

Growth and primary production are stimulated in seagrass and some phytoplankton (*high confidence*; 5.4.2.3, 6.3.2.2-3, 30.5.6). Harmful algal blooms could become more frequent (*limited evidence, medium agreement*). Ocean acidification may stimulate nitrogen fixation (*limited evidence, low agreement*; 6.3.2.2). It decreases the rate of calcification of most, but not all, sea-floor calcifiers (*medium agreement*, *robust evidence*) such as reef-building corals (Box CC-CR), coralline algae, bivalves and gastropods reducing the competitiveness with non-calcifiers (5.4.2.2, 5.4.2.4, 6.3.2.5). Ocean warming and acidification promote higher rates of calcium carbonate dissolution resulting in the net dissolution of carbonate sediments and frameworks and loss of associated habitat (*medium confidence*; 5.4.2.4, 6.3.2.5, 6.3.5.4-5). Some corals and temperate fishes experience disturbances to behavior, navigation and their ability to tell conspecifics from predators (6.3.2.4). However, there is no evidence for these effects to persist on evolutionary timescales in the few groups analyzed (6.3.2).

Some phytoplankton and mollusks displayed adaptation to ocean acidification in long-term experiments (*limited evidence, medium agreement*; 6.3.2.1), indicating that the long-term responses could be less than responses obtained in short-term experiments. However, mass extinctions in Earth history occurred during much slower rates of ocean acidification, combined with other drivers changing, suggesting that evolutionary rates are not fast enough for sensitive animals and plants to adapt to the projected rate of future change (*medium confidence*; 6.1.2).

Projections of ocean acidification effects at ecosystem level are made difficult by the diversity of species-level responses. Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions (6.3.2.5, 6.3.5-6), which could impact food webs and higher trophic levels (*limited evidence, high agreement*). Natural analogues at CO_2 vents indicate decreased species diversity, biomass and trophic complexity of communities (Box CC-CR; 5.4.2.3, 6.3.2.5, 30.3.2.2, 30.5). Shifts in community structure have also been documented in regions with rapidly declining pH (5.4.2.2).

Due to an incomplete understanding of species-specific responses and trophic interactions the effect of ocean acidification on global biogeochemical cycles is not well understood (*limited evidence, low agreement*) and represents an important knowledge gap. The additive, synergistic or antagonistic interactions of factors such as temperature, concentrations of oxygen and nutrients, and light are not sufficiently investigated yet.

Risks, Socioeconomic Impacts and Costs

The risks of ocean acidification to marine organisms, ecosystems, and ultimately to human societies, include both the probability that ocean acidification will affect fundamental physiological and ecological processes of organisms (6.3.2.1), and the magnitude of the resulting impacts on ecosystems and the ecosystem services they provide to society (Box 19-2). For example, ocean acidification under RCP4.5 to RCP8.5 will impact formation and maintenance of coral reefs (*high confidence*; Box CC-CR, 5.4.2.4) and the goods and services that they provide such as fisheries, tourism and coastal protection (*limited evidence, high agreement*; Box CC-CR, 6.4.1.1,19.5.2, 27.3.3, 30.5, 30.6). Ocean acidification poses many other potential risks, but these cannot yet be quantitatively assessed due to the small number of studies available, particularly on the magnitude of the ecological and socioeconomic impacts (19.5.2).

Global estimates of observed or projected economic costs of ocean acidification do not exist. The largest uncertainty is how the impacts on lower trophic levels will propagate through the food webs and to top predators. However, there are a number of instructive examples that illustrate the magnitude of potential impacts of ocean acidification. A decrease of the production of commercially-exploited shelled mollusks (6.4.1.1) would result in a reduction of US production of 3 to 13% according to the SRES A1FI emission scenario (*low confidence*). The global cost of production loss of mollusks could be over 100 billion USD by 2100 (*limited evidence, medium agreement*). Models suggest that ocean acidification will generally reduce fish biomass and catch (*low confidence*) and that complex additive, antagonistic and/or synergistic interactions will occur with other environmental (warming) and human (fisheries management) factors (6.4.1.1). The annual economic damage of ocean-acidification-induced coral reef loss by 2100 has been estimated, in 2009, to be 870 and 528 billion USD, respectively for the A1 and B2 SRES emission scenarios (*low confidence*; 6.4.1). Although this number is small compared to global GDP, it can represent a very large GDP loss for the economies of many coastal regions or small islands that rely on the ecological goods and services of coral reefs (25.7.5, 29.3.1.2).

Mitigation and Adaptation

Successful management of the impacts of ocean acidification includes two approaches: mitigation of the source of the problem (i.e. reduce anthropogenic emissions of CO_2), and/or adaptation by reducing the consequences of past and future ocean acidification (6.4.2.1). Mitigation of ocean acidification through reduction of atmospheric CO_2 is the most effective and the least risky method to limit ocean acidification and its impacts (6.4.2.1). Climate geoengineering techniques based on solar radiation management will not abate ocean acidification and could increase it under some circumstances (6.4.2.2). Geoengineering techniques to remove carbon dioxide from the atmosphere could directly address the problem but are very costly and may be limited by the lack of CO_2 storage capacity (6.4.2.2). Additionally, some ocean-based approaches, such as iron fertilization, would only re-locate ocean acidification from the upper ocean to the ocean interior, with potential ramifications on deep-water oxygen levels (6.4.2.2; 30.3.2.3 and 30.5.7). A low-regret approach, with relatively limited effectiveness, is to limit the number and the magnitude of drivers other than CO_2, such as nutrient pollution (6.4.2.1). Mitigation of ocean acidification at the local level could involve the reduction of anthropogenic inputs of nutrients and organic matter in the coastal ocean (5.3.4.2). Some adaptation strategies include drawing water for aquaculture from local watersheds only when pH is in the right range, selecting for less sensitive species or strains, or relocating industries elsewhere (6.4.2.1).

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Box CC-PP. Net Primary Production in the Ocean

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Net Primary Production (NPP) is the rate of photosynthetic carbon fixation minus the fraction of fixed carbon used for cellular respiration and maintenance by autotrophic planktonic microbes and benthic plants (6.2.1, 6.3.1). Environmental drivers of NPP include light, nutrients, micronutrients, carbon dioxide, and temperature (Panel A). These drivers in turn, are influenced by oceanic and atmospheric processes, including cloud cover, sea-ice extent, mixing by winds, waves and currents, convection, density stratification, and various forms of upwelling induced by eddies, frontal activity and boundary currents. Temperature has multiple roles as it influences rates of phytoplankton physiology and heterotrophic bacterial recycling of nutrients, in addition to stratification of the water column and sea-ice extent (Panel A). Climate change is projected to strongly impact NPP through a multitude of ways that depend on the regional and local physical settings (WGI, Ch. 3), and on ecosystem structure and functioning (*medium confidence*, 6.3.4, 6.5.1). The influence of environmental drivers on NPP causes as much as a 10-fold variation in regional productivity: from <50 g C m^{-2} $year^{-1}$ in nutrient-poor subtropical waters and light-limited Arctic waters to >> 300 g C m^{-2} $year^{-1}$ in productive upwelling regions and highly eutrophic coastal regions (Panel B).

The oceans currently provide ~50 x 10^{15} g C $year^{-1}$, or about half of global NPP (Field *et al*. 1998). Global estimates of NPP are mainly obtained from satellite remote-sensing (6.1.2), which provides unprecedented spatial and temporal coverage, and may be validated regionally against oceanic measurements. Observations reveal significant changes in rates of NPP when environmental controls are altered by episodic natural perturbations, such as volcanic eruptions enhancing iron supply, as observed in high-nitrate low-chlorophyll waters of the NE Pacific (Hamme *et al*., 2010). Climate variability can drive pronounced changes in NPP (Chavez *et al*., 2011), such as during El Niño to La Niña transitions in Equatorial Pacific, when vertical nutrient and trace element supply are enhanced (Chavez *et al*., 1999).

Multi-year time-series records of NPP have been used to assess spatial trends in NPP in recent decades. Behrenfeld *et al*. (2006) using satellite data, reported a prolonged and sustained global NPP decrease of 190 x 10^{12} g C $year^{-1}$, for the period 1999 to 2005 - an annual reduction of ~0.4 % of global NPP. In contrast, a time-series of directly measured NPP between 1988 to 2007 by Saba *et al*. (2010) (i.e. *in situ* incubations using the radiotracer ^{14}C-bicarbonate) revealed an increase (2 % $year^{-1}$) in NPP for two low latitude open ocean sites. This discrepancy between *in situ* and remotely-sensed NPP trends points to uncertainties in either the methodology used and/or the extent to which discrete sites are representative of oceanic provinces (Saba *et al*., 2010, 2011). Modeling studies have subsequently revealed that the <15 year archive of satellite-derived NPP is insufficient to distinguish climate-change mediated shifts in NPP from those driven by natural climate variability (Henson *et al*., 2010; Beaulieu *et al*., 2013). Although multidecadal, the available time-series of oceanic NPP measurements are also not of sufficient duration relative to the timescales of climate variability modes (up to 60-70 years for AMO, for example, Figure 6-1). Recent attempts to synthesize longer (i.e. centennial) records of chlorophyll as a proxy for phytoplankton stocks (e.g., Boyce *et al*., 2010) have been criticized for relying on questionable linkages between different proxies for chlorophyll over a century of records (e.g., Rykaczewski and Dunne, 2011).

Models in which projected climate-change alters the environmental drivers of NPP provide estimates of spatial changes and of the rate of change of NPP. For example, four global coupled climate-ocean biogeochemical Earth System Models (WGI Ch. 6) projected an increase in NPP at high latitudes as a result of alleviation of light and temperature limitation of NPP particularly in Northern and Southern Hemisphere 'subpolar gyre' biomes (Steinacher *et al*., 2010). However, this regional increase in NPP was more than offset by decreases in NPP at lower latitudes and at mid-latitudes due to the reduced input of macro-nutrients into the photic zone. The reduced mixed-layer depth and reduced rate of circulation may cause a decrease in the flux of macronutrients to the photic zone (Figure 6-2). These changes to oceanic conditions result in a reduction in global mean NPP by 2 to 13% by 2100 relative to 1860 under a high emission scenario (Polovina *et al*., 2011; SRES A2, between RCP6.0 and RCP8.5). This is consistent with a more recent analysis based on 10 Earth System Models (Bopp *et al*., 2013), which project decreases in global NPP by 8.6 (±7.9), 3.9 (±5.7), 3.6 (±5.7), 2.0 (±4.1) % in the 2090s relative to the 1990s, under the scenarios RCP8.5, RCP6.0, RCP4.5 and RCP2.6, respectively. However, the magnitude of projected changes varies widely between models (e.g. from 0 to 20% decrease in NPP globally under RCP 8.5). The various models show very large differences in NPP at regional (i.e. provinces, see panel B) scales.

Earlier model projections had predicted changes in global NPP from a decrease of > 10% (Field *et al*., 1998; Boyd and Doney, 2002) to an increase of up to 8.1% under an intermediate scenario (SRES A1B, similar to RCP6.0) (Sarmiento *et al*., 2004; Schmittner *et al*., 2008). These projections did not consider the potential contribution of primary production derived from atmospheric nitrogen fixation in tropical and subtropical regions, favoured by increasing stratification and reduced nutrient inputs from mixing. This mechanism is potentially important, although such episodic increases in nitrogen fixation are not sustainable without the presence of excess phosphate (e.g. Moore *et al*., 2009; Boyd *et al*., 2010). This may lead to an underestimation of NPP (Mohr *et al*., 2010; Mulholland *et al*., 2012; Wilson *et al*., 2012), however, the extent of such underestimation is unknown (Luo *et al*., 2012).

Care must be taken when comparing global, provincial (e.g. low latitude waters, for example Behrenfeld *et al*., 2006) and regional trends in NPP derived from observations, as some regions have additional local environmental influences such as enhanced density stratification of the upper ocean from melting sea ice. For example, a longer phytoplankton growing season, due to more sea-ice free days, may have increased NPP (based on a regionally validated time-series of satellite NPP) in Arctic waters (Arrigo and van Dijken, 2011) by an average of 8.1 Tg C year^{-1} between 1998 and 2009. Other regional trends in NPP are reported in 30.5.1-6. In addition, although future model projections of global NPP from different models (Steinacher *et al*., 2010; Bopp *et al*., 2013) are comparable, regional projections from each of the models differ substantially. This raises concerns as to which aspect(s) of the different model NPP parameterizations are responsible for driving regional differences in NPP, and moreover, how accurate model projections are of global NPP.

From a global perspective, open ocean NPP will decrease moderately by 2100 under both low (SRES B1 or RCP4.5) and high emission scenarios (A2 or RCP6.0 - 8.5, 6.3.4, 6.5.1, *medium confidence*), paralleled by an increase in NPP at high latitudes and a decrease in the tropics (*medium confidence*). However, there is *limited evidence* and *low agreement* on the direction, magnitude and differences of a change of NPP in various ocean regions and coastal waters projected by 2100 (*low confidence*).

[INSERT FIGURE PP-1 HERE
Figure PP-1: A) Environmental factors controlling Net Primary Production (NPP). NPP is mainly controlled by three basic processes: 1) Light conditions in the surface ocean, i.e. the photic zone where photosynthesis occurs, 2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, 3) Regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. B) Annual composite map of global areal NPP rates (derived from MODIS Aqua satellite climatology from 2003-2012; NPP was calculated with the Carbon-based Production Model (CbPM, Westberry *et al*., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.]

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Box CC-UP. Uncertain Trends in Major Upwelling Ecosystems

[Salvador E. Lluch-Cota (Mexico), Ove Hoegh-Guldberg (Australia), David Karl (USA), Hans O. Pörtner (Germany), Svein Sundby (Norway), Jean-Pierre Gatusso (France)]

Upwelling is the vertical transport of cold, dense, nutrient-rich, relatively low-pH and often oxygen-poor waters to the euphotic zone where light is abundant. These waters trigger high levels of primary production and a high biomass of benthic and pelagic organisms. The driving forces of upwelling include wind stress and the interaction of ocean currents with bottom topography. Upwelling intensity also depends on water column stratification. The major upwelling systems of the Planet, the Equatorial Upwelling System (EUS, 30.5.2, Figure 30.1A) and the Eastern Boundary Upwelling Ecosystems (EBUE, 30.5.5, Figure 30.1A), represent only 10% of the ocean surface but contribute nearly 25 % to global fish production (Figure 30.1B, Table S30.1).

Marine ecosystems associated with upwelling systems can be influenced by a range of 'bottom-up' trophic mechanisms, with upwelling, transport, and chlorophyll concentrations showing strong seasonal and interannual couplings and variability. These, in turn, influence trophic transfer up the food chain, affecting zooplankton, foraging fish, seabirds and marine mammals.

There is considerable speculation as to how upwelling systems might change in a warming and acidifying ocean. Globally, the heat gain of the surface ocean has increased stratification by 4% (WGI 3.2, 3.4.4, 3.8), which means that more wind energy is needed to bring deep waters to the surface. It is as yet unclear to what extent wind stress can offset the increased stratification, due to the uncertainty in wind speed trends (WGI, 3.4.4). In the tropics, observations of reductions in trade winds over several decades contrast more recent evidence indicating their strengthening since the early 1990s (WGI, 9.4.1.3.4). Observations and modelling efforts in fact show diverging trends in coastal upwelling at the eastern boundaries of the Pacific and the Atlantic. Bakun (1990) proposed that the the difference in heat gaining rates between land and ocean causes an increase in the pressure gradient, which results in increased alongshore winds and leads to intensified offshore transport of surface water through Ekman pumping, and the upwelling of nutrient rich, cold waters (Figure CC-UP). Some regional records support this hypothesis, others do not. There is considerable variability in warming and cooling trends over the past decades both within and among systems making it difficult to predict changes in the intensity of all Eastern Boundary Upwelling Ecosystems (30.5.5).

Understanding whether upwelling and climate change will impact resident biota in an additive, synergistic or antagonistic manner is important for projections of how ecological goods and services provided for human society will change. Even though upwellings may prove more resilient to climate change than other ocean ecosystems because of their ability to function under extremely variable conditions (Capone and Hutchins, 2013), consequences of their shifts are highly relevant since these are the most biologically active systems in the ocean. Increased upwelling would enhance fisheries yields. However, the export of organic material from surface to deeper layers of the ocean may increase and stimulate its decomposition by microbial activity, thereby enhancing oxygen depletion and CO_2 enrichment in deeper water layers. Once this water returns to the surface through upwelling benthic and pelagic coastal communities will be exposed to acidified and deoxygenated water which may combine with anthropogenic impact to negatively affect marine biota and ecosystem structure of the upper ocean (high confidence, 6.3.2, 6.3.3; 30.3.2.2, 30.3.2.3). Extreme hypoxia may result in abnormal mortalities of fishes and invertebrates (Keller *et al.*, 2010), reduce the fisheries catch potential and impact aquaculture in coastal areas (5.4.3.3, 6.3.7, 30.5.1.1.2, 30.5.5.1.3, Barton *et al.*, 2012). Shifts in upwelling also coincide with an apparent increase in the frequency of submarine eruptions of methane and hydrogen sulphide gas, caused by enhanced formation and sinking of phytoplankton biomass to the hypoxic or anoxic sea floor . This combination of factors has been implicated in the extensive mortality of coastal fishes and invertebrates (Bakun and Weeks, 2004), resulting in significant reductions in fishing productivity, such as Cape hake (*Merluccius capensis*), Namibia's most valuable fishery (Hamukuaya *et al*., 1998).

Reduced upwelling would also reduce the productivity of important pelagic fisheries, such as for sardines, anchovies and mackerel, with major consequences for the economies of several countries (6.4.1, Chp 7, Figure 30.1A, B, Table S30.1). However, under projected scenarios of reduced upward supply of nutrients due to stratification of the open ocean , upwelling of both nutrients and trace elements may become increasingly important to maintaining upper ocean nutrient and trace metal inventories. It has been suggested that upwelling areas may also increase nutrient content and productivity under enhanced stratification, and that upwelled and partially denitrified waters containing excess phosphate may select for N_2-fixing microorganisms (Deutsch *et al*., 2007; Deutsch and Weber, 2012), but field observations of N2 fixation in these regions have not supported these predictions (Fernandez *et al*., 2011; Franz *et al*., 2012). The role of this process in global primary production thus needs to be validated (*low confidence*).

The central question therefore is whether or not upwelling will intensify, and if so, whether the effects of intensified upwelling on O_2 and CO_2 inventories will outweigh its benefits for primary production and associated fisheries and aquaculture (*low confidence*). In any case increasing atmospheric CO_2 concentrations will equilibrate with upwelling waters that may cause them to become more corrosive, depending upon pCO_2 of the upwelled water, and potentially increasingly impact the biota of Eastern Boundary Upwelling Ecosystems.

[INSERT FIGURE UP-1 HERE
Figure UP-1: Upper panel: Schematic hypothetic mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decreased coastal fisheries due to an augmented exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.]

Box CC-UP References

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Table 30-1: Regional changes in sea surface temperature (SST) over the period 1950–2009 using the Ocean regionalization specified in Figure 30-1a (for further detail of regions defined for analysis, see Figure SM30-1 and Table 30-2, column 1). A linear regression was fitted to the average of all 1×1 degree monthly SST data extracted from the HadISST1.1 data set [*Rayner et al.*, 2003] for each sub-region over the period 1950–2009. All SST values less than -1.8ºC, together with all SST pixels that were flagged as being sea ice, were reset to the freezing point of seawater (-1.8ºC) to reflect the sea temperature under the ice. Separate analyses were also done to explore trends in the temperatures extracted from the coldest-ranked and the warmest-ranked month of each year (Table SM30-2). The table includes the slope of the regression (°C $decade^{-1}$), the p-value for the slope being different from zero and the total change over 60 years (i.e., the slope of linear regression multiplied by 6 decades) for each category. The p-values that exceed 0.05 plus the associated slope and change values have a gray background, denoting the lower statistical confidence in the slope being different from zero (no slope). Note, changes with higher p-values may still describe informative trends although the level of confidence is lower that the slope is different from zero.

	Regression slope			**Total change over 60 years**			**p value, slope different from zero**		
Sub-region	**°C/Decade Coolest Month**	**°C/Decade All months**	**°C/Decade Warmest Month**	**Change over 60 years (coolest month)**	**Change over 60 years (all months)**	**Change over 60 years (warmest month)**	**°C/Decade Coolest Month**	**°C/Decade All months**	**°C/Decade Warmest Month**
1. High Latitude Spring Bloom Systems (HLSBS)									
Indian Ocean	**0.056**	**0.087**	**0.145**	**0.336**	**0.522**	**0.870**	**0.000**	**0.003**	**0.000**
North Atlantic	**0.054**	0.073	**0.116**	**0.324**	0.438	**0.696**	**0.001**	0.15	**0.000**
South Atlantic	**0.087**	0.063	**0.097**	**0.522**	0.378	**0.582**	**0.000**	0.098	**0.000**
North Pacific (west)	0.052	0.071	0.013	0.312	0.426	0.078	0.52	0.403	0.462
North Pacific (east)	0.016	0.04	0.016	0.096	0.24	0.096	0.643	0.53	0.444
Total North Pacific	0.033	0.055	0.015	0.198	0.33	0.09	0.284	0.456	0.319
South Pacific (west)	**0.043**	0.017	0.044	**0.258**	0.102	0.264	**0.016**	0.652	0.147
South Pacific (east)	**0.047**	0.031	**0.052**	**0.282**	0.186	**0.312**	**0.000**	0.396	**0.003**
Total South Pacific	**0.046**	0.027	**0.050**	**0.276**	0.162	**0.300**	**0.000**	0.467	**0.000**
2. Equatorial Upwelling Systems (EUS)									
Atlantic Equatorial	**0.101**	**0.090**	**0.079**	**0.606**	**0.540**	**0.474**	**0.000**	**0.000**	**0.000**
Pacific Equatorial	0.079	**0.071**	0.065	0.474	**0.426**	0.39	0.096	**0.001**	0.071
3. Semi-Enclosed Seas (SES)									

	Arabian Gulf	0.027	0.099	0.042	0.162	0.594	0.252	0.577	0.305	0.282	
	Baltic Sea	**0.352**	0.165	0.06	**2.112**	0.99	0.36	**0.000**	0.155	0.299	
	Black Sea	-0.004	0.053	**0.139**	-0.024	0.318	**0.834**	0.943	0.683	**0.009**	
	Mediterranean Sea	0.035	0.084	**0.110**	0.21	0.504	**0.660**	0.083	0.32	**0.006**	
	Red Sea	0.033	0.07	**0.047**	0.198	0.42	**0.282**	0.203	0.138	**0.042**	
4. Coastal Boundary Systems (CBS)											
	Western Atlantic	**0.137**	**0.123**	**0.127**	**0.822**	**0.738**	**0.762**	**0.000**	**0.000**	**0.000**	
	Caribbean/Gulf of Mexico	0.023	0.024	0.019	0.138	0.144	0.114	0.193	0.498	0.281	
	Western Indian Ocean	**0.097**	**0.100**	**0.096**	**0.582**	**0.600**	**0.576**	**0.000**	**0.000**	**0.000**	
	Eastern Indian Ocean	**0.099**	**0.092**	**0.080**	**0.594**	**0.552**	**0.480**	**0.000**	**0.000**	**0.000**	
	E Indian/SE Asia/W Pacific	**0.144**	**0.134**	**0.107**	**0.864**	**0.804**	**0.642**	**0.000**	**0.000**	**0.000**	
5. Eastern Boundary Upwelling Ecosystems (EBUE)											
	Benguela Current	**0.062**	0.032	0.002	**0.372**	0.192	0.012	**0.012**	0.437	0.958	
	California Current	**0.117**	**0.122**	0.076	**0.702**	**0.732**	0.456	**0.026**	**0.011**	0.125	
	Canary Current	0.054	**0.089**	**0.106**	0.324	**0.534**	**0.636**	0.166	**0.014**	**0.000**	
	Humboldt Current	0.051	0.059	**0.104**	0.306	0.354	**0.624**	0.285	0.205	**0.013**	
6. Sub-Tropical Gyres											
	Indian Ocean	**0.141**	**0.112**	**0.103**	**0.846**	**0.672**	**0.618**	**0.000**	**0.000**	**0.000**	
	North Atlantic	**0.042**	0.046	**0.029**	**0.252**	0.276	**0.174**	**0.048**	0.276	**0.038**	
	South Atlantic	**0.079**	**0.083**	**0.098**	**0.474**	**0.498**	**0.588**	**0.000**	**0.017**	**0.000**	
	North Pacific (west)	**0.065**	**0.071**	**0.059**	**0.390**	**0.426**	**0.354**	**0.000**	**0.018**	**0.000**	
	North Pacific (east)	0.008	0.042	**0.051**	0.048	0.252	**0.306**	0.617	0.133	**0.014**	
	Total North Pacific	**0.034**	0.055	**0.051**	**0.204**	0.33	**0.306**	**0.001**	0.053	**0.000**	
	South Pacific (west)	**0.060**	**0.076**	**0.092**	**0.360**	**0.456**	**0.552**	**0.002**	**0.000**	**0.000**	
	South Pacific (east)	**0.055**	0.056	**0.088**	**0.330**	0.336	**0.528**	**0.000**	0.058	**0.000**	
	Total South Pacific	**0.056**	**0.060**	**0.089**	**0.336**	**0.360**	**0.534**	**0.000**	**0.027**	**0.000**	

7. Coral Reef Provinces (Figure 30-3)											
	Caribbean/Gulf of Mexico	0.026	0.024	0.023	0.156	0.144	0.138	0.107	0.382	0.203	
	Coral Triangle & SE Asia	**0.137**	**0.131**	**0.098**	**0.822**	**0.786**	**0.588**	**0.000**	**0.000**	**0.000**	
	Eastern Indian Ocean	**0.081**	**0.097**	**0.116**	**0.486**	**0.582**	**0.696**	**0.000**	**0.000**	**0.000**	
	Western Indian Ocean	**0.091**	**0.100**	**0.102**	**0.546**	**0.600**	**0.612**	**0.000**	**0.000**	**0.000**	
	Eastern Pacific Ocean	**0.079**	**0.094**	**0.101**	**0.474**	**0.564**	**0.606**	**0.106**	**0.000**	**0.023**	
	Western Pacific Ocean	**0.072**	**0.073**	**0.073**	**0.432**	**0.438**	**0.438**	**0.000**	**0.000**	**0.000**	
8. Basin Scale											
	North Atlantic (combined)	**0.045**	0.061	**0.090**	**0.270**	0.366	**0.540**	**0.002**	0.198	**0.000**	
	South Atlantic (combined)	**0.076**	**0.074**	**0.101**	**0.456**	**0.444**	**0.606**	**0.000**	**0.041**	**0.000**	
	Atlantic Ocean Basin	**0.060**	**0.068**	**0.091**	**0.360**	**0.408**	**0.546**	**0.000**	**0.000**	**0.000**	
	Total North Pacific	**0.030**	0.052	**0.046**	**0.180**	0.312	**0.276**	**0.000**	0.248	**0.006**	
	Total South Pacific	**0.055**	0.048	**0.075**	**0.330**	0.288	**0.450**	**0.000**	0.115	**0.000**	
	Pacific Ocean Basin	**0.043**	**0.052**	**0.046**	**0.258**	**0.312**	**0.276**	**0.000**	**0.000**	**0.006**	
	Indian Ocean Basin	**0.130**	**0.108**	**0.106**	**0.780**	**0.648**	**0.636**	**0.000**	**0.000**	**0.000**	

Table 30-2: Examples of priority adaptation options and supporting policies to assist Pacific Island countries and territories to minimize the threats of climate change to the socio-economic benefits derived from pelagic and coastal fisheries and aquaculture, and to maximize the opportunities. These measures are classified as 'win-win' (W-W) adaptations, which address other drivers of the sector in the short-term and climate change in the long-term, or 'lose-win' (L-W) adaptations, where benefits exceed costs in the short-term but accrue under longer-term climate change (modified from [*Bell et al.*, 2013b]).

Adaptation options	Supporting policies
Economic development	
• Full implementation of the vessel day scheme (VDS) to control fishing effort by the Parties to the Nauru Agreements (W-W). • Diversify sources of fish for canneries in the region and maintain trade agreements, e.g., an Economic Partnership Agreement with the European Union (W-W). • Continued conservation and management measures for all species of tuna to maintain stocks at healthy levels and make these valuable species more resilient to climate change (W-W). • Energy efficiency programmes to assist fleets to cope with oil price rises and minimise CO_2 emissions, and reduce costs of fishing further afield as tuna distributionsshift east (W-W). • Pan-Pacific tuna management through merger of the Western and Central Pacific Fisheries Commission (WCPFC) and Inter-American Tropical Tuna Commission to coordinate management measures across the tropical Pacific (L-W).	• Strengthen national capacity to administer the VDS. • Adjust national tuna management plans and marketing strategies to provide flexible arrangements to buy and sell tuna. • Include implications of climate change in management objectives of the WCPFC. • Apply national management measures to address climate change effects for subregional concentrations of tuna in archipelagic waters beyond the mandate of WCPFC. • Require all industrial tuna vessels to provide operational-level catch and effort data to improve the models for redistribution of tuna stocks during climate change.
Food security	
• Manage catchment vegetation to reduce transfer of sediments and nutrients to coasts to reduce damage to adjacent coastal coral reefs, mangroves and seagrasses that support coastal fisheries (W-W). • Foster the care of coral reefs, mangroves and seagrasses by preventing pollution, managing waste and eliminating direct damage to these coastal fish habitats (W-W). • Provide for migration of fish habitats by prohibiting construction adjacent to mangroves and seagrasses and installing culverts beneath roads to help the plants colonise landward areas as sea level rises; (L-W). • Sustain and diversify catches of demersal coastal fish to maintain the replenishment potential of all stocks (L-W). • Increase access to tuna caught by industrial fleets through storing and selling tuna and by-catch landed at major ports to provide inexpensive fish for rapidly growing urban populations (W-W). • Install fish aggregating devices (FADs) close to the coast to improve access to fish for rural communities	• Strengthen governance for sustainable use of coastal fish habitats by: (1) building national capacity to understand the threats of climate change; (2) empowering communities to manage fish habitats; and (3) changing agriculture, forestry and mining practices to prevent sedimentation and pollution. • Minimise barriers to landward migration of coastal habitats during development of strategies to assist other sectors to respond to climate change. • Apply 'primary fisheries management' to stocks of coastal fish and shellfish to maintain their potential for replenishment. • Allocate the necessary quantities of tuna from total national catches to food security to increase access to fish for both urban and coastal populations. • Dedicate a proportion of the revenue from fishing licences to improve access to tuna for food security. • Include anchored inshore FADs as part of national infrastructure for food security.

as human populations increase and demersal fish decline (W-W). • Develop coastal fisheries for small pelagic fish species, e.g. mackerel, anchovies, pilchards, sardines and scads (W-W?). • Promote simple post-harvest methods, such as traditional smoking, salting and drying, to extend the shelf life of fish when abundant catches are landed (W-W).	
Livelihoods	
• Relocate pearl farming operations to deeper water and to sites closer to coral reefs and seagrass/algal areas where water temperatures and aragonite saturation levels are likely to be more suitable for good growth and survival of pearl oysters, and formation of high-quality pearls (L-W). • Raise the walls and floor of shrimp ponds so that they drain adequately as sea level rises (L-W). • Identify which shrimp ponds may need to be rededicated to producing other commodities (L-W).	• Provide incentives for aquaculture enterprises to assess risks to infrastructure so that farming operations and facilities can be ‘climate-proofed’ and relocated if necessary. • Strengthen environmental impact assessments for coastal aquaculture activities to include the additional risks posed by climate change. • Develop partnerships with regional technical agencies to provide support for development of sustainable aquaculture.

a = The Parties to the Nauru Agreement (PNA) are Palau, Federated States of Micronesia, Papua New Guinea, Solomon Islands, Marshall Islands, Nauru, Kiribati, and Tuvalu.

Table 30-3: Key risks to ocean and coastal issues from climate change and the potential for risk reduction through mitigation and adaptation. Key risks are identified based on assessment of the literature and expert judgments made by authors of the various WGII AR5 chapters, with supporting evaluation of evidence and agreement in the referenced chapter sections. Each key risk is characterized as very low, low, medium, high, or very high. Risk levels are presented for the near-term era of committed climate change (here, for 2030–2040), in which projected levels of global mean temperature increase do not diverge substantially across emissions scenarios. Risk levels are also presented for the longer-term era of climate options (here, for 2080–2100), for global mean temperature increases of 2°C and 4°C above pre-industrial levels. For each timeframe, risk levels are estimated for the current state of adaptation and for a hypothetical highly adapted state. As the assessment considers potential impacts on different physical, biological, and human systems, risk levels should not necessarily be used to evaluate relative risk across key risks. Relevant climate variables are indicated by symbols.

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Risks to ecosystems and adaptation options					
Changes in ecosystem productivity associated with the redistribution and loss of net primary productivity in open oceans, with regional differences in gains and losses (*medium confidence*)	To maintain existing levels of seafood production, adaptation options are limited to the relocation of industrial fishing activities due to regional decreases (low latitude) versus increases (high latitude) in productivity, and/or to the expansion of aquaculture.		6.1.1, 6.3.4, 6.5.1, 30.5.1-2, Table 30-4 Box CC-PP	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Distributional shift in fish and invertebrate species, fall in fishery catch potential at low latitudes, e.g., in EUS, CBS and STG regions (*high confidence*)	Evolutionary adaptation potential of fish and invertebrate species to warming is limited. Human adaptation options involve adjusting fishing gears and fishing grounds, and the large scale relocation of industrial fishing activities following the regional decreases (low latitude) versus (possibly transient) increases (high latitude) in catch potential, as well deploying flexible management that can react to variability and change. Further options include building resilience by reducing other stressors like pollution and eutrophication, diversification of fish catches, or the expansion of aquaculture.		6.1.1, 6.3.1, 6.5.2-3 30.5.1-4, 30.5.6, 30.6.2, Box CC-MB	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
High mortalities and loss of habitat to larger fauna including commercial species due to hypoxia expansion and effects, particularly in EBUE, some SES and CBS regions (*high confidence*)	Human adaptation options involve the large scale relocation of fishing activities as a consequence of the hypoxia induced decreases in biodiversity and fisheries catch of pelagic fish and squid. Specific fisheries may benefit (Humboldt squid). Reducing the amount of organic carbon running of coastlines by controlling nutrients and pollution running off agricultural areas can reduce microbial activity and consequently limit the extent of the oxygen drawdown and the formation of coastal dead zones.		6.1.1, 6.3.3, 30.5.3-5	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Ocean acidification: Reduced growth and survival of commercially valuable shellfish and other calcifiers, e.g., reef building corals, calcareous red algae (*high confidence*)	Evidence for differential resistance and evolutionary adaptation of some species exists but is likely to be limited at higher CO2 concentrations and temperatures reached; adaptation options include the shift to exploiting more resilient species or the protection of habitats with low natural CO2 levels, as well as the reduction of other stresses, mainly pollution and limiting pressures from tourism and fishing.		5.3.3.5, 6.1.1, 6.3.2, 6.4.1.1, 30.3.2.2, Box CC-OA	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Reduced biodiversity, fisheries abundance and coastal protection by coral reefs due to heat induced mass coral bleaching and mortality increases, e.g., in CBS, SES, and STG regions (*high confidence*)	Evidence of rapid evolution by corals is limited or non-existent. Some corals may migrate to higher latitudes. However, the movement of entire reef systems is unlikely. Human adaptation options are limited to reducing other stresses, mainly enhancing water quality and limiting pressures from tourism and fishing. This option will delay the impacts of climate change by a few decades but is likely to disappear as thermal stress increases.		5.4.2.4, 6.3.1-2, 6.4.2, 30.5.4-6 Box CC-CR	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Coastal inundation and habitat loss due to sea level rise and intensified precipitation and flood events, e.g., in CBS and STG subregions (*medium to high confidence*)	Options to maintain ecosystem integrity are limited to the reduction of other stresses, mainly pollution and limiting pressures from tourism, fishing and aquaculture. Loss of ecosystems such as sea grass, mangroves and coral reefs can be reduced by reducing deforestation and increasing reforestation of river catchments and coastal areas to retain sediments and nutrients. Application of "Blue Carbon' strategies to avoid degradation of coastal vegetated habitats and loss of carbon sinks, and enhance carbon sequestration.		5.4.2.3-7, 30.6.1, 30.6.2.2 Box CC-CR	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high
Marine biodiversity loss with high rate of climate change (*medium confidence*)	Adaptation options are limited to the reduction of other stresses, mainly to reducing pollution and to limiting pressures from coastal human activities such as tourism and fishing.		6.3.1-3, 6.4.1.2-3 Table 30.4 Box CC-MB	Present Near-term (2030-2040) Long-term (2080-2100) 2°C 4°C	Very low – Medium – Very high

Climatic drivers of impacts: Warming trend; Extreme temperature; Precipitation; Extreme precipitation; Damaging cyclone; Sea level; Hypoxia; Ocean acidification

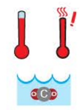
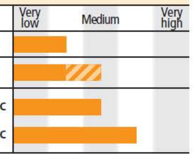
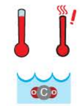
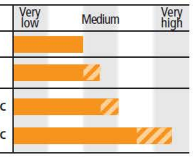
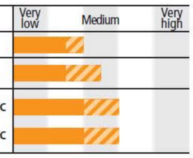
Risk & potential for adaptation: Potential for adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Risks to fisheries					
Decreased production of global shellfish fisheries, especially in HLSBS, EBUE and CBS (*high confidence*)	Help facilitate shift to alternative livelihoods by vulnerable people, changes in food consumption patterns and adjustment of (global) markets.		6.3.2, 6.3.5, 6.4.1.1, 30.5.5, 30.6.2, Box CC-OA	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Global redistribution and decrease of low latitude fisheries yields are paralleled by a global trend to catches having smaller fishes, particularly in STG and CBS (*medium confidence*)	Reduced food security and the increasing coastal poverty at low latitudes as fisheries becomes smaller - partially compensated by the expansion of aquaculture and marine spatial planning, to protect and enhance fisheries production as well as enhanced industrialized fishing efforts.		6.3.1, 6.4.1, 6.5.3, 30.5.4, 30.5.6, 30.6.2, Table 30-3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Redistribution of catch potential of large pelagic-highly migratory fish resources, such as tropical Pacific and Indian Ocean tuna fisheries (*high confidence*)	International fisheries agreements and instruments, such as cooperative agreements over tuna, may have limited success in establishing sustainable fisheries yields.		6.3.1, 6.4.3, Table 30-2, Table 30-4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Variability of small pelagic fishes in EBUE and EUS is becoming more extreme at interannual to multidecadal scales, making industry and management decisions more uncertain (*medium confidence*)	Development of new and specific management tools and models may have limited success to sustain yields. Reduction in fishing intensity has potential to increase resilience of the fisheries. Reduction of aquaculture dependance on fishmeal and fishoil from small pelagic fish.		6.3.2-3, 30.5.2, 30.5.5, 30.6.2 Table 30.4 Box CC-UP	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Decrease in catch and species diversity of fisheries in tropical coral reefs, exacerbated by interactions with other human drivers such as eutrophication and habitat destruction (*high confidence*)	Restoration of overexploited fisheries and reduction of other stressors on coral reefs delay ecosystem changes. Human adaptation includes the usage of alternative livelihoods and food sources (e.g., coastal aquaculture).		6.4.1, 30.5.3-4, 30.5.6, Table 30-3, Table 30-4 Box CC-CR	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Current spatial management units, especially the MPAs may fail in the future due to shifts in species distribution and community structure (*high confidence*) MPA: Marine Protected Area	Continuous revision and shifts of MPA borders, and of MPA goals and performance.		6.3.1, 6.4.2.1, 30.5.1, Box CC-MB	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high
Risks to humans and infrastructure					
Coastal socio-economic security from changing habitat and ecosystem structure, as well as sea level rise (*high confidence*)	Human adaptation options involve (1) Protection using coastal defences (e.g. seawalls) and soft measures (e.g. mangrove replanting and enhancing coral growth), (2) Accommodation to allow continued occupation of coastal areas by making changes to human activities and infrastructure, and (3) Managed retreat may represent only option in some areas. Vary from large-scale engineering works to smaller scale community projects. Options are available under the more traditional CZM (coastal zone management) framework but increasingly under DRR (disaster risk reduction) and CCA (climate change adaptation) frameworks.		5.5.2, 5.5.4, 30.6.5, 30.7.1, Table 30-3, Table 30-4	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high *
Reduced livelihoods and increased poverty (*medium confidence*)	Human adaptation options involve the large scale relocation of industrial fishing activities following the regional decreases (low latitude) versus increases (high latitude) in catch potential and shifts in biodiversity. Artisanal local fisheries are extremely limited in their adaptation options by available financial resources and technical capacities, except for their potential shift to other target species.		6.4.1-2, 30.6.2, 30.6.5, Table 30-3	Present; Near-term (2030-2040); Long-term (2080-2100) 2°C, 4°C	Very low – Medium – Very high

*high confidence in existence of adaptation measures, low confidence in magnitude of risk reduction

Climatic drivers of impacts: Warming trend; Extreme temperature; Precipitation; Extreme precipitation; Damaging cyclone; Sea level; Hypoxia; Ocean acidification

Risk & potential for adaptation: Potential for adaptation to reduce risk; Risk level with **high** adaptation; Risk level with **current** adaptation

Key risk	Adaptation issues and prospects	Climatic drivers	Supporting ch. sections	Timeframe	Risk for current and high adaptation
Risks to humans and infrastructure (continued)					
Impacts due to increased frequency of harmful algal blooms (*medium confidence*)	Adaptation options include improved monitoring and early warning system, reduction of stresses favouring harmful algal blooms, mainly pollution and eutrophication, as well as the avoidance of contaminated areas and fisheries products.		6.4.2.3, 30.6.3, Table 30-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	
Impacts on marine resources threatening regional security as territorial disputes and food security challenges increase (*limited evidence, medium agreement*)	Decrease in marine resources, movements of fish stocks and opening of new seaways , and impacts of extreme events coupled with increasing populations will increase the potential for conflict in some regions, drive potential migration of people and increase humanitarian crises.		AR5 SREX, 30.6.5, 30.7.2 12.4-12.6, 29.3	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	
Impacts on shipping and infrastructure for energy and mineral extraction increases as storm intensity and wave height increase in some regions (e.g., high latitudes) (*high confidence*)	Adaptation options are to limit activities to particular times of the year and/or develop strategies to decrease the vulnerability of structures and operations.		AR5 SREX, 30.6.2.3-4, Table 30-4	Present Near-term (2030-2040) Long-term (2080-2100) 2°C / 4°C	

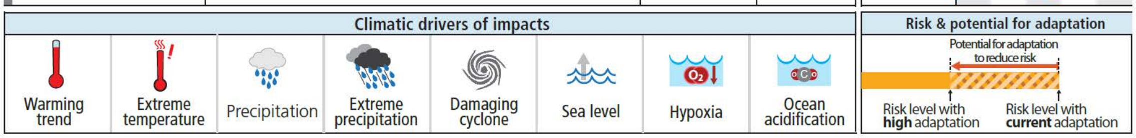


Table 30-4: Ramifications, adaptation options and frameworks for decision-making for ocean regions. Symbols are as follows: T = sea temperature; UW = upwelling; OA = ocean acidification; NU = nutrient concentration; IC = ice cover; SS = storm strength; SLR = sea level rise (↑ = Increased; ↓ = decreased; italics = uncertain). Acronyms are: CBD (Convention on Biological Diversity); CTI (Coral Triangle Initiative); GEF (Global Environment Facility); IHO (International Hydrographic Organization); ILO (International Labor Organization); IOM (International Organization of Migration); ISPS (International Ship and Port Facility Security); MARPOL (International Convention for the Prevention of Pollution From Ships); PACC (Pacific Adaptation to Climate Change Project); PEMSEA (Partnerships in Environmental Management for the Seas of East Asia); RFMO (Regional Fisheries Management Organizations); SPREP (Secretariat of the Pacific Regional Environment Programme); UNCLOS (United Nations Convention on the Law of the Sea); UNHCR (United Nations High Commissioner for Refugees); UNSFSA (Straddling Fish Stocks Agreement); and WHO (World Health Organization).

Primary driver(s)	**Biophysical change projected**	**Key risks and vulnerabilities**	**Ramifications**	**Adaptation options**	**Policy frameworks and initiatives (examples)**	**Key References and Chapter sections**
↑**T**, ↑*OA*	Spatial and temporal variation in primary productivity (*medium confidence* at global scales, Box CC-PP)	Reduced fisheries production impacts important sources of income to some countries while others may see increase productivity (e.g., as tuna stocks shift eastwards in the Pacific)(*medium confidence*).	Reduced national income, increased unemployment, plus increase in poverty. Potential increase in disputes over national ownership of key fishery resources (*likely*)	Increased international cooperation over key fisheries. Improved understanding of linkages between ocean productivity, recruitment and fisheries stock levels. Implementation of the regional 'vessel day scheme', provide social and economic incentives to fisheries and fishersfor adaptation,.	LOSC, PEMSEA, CTI, RFMO agreements, UNSFSA,	[*Tsamenyi and Hanich*, 2012] [*Bell et al.*, 2011; *Bell et al.*, 2013a] 6.4.1, 6.5.3, 30.6.2.1, 30.7.2, Box CC-PP,
↑**T**, ↑*OA*	Ecosystem regime shifts (e.g., coral to algal reefs; structural shifts in phytoplankton communities, *medium confidence*)	Reduced fisheries production as coastal habitats and ecosystems such as coral reefs (*medium confidence*).	Decreased food and employment security and human migration away from coastal zone (*likely*)	Strengthen coastal zone management to reduce contributing stressors (e.g., coastal pollution, over-harvesting and physical damage to coastal resources). Promote Blue Carbon* initiatives.	PEMSEA, CTI, PACC, MARPOL, UNHCR, CBD, IOM, GEF, ILO	[*Bell et al.*, 2013a]; 5.4.3, 6.3.1-2, 12.4, 30.5.2-4, 29.3.1, 29.3.3, 30.5.6, 30.6.1, 30.6.2.1, Box CC-CR
		Tourist appeal of coastal assets decreases as ecosystems change to less 'desirable' state reducing income to some countries (*low confidence*).	Increased levels of coastal poverty in some countries as tourist income decreases (*likely*).	As above, strengthen coastal zone management and reduce additional stressors on tourist sites; implement education programs and awareness among visitors. Diversify tourism activities.	CBD, PEMSEA, CTI, PACC, UNHCR, MARPOL	[*Kenchington and Warner*, 2012], 5.5.4.1, 6.4.1–2, 10.6, 30.6.2.2,

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key References and Chapter sections
		Increased risk of some diseases (e.g., ciguatera, harmful algal blooms) as temperatures increase shift and ecosystems shift away from coral dominance (*low confidence*)	Increased disease and mortality; decreases in coastal food resources and fisheries income (*likely*).	Increased monitoring and education surrounding key risks (e.g., ciguatera); develop alternate fisheries and income for periods when disease incidence increases, develop or update health response plans.	National policy strategies as well as and regional cooperation needed	[*Llewellyn*, 2010] 6.4.2.3, 10.6, 29.3.3.2, 29.5.3, 30.6.3,
		Increased poverty and dislocation of coastal people (particularly in the tropics) as coastal resources such as fisheries degrade (*medium confidence*).	Increased population pressure on migration destinations (e.g. large regional cities), and reduced freedom to navigate in some areas (as criminal activity increases; *likely*).	Develop alternative industries and income for affected coastal people. Strengthen coastal security both nationally and across regions. Increase cooperation over criminal activities.	UNCLOS, PEMSEA, CTI, ISPS, IMO, Bali Process on Transnational Crime ASEAN Mutual legal Assistance treaty and bilateral extradition and MLA agreements	[*Kaye*, 2012; *Rahman*, 2012] 12.4-6,29.3.3, 29.6.2, 30.6.5
↑T	Migration of organisms and ecosystems to higher latitudes (*high confidence*).	Reorganization of commercial fish stocks and ecological regime shifts (medium to high confidence).	Social and economic disruption (*very likely*)	Increased international cooperation and improve understanding of regime changes; early-detection monitoring of physical and biological variables and regional seasonal forecasting; include related uncertainties into fisheries management; social and economic incentives for industry.	UNCLOS, CBD, RFMO agreements, UNSFSA	7.4.2, 6.5, 30.5, 30.6.2.1, Box CC-MB,
		Increased in abundance, growing season and distributional extent ofpests and fouling species (*medium confidence*).	Increased disease risk to aquaculture and fisheries. Income loss and increased operating and maintenance costs (*very likely*)	Increase environmental monitoring; ; technological advances to deal with pest and fouling organisms; increase vigilance and control related to biosecurity.	IMO, BWM, Anti Fouling Convention	6.4.1.5, 7.3.2.4, 29.5.3-4, 30.6.2.1, Box CC-MB
		Threats to human health increase due to expansion of pathogens distribution to higher latitudes (*low confidence*).	Increased disease and mortality in some coastal communities (*likely*)	Reduce exposure through increased monitoring and education, adoption or update of health response plans to outbreaks	UNICEF, WHO, IHOs, and national governments.	[*Myers and Patz*, 2009]; 6.4.3, 10.8.2, 11.7, 29.3.3, 30.6.3, Box CC-MB

Primary driver(s)	**Biophysical change projected**	**Key risks and vulnerabilities**	**Ramifications**	**Adaptation options**	**Policy frameworks and initiatives (examples)**	**Key References and Chapter sections**
↑T, ↑NU, ↑*OA*	Increased incidence of harmful algal blooms (HABs, *low confidence*).	Increased threats to ecosystems, fisheries and human health (*medium confidence*).	Reduced supply of marine fish and shellfish and greater incidence of disease among some coastal communities (*likely*).	Provide early-detection monitoring and improve predictive models, provide education and adoption or update of health response plans.	CTI, PEMSEA, WHO, MARPOL	[*Llewellyn*, 2010], 30.6.3, 11.7, 6.4.2.3
↑T	Increased precipitation as a result of intensified hydrological cycle in some coastal areas (*medium confidence*)	Increased freshwater, sediment and nutrients flow into coastal areas, increase in number and severity of flood events(*medium to high confidence*).	Increasing damage to coastal reef systems with ecological regime shifts in many cases (*very likely*).	Improve management of catchment and coastal processes; expand riparian vegetation along creeks and rivers; improve agricultural retention of soils and nutrients.	CTI, PEMSEA, SPREP	3.4, 29.3.1, 30.5.4, 30.6.1
↑T	Changing weather patterns,, storm frequency , *medium confidence*)	Increased risk of damage to infrastructure such as that involved in shipping, and oil and gas exploration and extraction (*medium to low confidence*).	Increased damage and associated costs (*likely*)	Adjust infrastructure specifications, Developearly-warning systems and update emergency response plans to extreme events.	IMO	[*IPCC*, 2012], 10.4.4, 29.3, 30.6.2.3-4
↑SLR, **↑*SS***	Increased wave exposure of coastal areas and increased sea level (*high confidence*)	Exposure of coastal infrastructure and communities to damage and inundation, increase coastal erosion (*high confidence*)	Increased costs to human towns and settlements, numbers of displaced people and human migration (*very likely*).	Develop integrated coastal management that consider SLR in planning and decision-making; increase understanding of the issues through education.	UNICEF, IHOs, and national governments.	[*Warner*, 2012] 5.5, 12.4.1, 29.5.1, 30.3.1.2, 30.6.5
		Inundation of coastal aquifers reduces water supplies and decreased coastal agricultural productivity (*high confidence*).	Reduced food and water security leads to increased coastal poverty, reduced food security, and migration (*very likely*).	Assist communities to find alternatives for food and water, or assist in relocation of populations and agriculture from vulnerable areas.	UNICEF, IHOs, and national governments.	[*Warner*, 2012], 5.4.3, 12.4.1, 29.3.2, 30.3.1.2

Primary driver(s)	Biophysical change projected	Key risks and vulnerabilities	Ramifications	Adaptation options	Policy frameworks and initiatives (examples)	Key References and Chapter sections
↑SLR	Risk of inundation and coastal erosion, especially in low-lying countries (*high confidence*).	UNCLOS defined limits of maritime jurisdiction will contract as national baselines shift inland. Potential uncertainty increases in some areas with respect to the international boundaries to maritime jurisdiction (*high confidence*).	Lack of clarity increases as do disputes over maritime limits and maritime jurisdiction. Some nations at risk of major losses to their territorial waters (*very likely*).	Seek resolution of 'shifting national baselines' issue (retreat and redefinition, stabilization, or fixation of EEZ and other currently defined maritime jurisdiction limits.	UNCLOS	[*IPCC*, 2012; *Schofield and Arsana*, 2012; *Warner and Schofield*, 2012] 5.5, 30.6.5
↑T, ↓IC	Loss of summer sea ice (*high confidence*)	Access to northern coasts of Canada, USA and Russia increases security concerns (*high confidence*).	Potential for increased tension on different interpretations of access rights and boundaries (*likely to very likely*).	Seek early resolution of areas in dispute currently and in the future.	UNCLOS	Chapter 28
		New resources become available as ice retreats, increasing vulnerability of international borders in some cases (*medium confidence*).	Tensions over maritime claims and ownership of resources (*likely*).	International agreements need to be sorted.	UNCLOS	Chapter 28

*Blue Carbon initiatives include conservation and restoration of mangroves, saltmarsh and seagrass beds as carbon sinks (30.6.1).

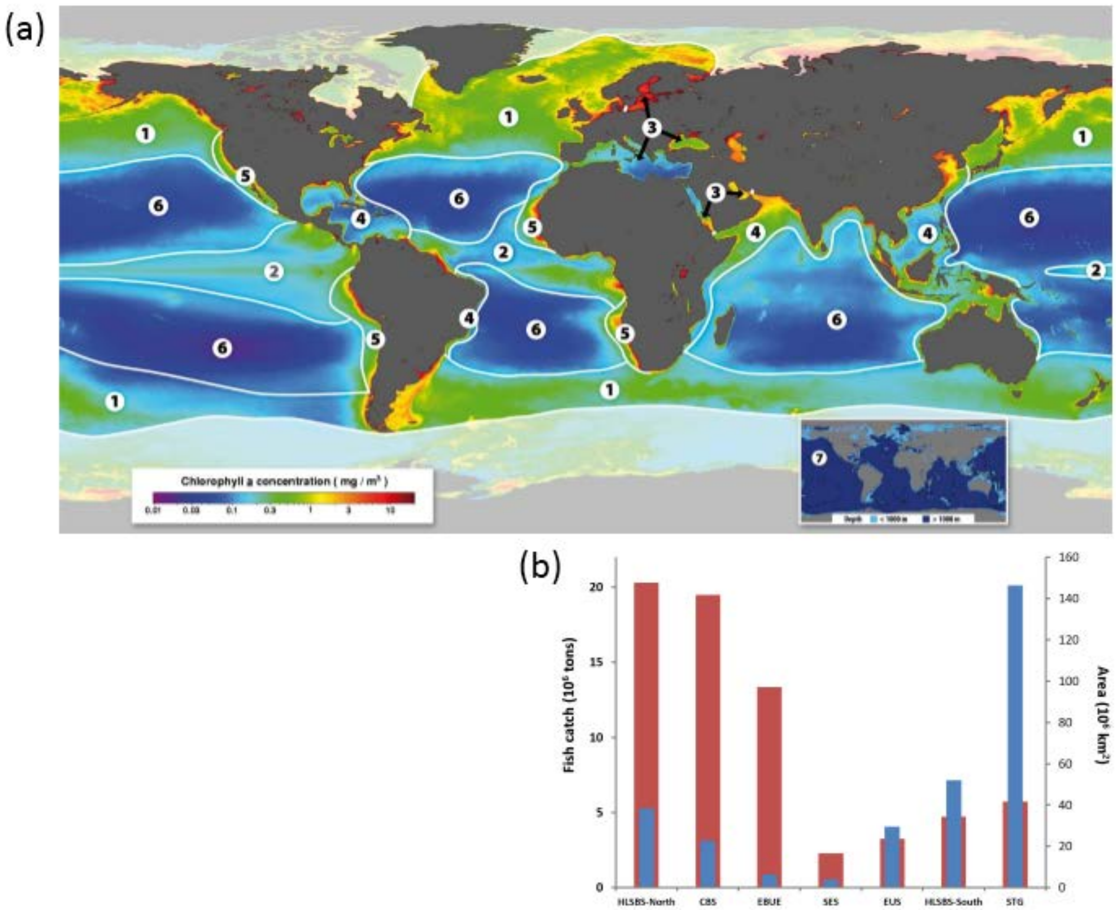


Figure 30-1: (a) Separation of the world's non-polar oceans into seven major sub-regions (excluding the polar oceans, which are considered in Chapter 28). The chlorophyll-*a* signal measured by SeaWiFS and averaged over the period from Sep 4, 1997 to 30 Nov 2010 (NASA) is provides a proxy for differences in marine productivity (with the caveats provided in Box CC-PP). Ecosystem structure and functioning, as well as key oceanographic features provided the basis for separating the Ocean into the sub-regions shown. The map insert shows the distribution of Deep Sea (DS) habitat (>1000 m; Bathypelagic and Abyssopelagic habitats combined). Numbers refer to: 1 = High Latitude Spring Bloom Systems (HLSBS); 2 = Equatorial Upwelling Systems (EUS); 3 = Semi-Enclosed Seas (SES); 4 = Coastal Boundary Systems (CBS); 5 = Eastern Boundary Upwelling Ecosystems (EBUE); 6 = Sub-Tropical Gyres (STG); and 7 = DS (>1000 m). (b) Relationship between fish catch and area for each ocean sub-region is shown in (a). Red columns: average fish catch (as millions tons yr^{-1}) for the period 1970–2006. Blue columns: area (millions km^2). The four left-hand columns (sub-regions HLSBS-North, CBS, EBUE, and SES) cover 20 % of the world oceans' area and deliver 80% of the world's fish catches. The values for the percent area of the Ocean, primary productivity, and fishery catch for the major sub-regions are listed in Table SM30-1.
[Illustration to be redrawn to conform to IPCC publication specifications.]

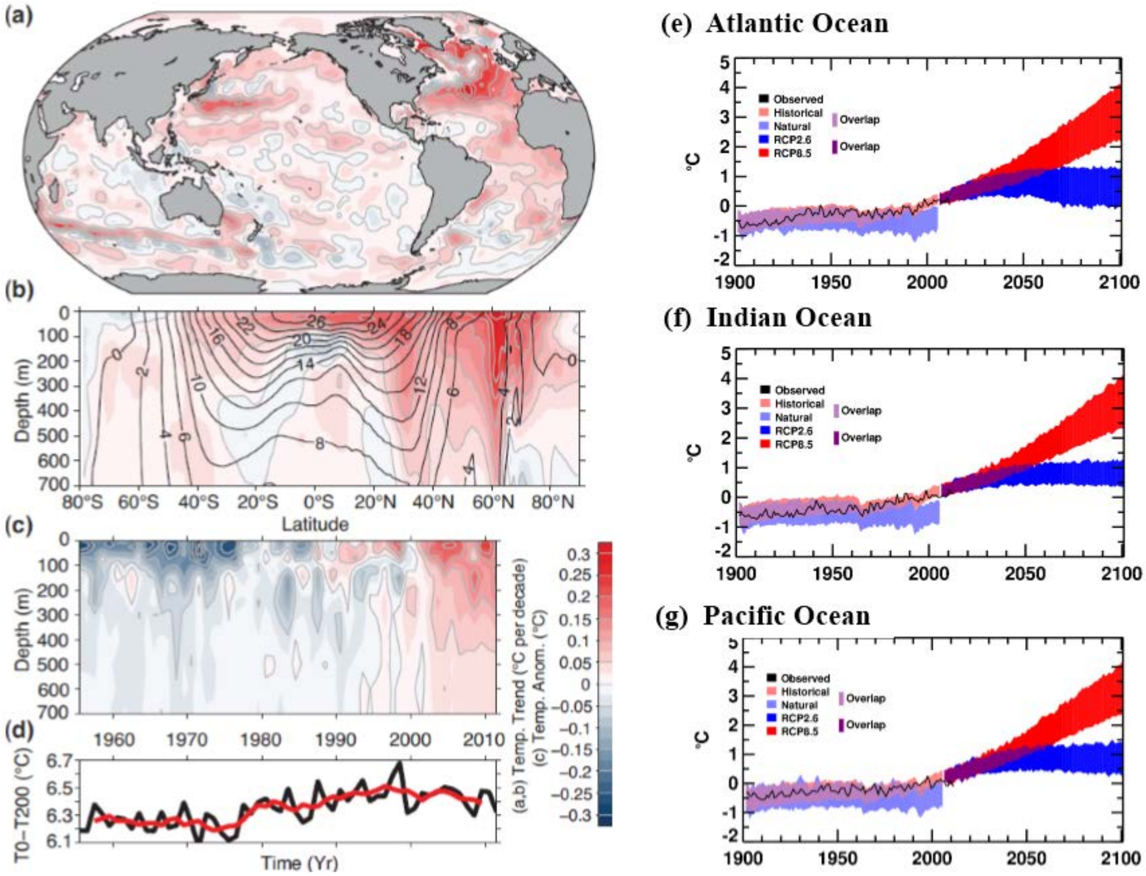


Figure 30-2: (a) Depth-averaged 0–700 m temperature trend for 1971–2010 (longitudinal versus latitude, colors and gray contours in °C per decade). (b) Zonally averaged temperature trends (latitude versus depth, colors and gray contours in °C per decade) for 1971–2010, with zonally averaged mean temperature over plotted (black contours in °C). (c) Globally-averaged temperature anomaly (Time versus depth, colors and grey contours in °C) relative to the 1971–2010 mean. (d) Globally-averaged temperature difference between the Ocean surface and 200 m depth (Black: annual values; red: five year running mean). Panels (a)–(d) from WGI Figure 3.1. (e)–(g) Observed and simulated variations in past and projected future annual average SST over three ocean basins (excluding regions within 300 km of the coast). The black line shows estimates from HadISST1.1 observational measurements. Shading denotes the 5–95 percentile range of climate model simulations driven with 'historical' changes in anthropogenic and natural drivers (62 simulations), historical changes in 'natural' drivers only (25), and the Representative Concentration Pathways: Dark Blue: RCP2.6; Light Blue: RCP4.5; Green: RCP6.0, and Red: RCP8.5). Data are anomalies from the 1986–2006 average of the HadISST1.1 data (for the HadISST1.1 time series) or of the corresponding historical all-forcing simulations. Further details are given in Box 21-2.
[Illustration to be redrawn to conform to IPCC publication specifications.]

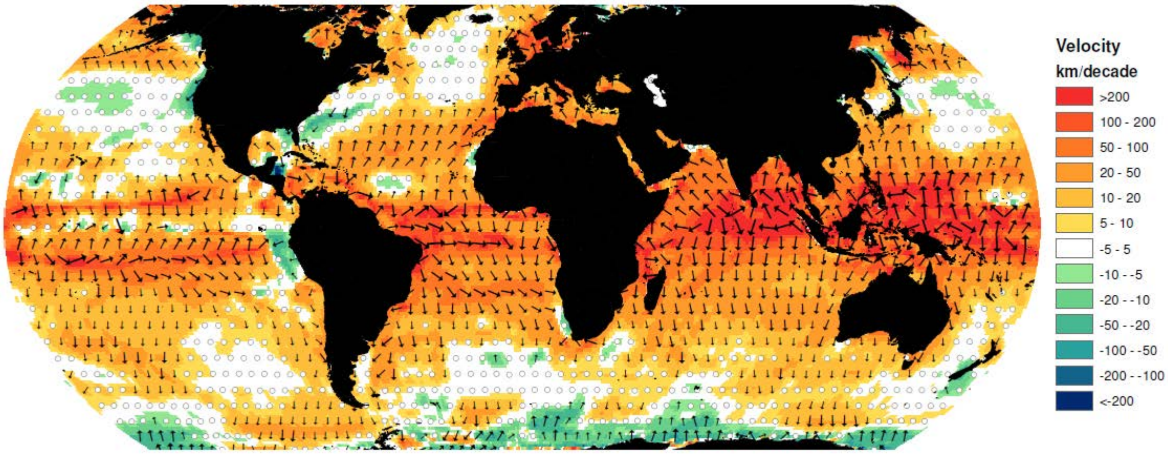


Figure 30-3: Velocity at which sea surface temperature (SST) isotherms shifted (km decade^{-1}) over the period 1960–2009 calculated using HaDISST1.1, with arrows indicating the direction and magnitude of shifts. Velocity of climate change is obtained by dividing the temperature trend in °C decade^{-1} by the local spatial gradient °C km^{-1}. The direction of movement of SST is denoted by the direction of the spatial gradient and the sign of the temperature trend: towards locally cooler areas with a local warming trend or towards locally warmer areas where temperatures are cooling. Adapted from [*Burrows et al.*, 2011].

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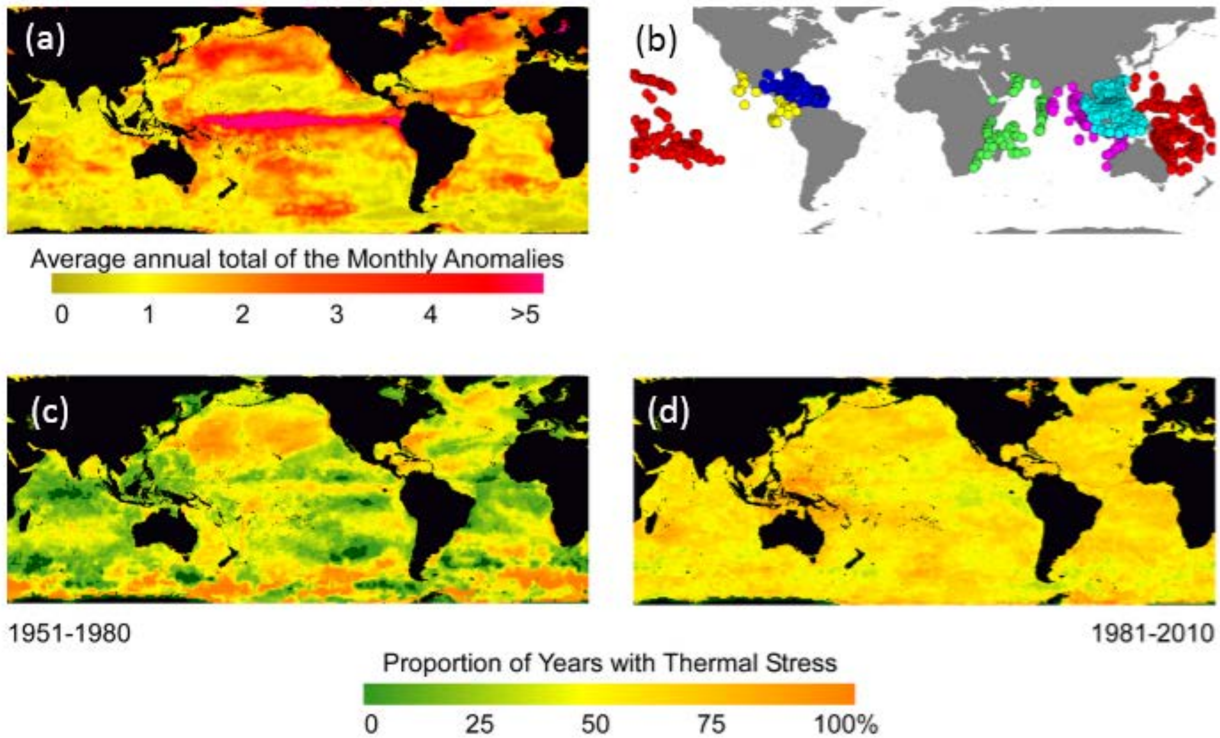

Figure 30-4: Recent changes in thermal stress calculated using HadISST1.1 data. A monthly climatology was created by averaging the HadISST monthly SST values over the period 1985–2000 to create twelve averages, one for each month of the year. The Maximum Monthly Mean (MMM) climatology was created by selecting the hottest month for each pixel. Anomalies were then created by subtracting this value from each SST value, but only allowing values to be recorded if they were greater than zero [*Donner et al.*, 2007]. Two measures of the change in thermal stress were calculated as a result: (a) The total thermal stress for the period 1981–2010, calculated by summing all monthly thermal anomalies for each grid cell. (b) The location of coral reef grid cells used in Table 30-1 and for comparison to regional heat stress here. Each dot is positioned over a 1×1 degree grid cell within which lies at least one carbonate coral reef. The latitude and longitude of each reef is derived from data provided by the World Resources Institute's *Reefs at Risk* report (http://www.wri.org). The six regions are as follows: Red – Western Pacific Ocean; Yellow – Eastern Pacific Ocean; Dark Blue – Caribbean & Gulf of Mexico; Green – Western Indian Ocean; Pink – Eastern Indian Ocean; and Light Blue – Coral Triangle & SE Asia. (c) Proportion of years with thermal stress, which is defined as any year that has a thermal anomaly, for the periods 1951–1980 and (d) 1981–2010. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

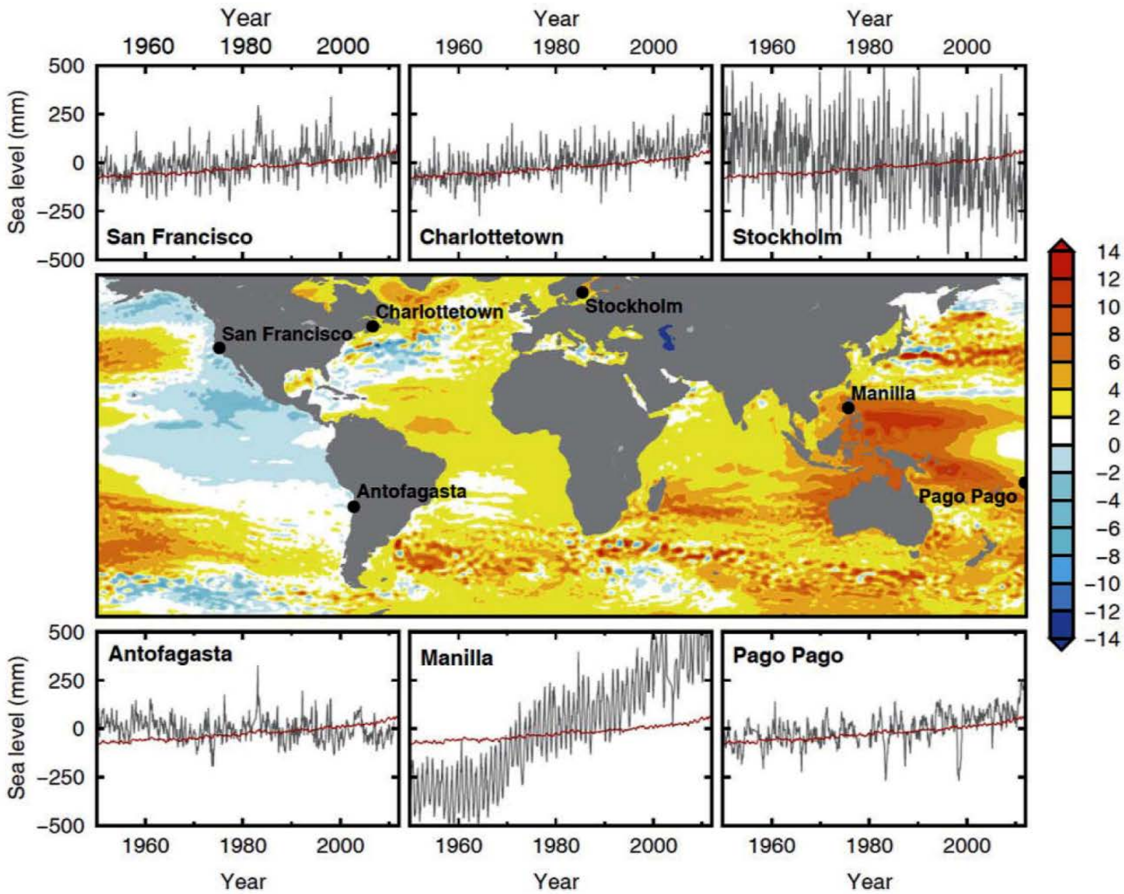

Figure 30-5. Map of the rate of change in sea surface height (geocentric sea level) for the period 1993–2012 derived from satellite altimetry. Also shown are relative sea level changes (gray lines) from selected tide gauge stations for the period 1950–2012. For comparison, an estimate of global mean sea level change is shown (red lines) with each tide gauge time series. The relatively large short-term oscillations in local sea level (gray lines) are due to the natural climate variability and ocean circulation. For example, the large regular deviations at Pago Pago are associated with the El Niño-Southern Oscillation. Figure originally presented in WGI FAQ 13.1, Figure 1).
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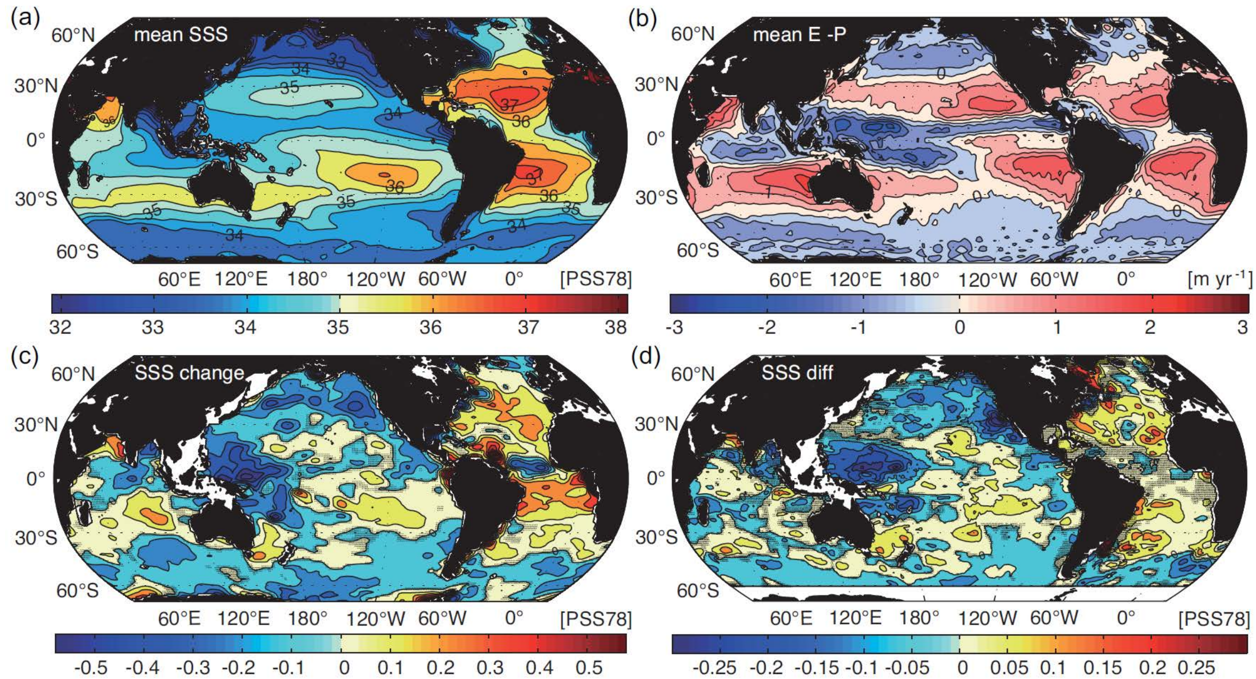

Figure 30-6: (a) The 1955–2005 climatological-mean sea surface salinity [*Antonov et al.*, 2010] color contoured at 0.5 PSS78 intervals (black lines). (b) Annual mean evaporation-precipitation averaged over the period 1950–2000 (NCEP) color contoured at 0.5 m yr–1 intervals (black lines). (c) The 58-year (2008 minus 1950) sea surface salinity change derived from the linear trend (PSS78), with seasonal and ENSO signals removed [*Durack and Wijffels,* 2010] color contoured at 0.116 PSS78 intervals (black lines). (d) The 30-year (2003–2007 average centered at 2005, minus the 1960–1989 average centered at 1975) sea surface salinity difference (PSS78) color contoured at 0.06 PSS78 intervals (black lines). Contour intervals in (c) and (d) are chosen so that the trends can be easily compared, given the different time intervals in the two analyzes. White areas in (c) and (d) are marginal seas where the calculations are not carried out. Regions where the change is not significant at the 99% confidence level are stippled in gray. Figure originally presented as WGI Figure 3.4 in WGI.
[Illustration to be redrawn to conform to IPCC publication specifications.]

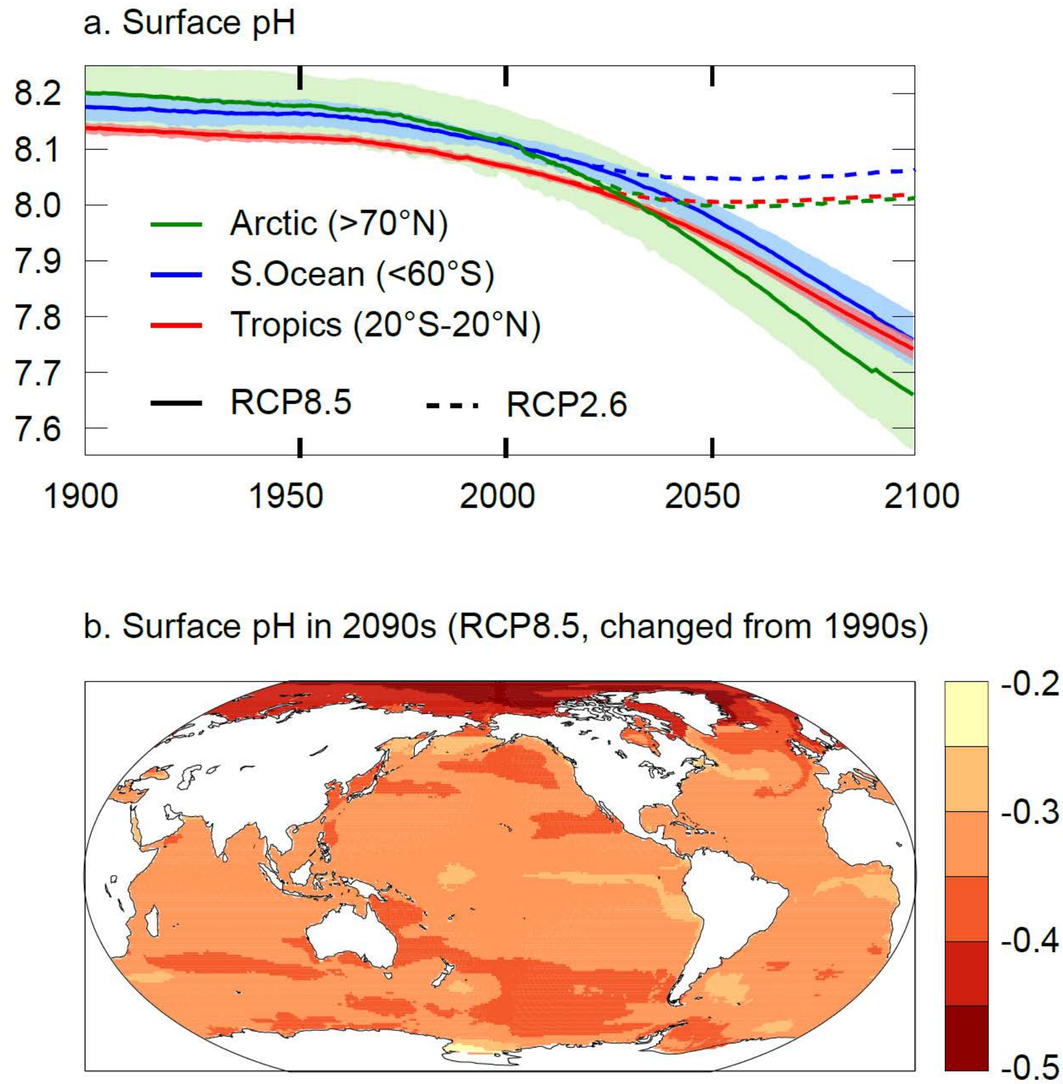

Figure 30-7: Projected ocean acidification from 11 CMIP5 Earth System models under RCP8.5 (other RCP scenarios have also been run with the CMIP5 models): (a) Time series of surface pH shown as the mean (solid line) and range of models (filled), given as area-weighted averages over the Arctic Ocean (green), the tropical oceans (red) and the Southern Ocean (blue). (b) Maps of the median model's change in surface pH from 1850–2100. Panel (a) also includes mean model results from RCP2.6 (dashed lines). Over most of the Ocean, gridded data products of carbonate system variables are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following [*Orr et al.*, 2005]. Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), the results are shown without bias correction. The bias correction reduces the range of model projections by up to a factor of 4, e.g., in panel (a) compare the large range of model projections for the Arctic (without bias correction) to the smaller range in the Southern Ocean (with bias correction). Figure originally presented in WGI Figure 6.28 in WGI.
[Illustration to be redrawn to conform to IPCC publication specifications.]

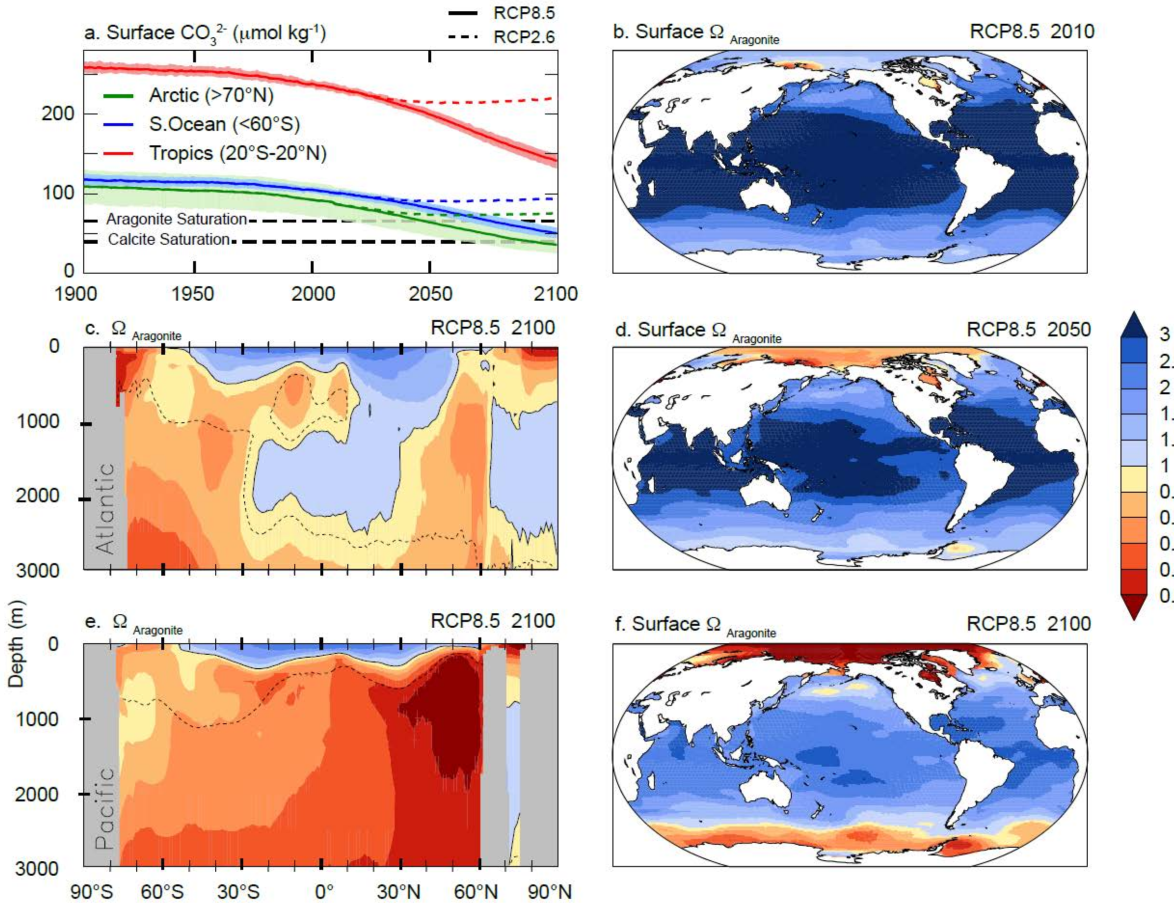

Figure 30-8: Projected aragonite saturation state from 11 CMIP5 Earth System models under RCP8.5 scenario: (a) time series of surface carbonate ion concentration shown as the mean (solid line) and range of models (filled), given as area weighted averages over the Arctic Ocean (green), the tropical oceans (red), and the Southern Ocean (blue); maps of the median model's surface ΩA in (b) 2010, (d) 2050, and (f) 2100; and zonal mean sections (latitude versus depth) of ΩA in 2100 over (c) the Atlantic Ocean and (e) the Pacific Ocean, while the ASH (Aragonite Saturation Horizon) is shown for 2010 (dotted line) and 2100 (solid line). Panel (a) also includes mean model results from RCP2.6 (dashed lines). As for Figure 30-7, gridded data products of carbonate system variables [*Key et al.*, 2004] are used to correct each model for its present-day bias by subtracting the model-data difference at each grid cell following [*Orr et al.*, 2005]. Where gridded data products are unavailable (Arctic Ocean, all marginal seas and the Ocean near Indonesia), results are shown without bias correction. Reprinted from Figure 6.29 in WGI.
[Illustration to be redrawn to conform to IPCC publication specifications.]

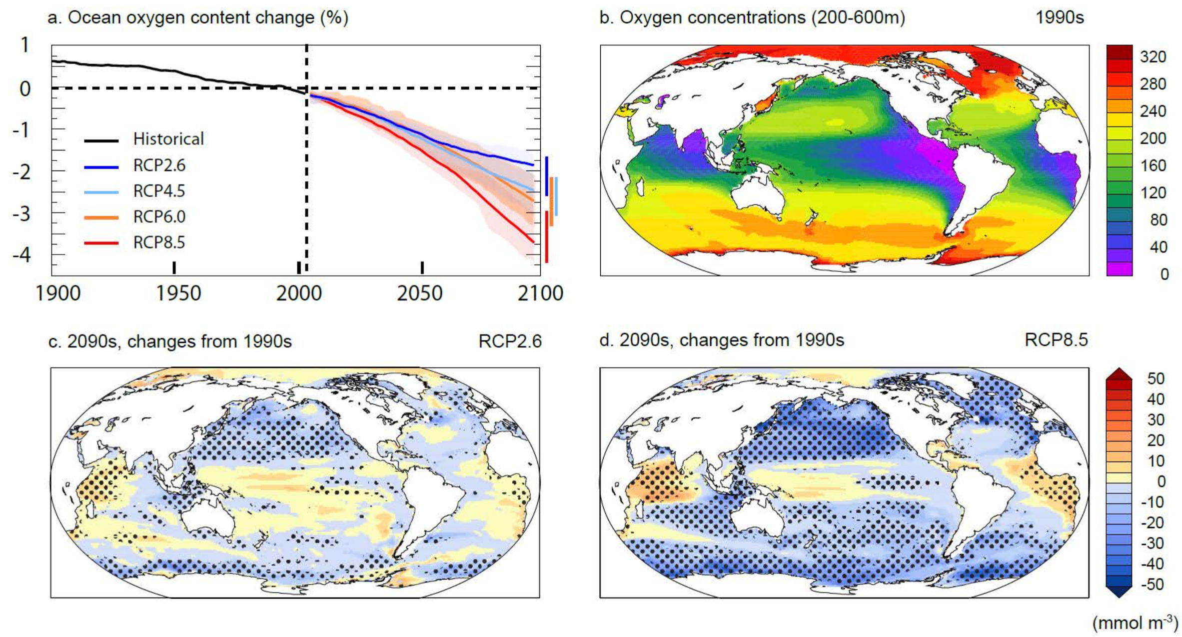

Figure 30-9: (a) Simulated changes in dissolved O_2 (mean and model range as shading) relative to 1990s for RCP2.6, RCP4.5, RCP6.0, and RCP8.5. (b) Multi-model mean dissolved O_2 (μmol m^{-3}) in the main thermocline (200–600 m depth average) for the 1990s, and changes in the 2090s relative to 1990s for RCP2.6 (c) and RCP8.5 (d). To indicate consistency in the sign of change, regions are stippled when at least 80% of models agree on the sign of the mean change. These diagnostics are detailed in [*Cocco et al.*, 2013] in a previous model inter-comparison using the SRES-A2 scenario and have been applied to CMIP5 models here. Models used: CESM1-BGC, GFDL-ESM2G, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MPI-ESM-LR, MPI-ESM-MR, NorESM1. Figure originally presented in WGI Figure 6.30 in WGI.
[Illustration to be redrawn to conform to IPCC publication specifications.]

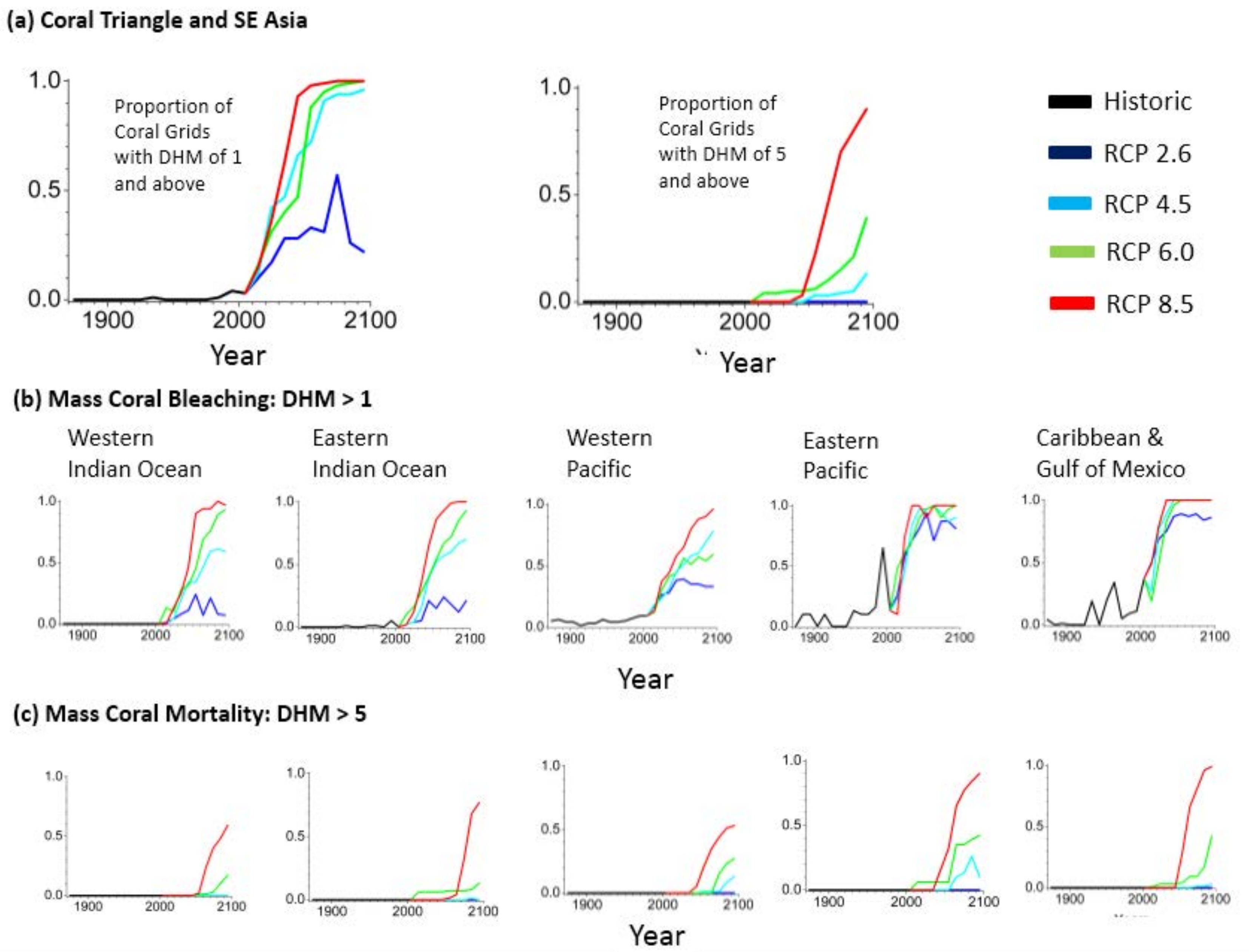
(a) Coral Triangle and SE Asia
Proportion of Coral Grids with DHM of 1 and above
Proportion of Coral Grids with DHM of 5 and above
Historic
RCP 2.6
RCP 4.5
RCP 6.0
RCP 8.5
1.0
0.5
0.0
1900
2000
2100
Year
(b) Mass Coral Bleaching: DHM > 1
Western Indian Ocean
Eastern Indian Ocean
Western Pacific
Eastern Pacific
Caribbean & Gulf of Mexico
Year
(c) Mass Coral Mortality: DHM > 5
Year

Figure 30-10: Annual maximum proportions of reef pixels with Degree Heating Months [*Donner et al.*, 2007]; DHM)≥1 (used for projecting coral bleaching; [*Strong et al.*, 1997; *Strong et al.*, 2011]) and DHM≥5 (associated with bleaching across 100% of affected areas with significant mortality, [*Eakin et al.*, 2010] for the period 1870–2009 for each of the six coral regions (Figure 30-4d) using the HadISST1.1 data set. The black line on each graph is the maximum annual area value for each decade over the period 1870–2009. This value is continued through 2010–2099 using CMIP5 data and splits into the four Representative Concentration Pathways (RCP2.6, 4.5, 6.0, and 8.5). DHM were produced for each of the four RCPs using the ensembles of CMIP models. From these global maps of DHM, the annual percentage of grid cells with DHM≥1 and DHM≥5 were calculated for each coral region. These data were then grouped into decades from which the maximum annual proportions were derived. The plotted lines for 2010–2099 are the average of these maximum proportion values for each RCP. Monthly SST anomalies were derived using a 1985–2000 maximum monthly mean (MMM) climatology derived in the calculations for Figure 30-4. This was done separately for HadISST1.1, the CMIP5 models, and each of the four RCPs, at each grid cell for every region. DHMs were then derived by adding up the monthly anomalies using a 4-month rolling sum. Figure SM30-3 presents past and future sea temperatures for the six major coral reef provinces under historic, un-forced, RCP4.5 and RCP8.5 scenarios.]

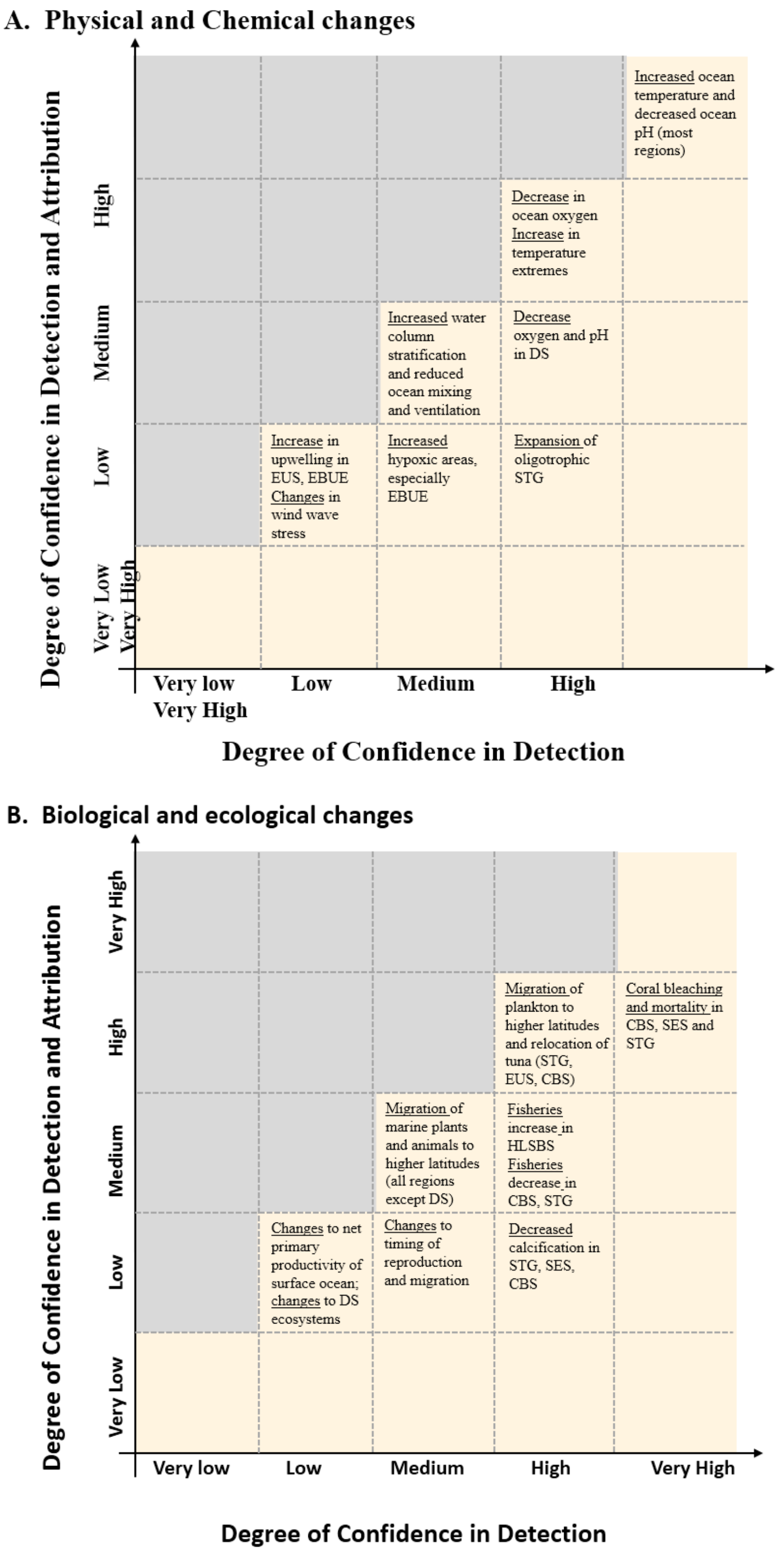

Figure 30-11: Expert assessment of degree of confidence in detection and attribution of physical and chemical changes (a) and ecological changes (b) across sub-regions, as designated in Figure 30-1a, and processes in the Ocean (based on evidence explored throughout Chapter 30 and elsewhere in AR5). Further explanation of this figure is given in 18.3.3–4 and 18.6. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

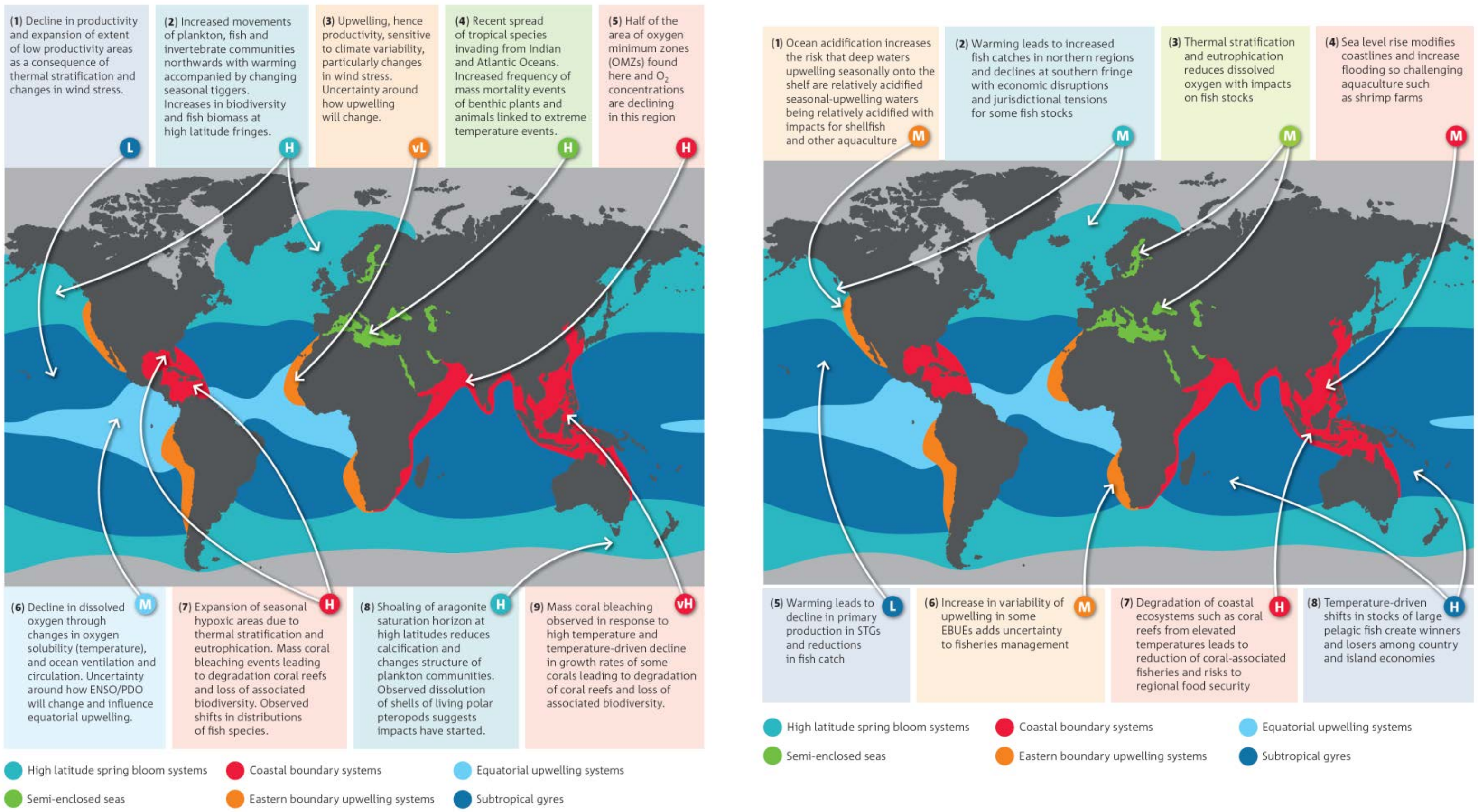

Figure 30-12: (a) Examples of projected impacts and vulnerabilities associated with climate change in Ocean sub-regions. (b) Examples of risks to fisheries from observed and projected impacts across Ocean sub-regions. Letters indicate level of confidence: (vL): Very low, (L): Low, (M): Medium, (H): High and (vH): Very high. Details of sub-regions are given in Table 30-1a and 30.1.1. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

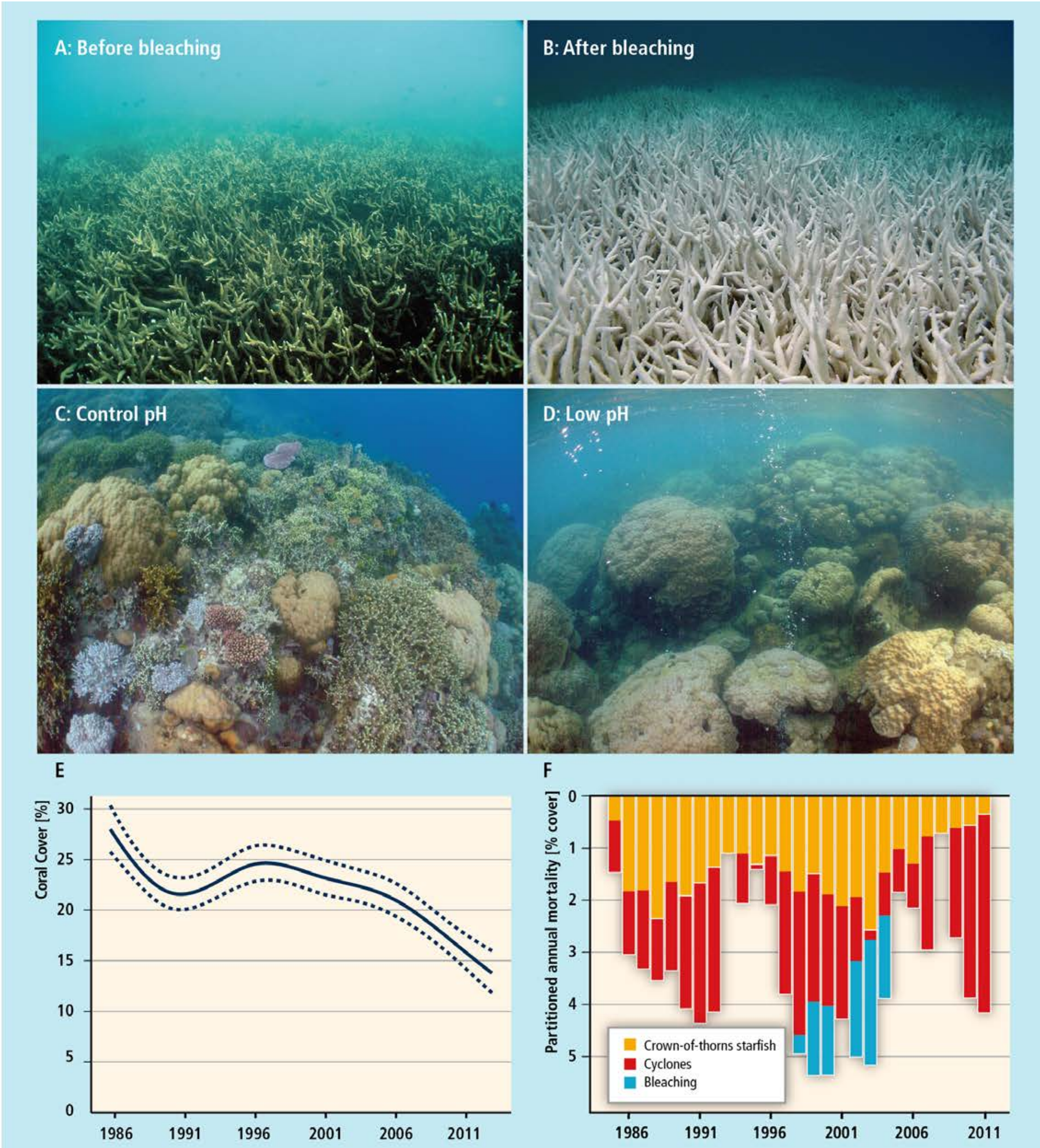

Figure CR-1: A and B: the same coral community before and after a bleaching event in February 2002 at 5 m depth, Halfway Island, Great Barrier Reef. Coral cover at the time of bleaching was 95% bleached almost all of it severely bleached, resulting in mortality of 20.9% (Elvidge *et al*., 2004). Mortality was comparatively low due in part because these coral communities were able to shuffle their symbiont to more thermo-tolerant types (Berkelmans and van Oppen, 2006; Jones *et al*., 2008). C and D: three CO_2 seeps in Milne Bay Province, Papua New Guinea show that prolonged exposure to high CO_2 is related to fundamental changes in the ecology of coral reefs (Fabricius *et al*., 2011), including reduced coral diversity (-39%), severely reduced structural complexity (-67%), lower density of young corals (-66%) and fewer crustose coralline algae (-85%). At high CO_2 sites (panel D; median pH_T ~7.8), reefs are dominated by massive corals while corals with high morphological complexity are underrepresented compared with control sites (D; median pH ~8.0). Reef development ceases at pH_T values below 7.7. pH_T: pH on the total scale. E: temporal trend in coral cover for the whole Great Barrier Reef over the period 1985–2012 (N, number of reefs, mean ± 2 standard errors; De'ath et al., 2012). F: composite bars indicate the estimated mean coral mortality for each year, and the sub-bars indicate the relative mortality due to crown-of-thorns starfish, cyclones, and bleaching for the whole Great Barrier Reef (De'ath et al., 2012). Photo credit: R. Berkelmans (A and B) and K. Fabricius (C and D).

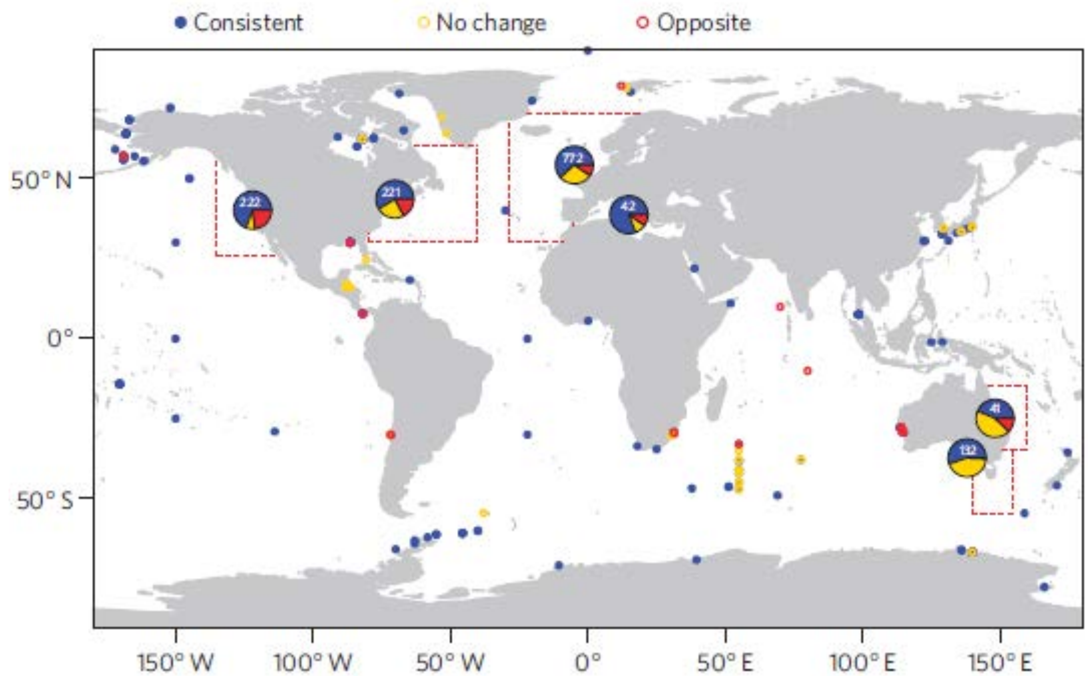

Figure MB-1: 1735 observed responses to climate change from 208 single- and multi-species studies. Changes attributed to climate change (blue), inconsistent with climate change (red) and are equivocal (yellow). Each circle represents the centre of a study area. Where points fall on land, it is because they are centroids of distribution that surround an island or peninsula. Pie charts show the proportions within regions bounded by red squares and in the Mediterranean; numbers indicate the total (consistent, opposite or equivocal) observations within each region. Note: 57% of the studies included were published since AR4 (from Poloczanska *et al.*, 2013).
[Illustration to be redrawn to conform to IPCC publication specifications.]

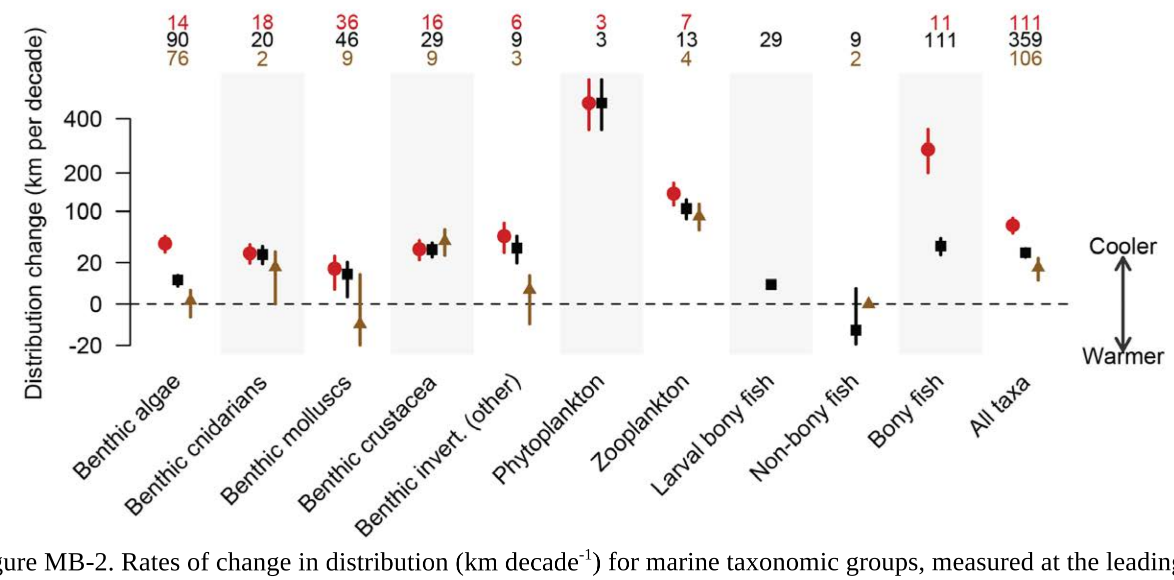

Figure MB-2. Rates of change in distribution (km decade^{-1}) for marine taxonomic groups, measured at the leading edges (red) and trailing edges (brown). Average distribution shifts calculated using all data, regardless of range location, are in black. Distribution rates have been square-root transformed; standard errors may be asymmetric as a result. Positive distribution changes are consistent with warming (into previously cooler waters, generally poleward). Means ± standard error are shown, along with number of observations (from Poloczanska et al., 2013).
[Illustration to be redrawn to conform to IPCC publication specifications.]

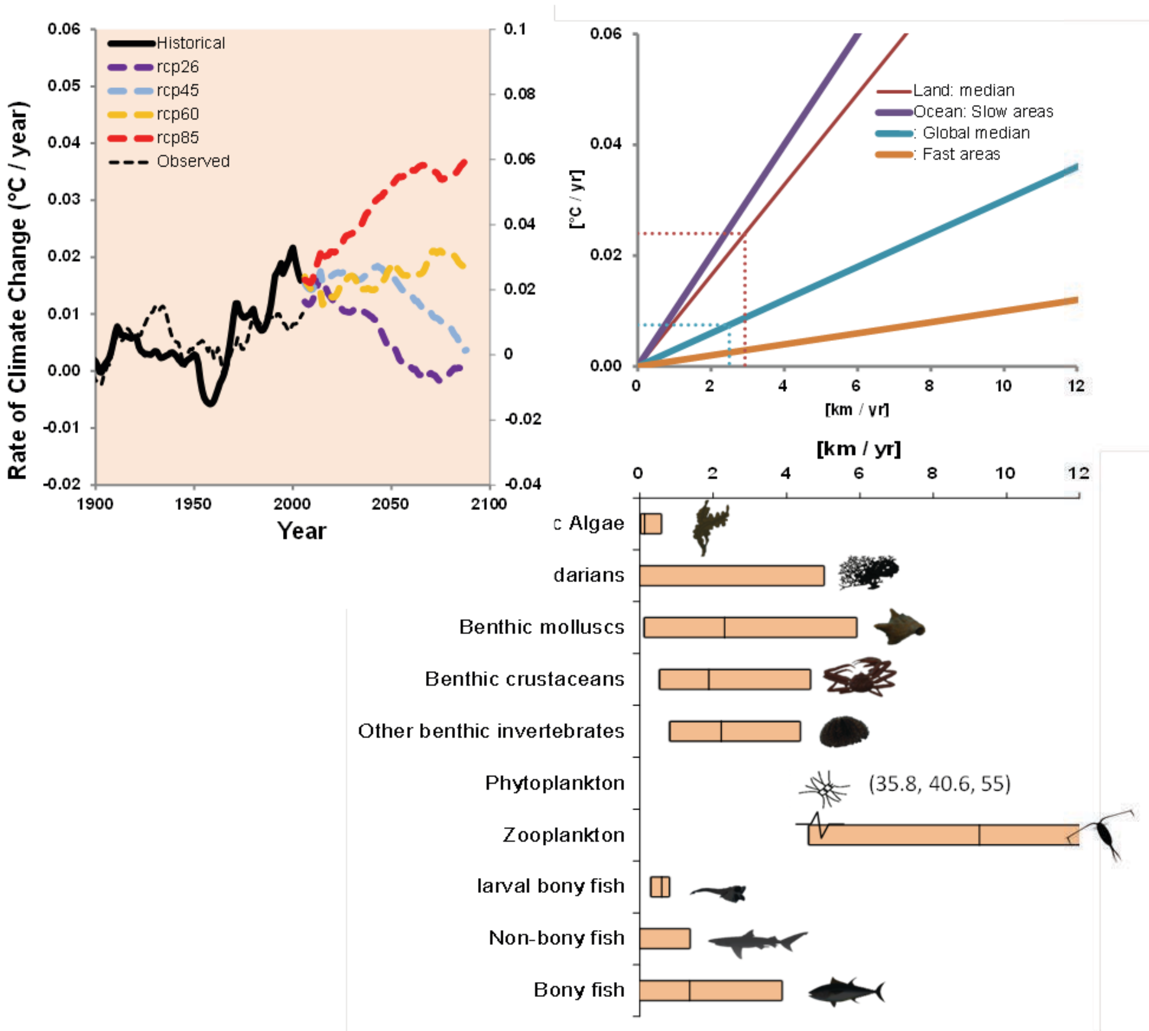

Figure MB-3. A. Rate of climate change for the Ocean (sea surface temperature (SST) °C); B. corresponding climate velocities for the Ocean and median velocity from land (adapted from Burrows et al., 2011); and C. observed rates of displacement of marine taxonomic groups over several decades until 2010. The thin dotted red arrows give an example of interpretation. Rates of climate change of 0.008 °C yr^{-1} correspond to ca. 2.4 km yr^{-1}median climate velocity in the Ocean. When compared to observed rates of displacement, many marine taxonomic groups have been able to track these velocities, except phyto- and zooplankton where rates of displacement greatly exceed climate velocity. All values are calculated for ocean surface with the exclusion of polar seas (Figure 30-1a). (A) Observed rates of climate change for Ocean SST (Black dotted line) are derived from HadISST1.1 data set, all other rates are calculated based on the average of the CMIP5 climate model ensembles (Table S30-3) for the historical period and for the future based on the four RCP emissions scenarios. Data were smoothed using a 20-year sliding window. (B) Median climate velocity calculated from HadISST1.1 dataset over 1960–2010 using the methods of Burrows et al., 2011. The three axes represent estimated median climate velocities are representative of areas of slow velocities such as Pacific subtropical gyre (STG) system (Purple line), the global Ocean surface (excluding polar seas, Blue line), and areas of high velocities such as the Coral Triangle and North Sea (Orange line). Figure 30-3 shows climate velocities over the ocean surface calculated over 1960–2010. The Red line corresponds to the median rate over global land surface calculated using historical surface temperatures from the CMIP5 model ensemble (Table S30-3). (C) Rates of displacement for marine taxonomic groups estimated by Poloczanska et al. 2013 using published studies (Figure MB-2 Black data set). Note the displacement rates for phytoplankton exceed the axis, so values are given. **[Illustration to be redrawn to conform to IPCC publication specifications.]**

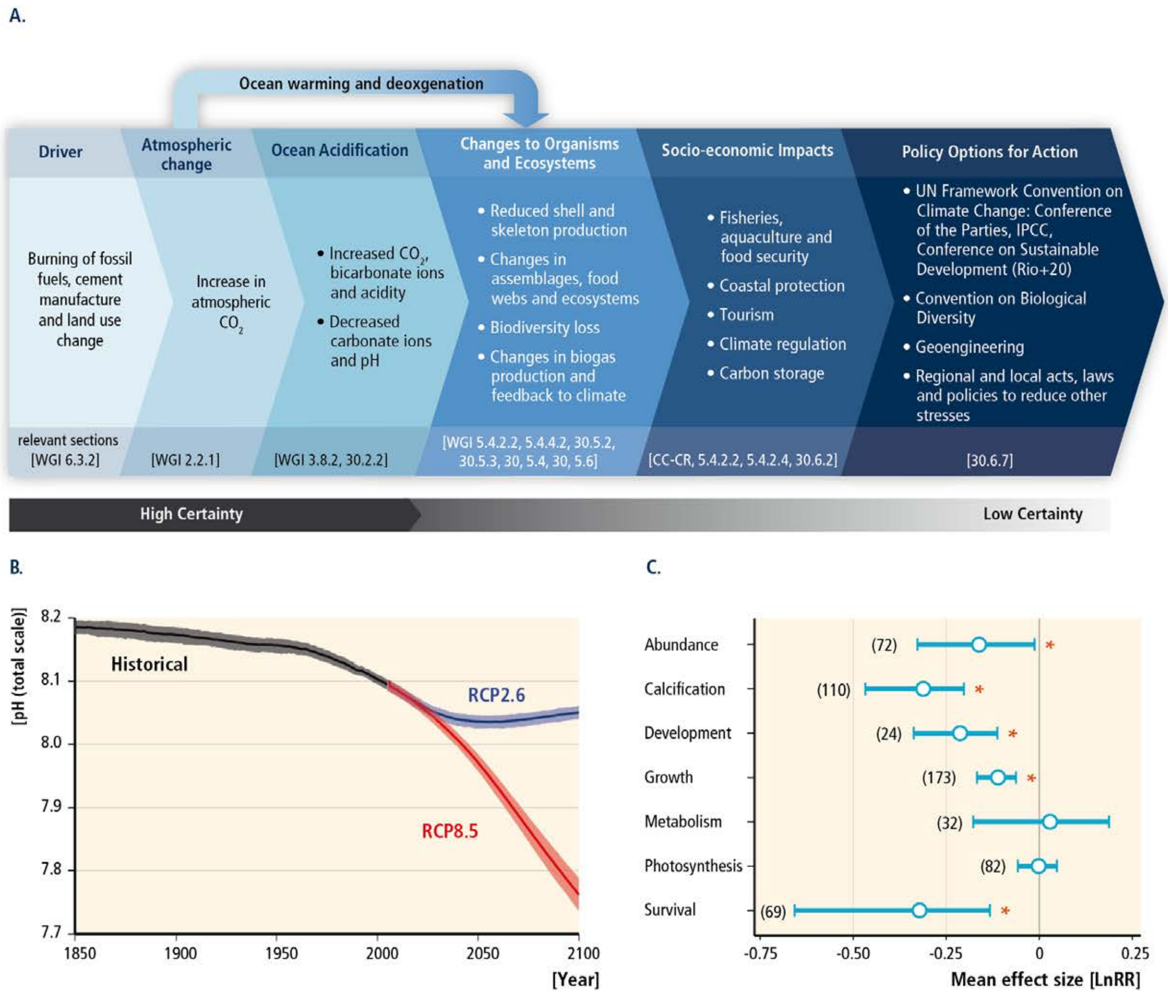

Figure OA-1: A: Overview of the chemical, biological, socio-economic impacts of ocean acidification and of policy options (adapted from Turley and Gattuso, 2012). B: Multi-model simulated time series of global mean ocean surface pH (on the total scale) from CMIP5 climate model simulations from 1850 to 2100. Projections are shown for emission scenarios RCP2.6 (blue) and RCP8.5 (red) for the multi-model mean (solid lines) and range across the distribution of individual model simulations (shading). Black (grey shading) is the modelled historical evolution using historical reconstructed forcings. The models that are included are those from CMIP5 that simulate the global carbon cycle while being driven by prescribed atmospheric CO_2 concentrations. The number of CMIP5 models to calculate the multi-model mean is indicated for each time period/scenario (WGI AR5 Figure 6.28). C: Effect of near future acidification (seawater pH reduction of 0.5 unit or less) on major response variables estimated using weighted random effects meta-analyses, with the exception of survival which is not weighted (Kroeker et al., 2013). The log-transformed response ratio (LnRR) is the ratio of the mean effect in the acidification treatment to the mean effect in a control group. It indicates which process is most uniformly affected by ocean acidification but large variability exists between species. Significance is determined when the 95% bootstrapped confidence interval does not cross zero. The number of experiments used in the analyses is shown in parentheses. * denotes a statistically significant effect.

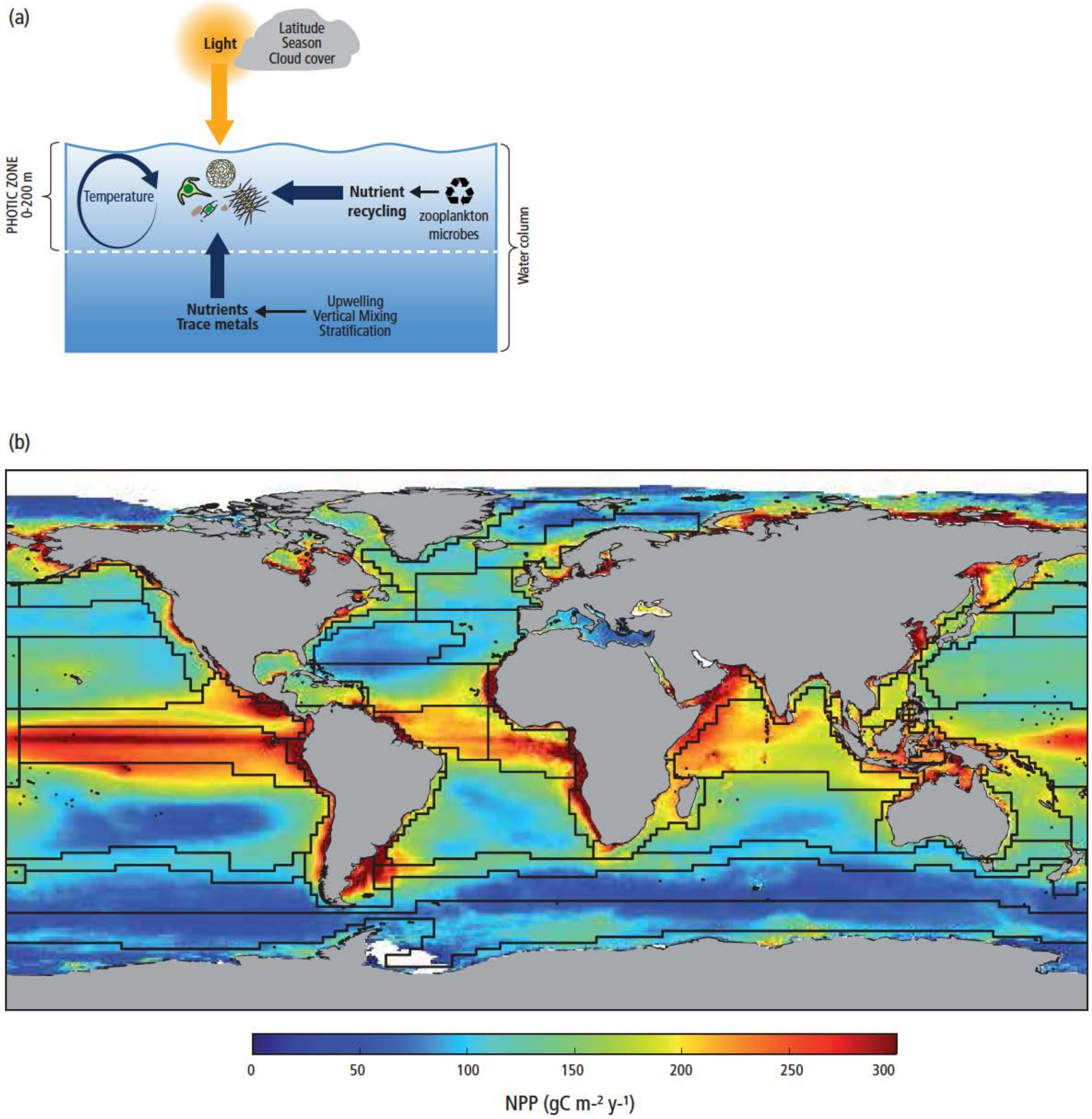

Figure PP-1: A) Environmental factors controlling Net Primary Production (NPP). NPP is mainly controlled by three basic processes: 1) Light conditions in the surface ocean, i.e. the photic zone where photosynthesis occurs, 2) upward flux of nutrients and micronutrients from underlying waters into the photic zone, 3) Regeneration of nutrients and micronutrients via the breakdown and recycling of organic material before it sinks out of the photic zone. All three processes are influenced by physical, chemical and biological processes and vary across regional ecosystems. In addition, water temperature strongly influences the upper rate of photosynthesis for cells that are resource-replete. Predictions of alteration of primary productivity under climate change depend on correct parameterizations and simulations of each of these variables and processes for each region. B) Annual composite map of global areal NPP rates (derived from MODIS Aqua satellite climatology from 2003-2012; NPP was calculated with the Carbon-based Production Model (CbPM, Westberry *et al*., 2008)). Overlaid is a grid of (thin black lines) that represent 51 distinct global ocean biogeographical provinces (after Longhurst, 1998 and based on Boyd and Doney, 2002). The characteristics and boundaries of each province are primarily set by the underlying regional ocean physics and chemistry. Figure courtesy of Toby Westberry (OSU) and Ivan Lima (WHOI), satellite data courtesy of NASA Ocean Biology Processing Group.
[Illustration to be redrawn to conform to IPCC publication specifications.]

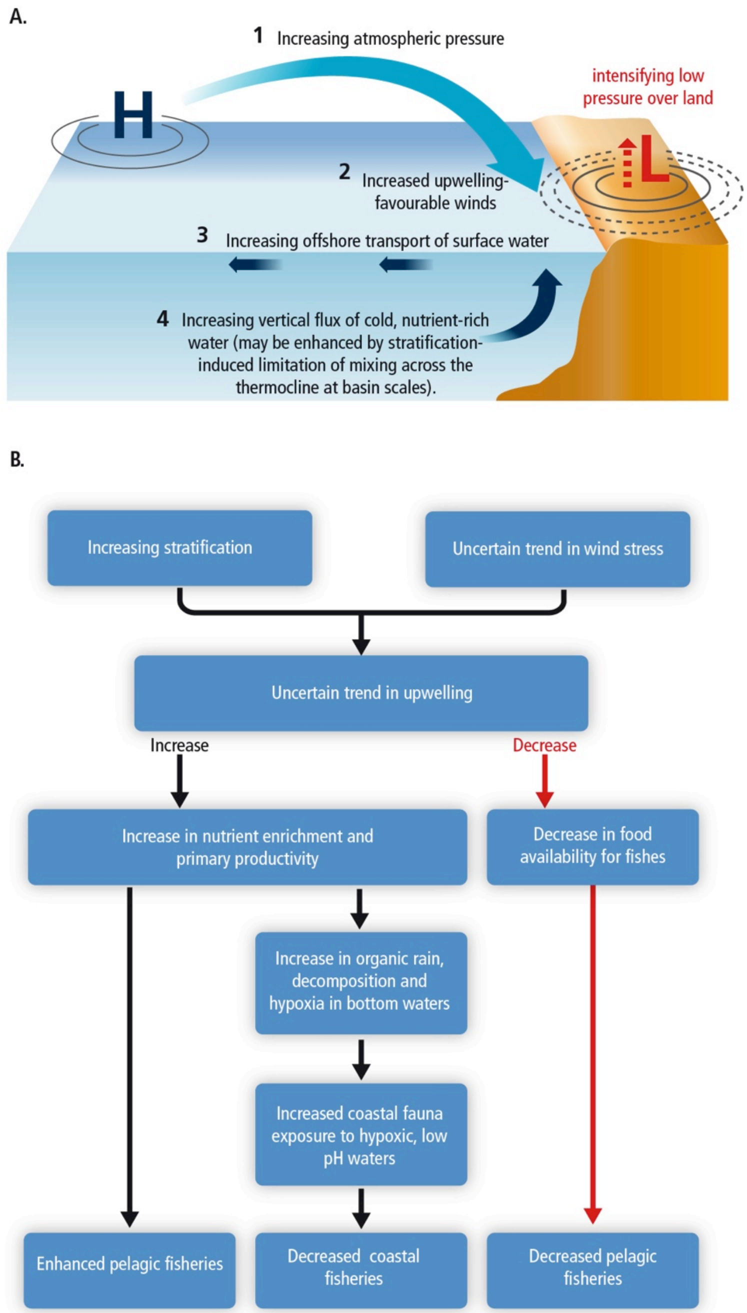

Figure UP-1: Upper panel: Schematic hypothetic mechanism of increasing coastal wind-driven upwelling at eastern boundary systems, where differential warming rates between land and ocean results in increased land-ocean pressure gradients (1) that produce stronger alongshore winds (2) and offshore movement of surface water through Ekman transport (3), and increased upwelling of deep cold nutrient rich waters to replace it (4). Lower panel: potential consequences of climate change in upwelling systems. Increasing stratification and uncertainty in wind stress trends result in uncertain trends in upwelling. Increasing upwelling may result in higher input of nutrients to the euphotic zone, and increased primary production, which in turn may enhance pelagic fisheries, but also decreased coastal fisheries due to an augmented exposure of coastal fauna to hypoxic, low pH waters. Decreased upwelling may result in lower primary production in these systems with direct impacts on pelagic fisheries productivity.