Chapter 21. Regional Context

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Executive Summary

Regional responses to climate change are acutely affected by the information flow between disciplines, sectors and across scales. To bridge these requires special attention to communicating concepts, language, and the formulation of information tailored from one sector for another. Chapter 21 forms one such interface through framing a critical assessment of the regional context of thematic and sectoral issues in a decision-making context.

The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather and longer-term climate trends – are assuredly regional or local in their occurrence, character and implications. Explicit recognition of geographical diversity is therefore an imperative for any scientific assessment of anthropogenic climate change. [21.2.1] An understanding of the context in which risk plays out, and the alternative options that may be considered to manage it, are thus not an afterthought, but a defining feature of an appropriate climate analysis, requiring a close interplay between decision-makers and providers of climate change and climate risk information. In this context, understanding and responding to regional change requires recognition of key concepts, and of the relative strengths and weaknesses of information at the appropriate scales. [21.2.2]

There is diversity in knowledge about adaptation, vulnerability and impacts among and within regions around the world. Evidence available for different global regions on adaptation, vulnerability and impacts varies in terms of robustness, quantity, scope, and regional representativeness. [21.3.3] There is mounting evidence that human adaptation is very likely to be occurring as an autonomous response to ongoing climate change in some regions.

The scales at which political decisions about climate change need to be made are frequently at odds with the definitions of regions. Climate change transcends political boundaries and is highly variable from region to region in terms of impacts and vulnerability. Likewise adaptation policies, options, and mitigation strategies are strongly region dependent and tied to local and regional development issues. [21.3.2] Climate change policy at regional scales is constrained by the dual challenge in achieving integration at multiple administrative scales from global through national to local (multi-level governance), and across different sectors (policy coherence). [21.3]

Cross-regional phenomena are very likely to be crucial for understanding the ramifications of climate change at regional scales, and its impacts and policies of response. [21.4] These include global trade and international financial transactions, which are linked to climate change as a direct or indirect cause of anthropogenic emissions, as a predisposing factor for regional vulnerability, through their sensitivity to climate trends and extreme climate events, and as an instrument for implementing mitigation and adaptation policies. Migration is also a cross-regional phenomenon, whether of people or of ecosystems, both requiring trans-boundary consideration of their causes, implications and possible interventions to alleviate human suffering and promote biodiversity.

Significant improvements have been made in the amount and quality of climate data that are available for establishing baseline reference states of climate-sensitive systems. [21.5.3] These include new and improved observational datasets, rescue and digitisation of historical datasets, and a range of improved global reconstructions of weather sequences. However, despite improvements, some questions remain unclear. For example, confidence in global precipitation estimates is low to medium due to incompleteness of data, and when all land areas are filled in using reconstruction methods, land precipitation shows little change since 1900 (in contrast to the AR4 assessment of a small increasing trend), along with a high degree of spatial and temporal variability in the trends.

Improved detection and attribution methods have shown that it is *extremely likely* that human activities have caused most of the global warming (more than 50%) since the 1950s and that this warming is not due to internal variability alone. The human influence on warming is *likely* over every inhabited continent (there are insufficient data to make an assessment over Antarctica). It is also *likely* that the human influence has altered sea level pressure patterns and related circulations. Attribution of changes in hydrological variables is less confident due to the lack of data though a human influence on zonal patterns of global and on high northern latitude precipitation changes has been detected (WGI Chapter 10).

Confidence in past and projected changes at regional scales is dependent on location and the variable being considered. Changes in global land surface air temperature exceed changes in global mean surface air temperature with continental interiors showing the largest changes. The increase in intensity of precipitation (and thus risk of flood) and summer drought occurrence over mid-continental land areas is a robust signature of global warming, both in observations for recent decades and in model projections. There is still little confidence in past trends and near term projections of tropical cyclone frequency and intensity. The mean regional pattern of sea surface salinity has been enhanced, with saline surface waters in the evaporation-dominated mid-latitudes becoming more saline, and relatively fresh surface waters in rainfall-dominated tropical and polar regions becoming fresher. It is virtually certain that the biogeochemical state of the ocean has changed (WGI Chapter 3). The uptake of CO2 by the ocean has resulted in a gradual acidification of seawater, with observations showing declines in pH in the mixed layer between -0.0015 and -0.0024 yr^{-1}. The retreat of Arctic ice in all seasons has continued, and the thickness, concentration and volume of arctic ice have also decreased. Conversely, the total extent of Antarctic ice has increased slightly with strong regional differences. Retreat of mountain glaciers is widespread, with varying rates across regions, and uncertainty about the global rate. Several hundred glaciers globally have completely disappeared in the last 30 years. Climate models indicate a nearly ice-free Arctic at the end of summer for warming greater than 2C. The models show no evidence of critical thresholds in the transition from perennial ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible. Projections of decrease in Northern Hemisphere spring snow covered area in the CMIP5 models are fairly coherent.

The uncertainty in near term climate projections is dominated by internal variability of the climate system, initial ocean conditions and inter-model response, rather than GHG forcing. The internal variability grows in importance at smaller spatial and temporal scales. The CMIP5 ensemble includes a new set of multidecadal near term prediction experiments (up to 2035) with initialized ocean state (WGI Chapter 11). Results from these experiments and analyses of un-initialized simulations show some evidence for the predictability of yearly to decadal averages of temperature both for the global average and for some geographical regions.

The time-mean rate of GMSL rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010, under all the RCP scenarios. [21.3.3] The ocean thermal expansion and glacier melting is *likely* to make the largest contributions to this rise. By the end of the 21st century it's *very likely* that over about 95% of the oceans will undergo sea level rise. The impacts of this sea-level rise, however, will also be a function of local and regional conditions, including coastal subsidence (or coastal uplift) and patterns of development near the coast.

The uncertainties inherent in climate model projections of regional climate changes have not decreased from AR4. [21.3.3] In some cases, the addition of regional forcings (e.g. topography) has increased some uncertainties.

The expanded use of multiple scenario elements beyond that of only climate scenarios still has unresolved issues. [21.5.3] Among these are the model-to-model variability of the integrated assessment models used to generate representative concentration pathways and shared socioeconomic pathways. This variability, and its consequences for impacts and adaptation analyses, or for understanding potential future climates, is largely unexplored.

Climate models continue to produce a range of projected futures where for some variables and locations the sign of projected change may differ from one model to another. [21.5.3] However, in many instances this indicates a lack of significant change compared to the natural variability for that region. The degree to which the model uncertainty can be reduced remains an open question.

Uncertainties of future climate remain centred on uncertainties over future climate forcing from emissions and concentrations, the climate system response to forcing, and the natural internal variability of the climate system. [21.5.3] The likelihood of reducing uncertainty in future emissions and concentrations appears low, and future scenarios are mainly presented as having equal plausibility. Uncertainty in the climate system uncertainty has multiple sources in constrained understanding of the system dynamics, in how the system components are modelled, and in the parameterization of processes.

Downscaling of coarse resolution global climate reconstructions and models has advanced to bring information closer to the temporal and spatial resolution requirements for projecting many regional impacts. [21.5.3] This information remains weakly coordinated, and current results indicate models can have significant errors in their high resolution reconstructions of the current climate.

Hotspots draw attention, from various perspectives and often controversially, to locations judged to be especially vulnerable to climate change. [21.4.4] Hotspots is an approach that has been used to indicate locations that stand out in terms of impacts, vulnerability or adaptive capacity (or all three). The approach exists in many fields and the meaning and use of the term hotspots differs, though their purpose is generally to set priorities for policy action and for further research. In the context of climate change, hotspots have been defined with respect to: climate changes themselves, biodiversity, health and disease, disasters, and food production and food security. Hotspots can be very effective as communication tools, but may also suffer from methodological weaknesses. They are often subjectively defined, relationships between indicator variables may be poorly understood and they can be highly scale-dependent. In part due to these ambiguities, there has been controversy surrounding the growing use of hotspots, particularly in relation to prioritising regions for climate change funding.

Improved regional scale climate information is now available to provide a more coherent picture of past and future regional changes with associated uncertainties. [21.3.3, 21.5.3] More targeted analysis of climate projections for impact assessment studies have been carried out, from which the leading messages to emerge include

- A strong regional variability of projected change is found for surface climate variables. Different indexes combining sets of climate variables and statistics indicate the emergence of various climate change hot-spots at different times in the future. Better process understanding is needed to increase confidence in the identification of climate change hot-spots (i.e. regions in which potential climate change impacts on the environment or different activity sectors can be particularly pronounced or where climate is especially responsive to global change).

- Broad regional patterns of late 21st century temperature and precipitation change projections, as well as changes in temperature and precipitation extremes, from the latest generation GCM simulations (CMIP5) are generally in line with previous projections available in the AR4.
- Preliminary analysis of decadal prediction experiments in the CMIP5 ensemble show that decadal predictability of unforced regional precipitation and temperature patterns over land is very low. Indications of some predictability of ocean temperatures of up to 10 years lead time is however found over some ocean basins
- A larger set of global and regional (both dynamical and statistical) model projections allow a better characterization of uncertainties than in the AR4, and more methods are available to produce probabilistic projections of changes for use in IAV assessment work.
- Projected changes in the oceans, sea level and cryosphere are also consistent, at least qualitatively, with previous estimates from the AR4 and with improved observations of recent past trends. Quantitative values of projected changes may however differ from the AR4 due to the availability of better models and larger ensembles, especially at the regional scale.
- Climate change is expected to substantially affect regional air quality, for example near surface ozone concentrations, however this effect also depends strongly on future emissions.

There is significant new information on many of the physical non-climatic factors, especially those that are components of the new RCPs used in the CMIP5. [21.5.3] Non-climatic factors relevant to assessing a system's vulnerability general involve a complex mix of physical and socio-economic influences. Often these are continually evolving and thus generally only a reference point in time rather than a reference state over a period of time can be defined. Improvements in observations of other factors have also occurred but, as with climate information, in many cases the quality is regionally dependent and there are resolution deficiencies. The literature on characterizing vulnerability on sub-national and regional scales is mixed – but it is clear that there is significant variation in vulnerability due to variability in wealth, income, social factors, and access to governance.

The derivation of the RCP's and the parallel process for scenario development has enabled the climate modeling community to consider explicit mitigation scenarios for the first time in systematic model intercomparisons. [21.5.3] Substantial regional information of economic activity, development trajectories, and emissions are available for analysis, but remain largely unexplored. The RCP's are known not to be unique pathways to the identified radiative forcing targets. Model to model variability of the IAM's used to generate the RCP's is also largely unexplored.

Achieving emission targets without putting a price on carbon emissions from land-use has the potential to lead to very large reductions in forested area, and much higher overall costs for mitigation, compared to meeting the same targets while putting a price on all carbon emissions. [21.5.3] Similarly, substantial regional variation in the availability of technologies exists, but the differences in how these are represented regionally is largely unexplored. A process (shared socioeconomic pathways, SSP's) has been initiated to identify shared assumptions and global scenarios for use in both mitigation and adaptation research. But although progress has been made, the vast majority of the impacts, adaptation, and vulnerability literature since AR4 continues to be based on the SRES.

Bulk transport of products, whether by air, sea or over land, is now highly likely to be a non-trivial contributor to emissions of greenhouse gases and aerosols. [21.4.1] Furthermore, the relocation of manufacturing has transferred net emissions via international trade from developed to developing countries and most developed countries have increased their consumption-based emissions faster than their domestic (territorial) emissions.

Contested definitions and alternative approaches to describing vulnerability to climate change pose problems of interpretating vulnerability indicators. [21.5.1] There are numerous studies that use ndicators to define aspects of vulnerability, quantifying these across regonal units (e.g. by country or municipality), often weighting and merging them into vulnerability indices and presenting them regionally as maps. However, methods of constructing indices are subjective, often lack transparency and can be difficult to interpret. Moreover, indices commonly combine indicators reflecting current conditions (e.g. of socio-economic capacity) with other indicators describing projected changes (e.g. of future climate or population), and have failed to reflect the dynamic nature of the various variables used as indicators.

The variability of vulnerability across regions, and across subpopulations within regions preclude general statements about the factors that control that variability, and how they might evolve in the future. [21.5.1] Trade and financial flows influence both vulnerability and adaptive capacity, and also the regionalization of emissions. At the same time, international and cross-regional financial instruments are being used to attempt to build adaptive capacity as well as mitigation capacity. Human migration in reaction to climate-driven phenomena, or extreme weather events, is usually within nations, but under some circumstances, can extend across nations. The migration of ecosystems in response to changes in climate emphasizes the need for cross-regional cooperation of conservation and resource management institutions.

21.1. Introduction

The framing of this chapter places the discussion of both global and regional issues in a decision-making context. This context identifies different scales of decisions that are made (e.g. global, international, regional, national) and the different economic or impact sectors that are often the objects of decision-making (e.g. agriculture, water resources, energy).

Within this framing, the chapter then provides three levels of synthesis. First is an evaluation of the state of knowledge of changes in the physical climate system, and the degree of confidence that we have in understanding those changes on a regional basis that is relevant to decision-making. The second is a discussion of the regional context of the sectoral discussions in Part A of Working Group II. The third is to discuss the regional variation revealed in subsequent chapters of Part B. In so doing, the goal is to examine how each regional chapter addresses decision-making issues in similar or different ways, and whether there is commonality of experience among regions that could be useful for decision-making.

Having analyzed similarities and differences among IPCC regions, the chapter then discusses trans-regional and cross-regional issues that affect both human systems (e.g. trade and financial flows) and natural systems (e.g. ecosystem migration). Finally, the chapter evaluates methodologies for assessing regional vulnerabilities and adaptations, impact analyses, and the development and application of scenarios of the future. These evaluations provide guidance for understanding how such methods might ultimately be improved, so that the confidence in research about possible future conditions and consequences might ultimately improve.

21.2. Defining Regional Context

The climate system may be global in extent, but its manifestations – through atmospheric processes, ocean circulation, bioclimatic zones, daily weather and longer-term climate trends – are assuredly regional or local in their occurrence, character and implications. Explicit recognition of geographical diversity is therefore an imperative for any scientific assessment of anthropogenic climate change. Moreover, the decisions that are or could be taken on the basis of climate change science play out on a range of scales, and the relevance and limitations of information on both biophysical impacts and social vulnerability differ strongly from global- to local-scale, and from one region to another. The following sections emphasize some of the crucial regional issues to be pursued in Part B of this report.

21.2.1 Decision-Making Context

This is the first full IPCC assessment to devote a single part of a report to regional aspects of climate change that cut across topics in all three IPCC Working Groups. Hence, this part of the report attempts to address many of the regional dimensions of the climate change issue that are regarded as relevant to decision making. Naturally, a lot of emphasis is placed on informing national and international climate change policy making, but the demand for information to support practical decision-making has assumed an increasingly sub-national focus. However, while expeditious use of case studies can provide useful illustrations of local-scale phenomena, geographical comprehensiveness is necessarily ruled out in this assessment. Instead, responsibility for compiling and disseminating local information rests with regional and national experts, while this report seeks to highlight robust examples of these, wherever possible.

A good understanding of the decision-making context is essential to define the type of information on climate change related risks required from physical climate science and impacts, adaptation and vulnerability assessments (e.g. IPCC, 2012a). While the importance of considering the decision-making context is a general issue for all impacts, adaptation and vulnerability assessments (cf. the chapters in Part A), it is especially important in the context of regional and sub-regional issues. Many studies are still driven by global data and assessment methods, whereas there is considerable variation in regional, national and local decision-making contexts, as well as across different groups of stakeholders and sectors. There is a growing body of scientific information on how to provide the most relevant climate risk information to suit specific decision-making processes (e.g., Willows and Connell, 2003; ADB, 2005; Kandlikar *et al.*, 2011 decision-making).

Table 21-1 illustrates the range of actors involved in decision-making to be informed by climate information at different scales in different sectors, ranging from international policy makers and agencies, to national and local government departments, to civil society organizations and the private sector at all levels, all the way to communities and individual households. The implications of climate change touch on almost all sectors of society, so the figure illustrates how policy makers face a dual challenge in achieving policy integration – vertically, through multiple levels of governance, and horizontally, across different sectors (Table 21-1). Many of the barriers to effective climate response are to be found in these two dimensions. For instance, in the vertical dimension, while a growing number of European countries have developed national adaptation strategies in recent years, the implementation of adaptation measures at a local level has lagged behind, because responsibility and resources for adaptation at the local level have yet to be properly assigned (Biesbroek *et al.*, 2010). In contrast, horizontal integration (policy coherence – Mickwitz *et al.*, 2009) often flies in the face of conventional practice, with sectoral policies that are designed to advance social or economic goals (e.g. development of an improved road network) frequently at odds with goals set in other sectors (e.g. environmental targets to limit greenhouse gas emissions or to reduce infrastructural exposure to flood risk). Finally, implicit in the framing of Table 21-1, is the temporal dimension of decision, manifested through their scheduling, cost and ultimate effectiveness. Though this dimension is not shown in Table 21-1, it is a crucial element to consider in interpreting both the types of response options facing decision-makers (for example, contrasting a one-off, long-term major infrastructural investment against multiple, incremental and flexible short-term measures) as well as the information used to inform those decisions.

[INSERT TABLE 21-1 HERE
Table 21-1: Dimensions of the institutions and actors involved in climate change decision-making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decison-making domains are illustrative. Modified and extended from Mickwitz (2009).]

Many climate change risk assessments have traditionally been undertaken either in the context of international climate policy-making (especially the United National Framework Convention on Climate Change – UNFCCC), or by (or for) national governments. In those cases, climate risk information commonly assumes a central role in the decision-making, for instance to inform mitigation policy, or for plans or projects designed specifically to adapt to a changing climate. More recently, increasing attention has been paid to more sector- or project-specific risk assessments, intended to guide planning and practice by a range of actors. In those contexts, climate may often be considered as only one contributor among a much wider set of considerations for a particular decision. In such cases, there is uncertainty about not only the future climate, but also many other aspects of the system at risk. Moreover, while analysts will seek the best available climate risk information to inform the relative costs and benefits of the options available to manage that risk, they will also need to consider the various constraints to action faced by the actors involved.

Some decision-making contexts, such as the design of large infrastructure projects, may require rigorous quantitative information to feed formal evaluations, often including cost-benefit analysis (e.g. PriceWaterHouseCoopers 2010), for more examples see also chapter 17). Others, especially at local level, such as decision-making in traditional communities, are often made more intuitively, with a much greater role for a wide range of social and cultural aspects, and may benefit much more from experience-based approaches, participatory risk assessments, or story-telling to evaluate future implications of possible decisions (e.g. Van Aalst *et al.,* 2008, World Bank, 2010). Multi-criteria analysis, scenario planning, and flexible decision paths offer options for taking action when faced with large uncertainties or incomplete information, and can help bridge adaptation strategies across scales (in particular between the national and local level).In most cases, an understanding of the context in which the risk plays out, and the alternative options that may be considered to manage it, are not an afterthought, but a defining feature of an appropriate climate risk analysis, which requires a much closer interplay between decision-makers and providers of climate risk information than often occurs in practice (e.g., Cardona *et al.,* 2012; Hellmuth *et al.,* 2010; Mendler de Suarez *et al.,* 2012).

These different decision-making contexts also determine the types of information required, including the climate variables of interest and the geographic and time scales on which they need to be provided. Many climate change impact assessments have traditionally focused on changes over longer time horizons (often out to 2100, though recently studies have begun to concentrate more on mid-century or earlier). In contrast, most decisions taken today have a planning horizon ranging from a few months to about two decades (e.g Wilby et al., 2009). For many such shorter-term decisions, recent climate variability and observed trends are commonly regarded as sufficient to inform adaptation (e.g. Hallegatte, 2009). However, in so doing, there is often scope to make better use of observed climatological information as well as seasonal and maybe also decadal climate forecasts (e.g. Wang *et al*., 2009; Ziervogel *et al*., 2010; Mehta *et al*., 2011; Kirtman *et al*., in prep., HLT, 2011). For longer-term decisions, such as decisions with irreversible long-term implications and investments with a long investment horizon and substantial vulnerability to changing climate conditions, longer-term climate risk information is needed (e.g. Reeder and Ranger, 2010). However, while that longer-term information is often used simply to plan for a best-guess scenario to optimize for most likely conditions, there is increasing attention for informing concerns about maladaptation (Barnett and O'Neill, 2010) and sequencing of potential adaptation options in a wider range of possible outcomes, requiring a stronger focus on ranges of possible outcomes and guidance on managing uncertainties, especially at regional, national and sub-national levels (Hall *et al*., 2012; Gersonius *et al*., 2013).

Section 21.3 summarises different approaches to impacts, vulnerability and adaptation assessment that have been applied at different scales in studies assessed in this volume, paying special attention to information contained in the regional chapters.

21.2.2. Defining Regions

As the preceding discussion implies, the most effective treatment of regional aspects of the observed and projected physical climate, its impacts and response options may frequently be at odds with the scales at which decisions actually need to be made. Earlier attempts by IPCC author teams to reconcile this mismatch are described below.

There has been an evolution in the treatment of regional aspects of climate change in IPCC reports (Table 21-2) from a patchwork of case examples in the First Assessment Report (FAR) and its supplements, through to attempts at a more systematic coverage of regional issues following a request from governments, beginning with the Special Report on the Regional Impacts of Climate Change in 1998. That report distilled information from the Second Assessment Report (SAR) for ten continental scale regions, and the subsequent Third (TAR) and Fourth (AR4) assessments each contained comparable chapters on impacts, adaptation and vulnerability in the Working Group (WG) II volumes. WG I and III reports have also addressed regional issues in various chapters, using different methods of mapping, statistical aggregation and spatial averaging to provide regional information.

[INSERT TABLE 21-2 HERE
Table 21-2: Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SR). Major assessments are subdivided by the three Working Group reports, each described by generic titles.]

Part B of this WG II Fifth Assessment (AR5) is the first to address regional issues treated in all three WGs. It comprises chapters on eight regions plus open oceans. These are depicted in Figure 21-1.

[INSERT FIGURE 21-1 HERE
Figure 21-1: Map showing regions described in chapters 22-30 of Part B (colours) with numbered [26] open polygons defining sub-regions over land used to summarise projected changes in climate in this chapter Note that regional specifications are approximate, as aspects of some regions or territories are treated in more than one chapter. Supplementary material contains more details of chapter assignment (Table S21-1) as well as co-ordinates of the polygons (Table S21-2).]

Some of the main topics demanding a regional treatment are:

- *Climate*, typically represented by sub-continental regions, a scale at which trends in observations tend to be fairly robust, and at which signal:noise ratios for projections from global models may also offer some confidence. While maps are widely used to represent climatic patterns, regional aggregation of this (typically gridded) information is still required to summarise the processes and trends they depict. Examples, including information on climate extremes, are presented elsewhere in this chapter, with systematic coverage of all regions provided in supplementary material. Excerpts from maps produced for an atlas of global and regional climate projections accompanying the WG I report (Collins *et al.*, in prep.) can also be found in several regional chapters of this volume. In Figure 21-1, the sub-continental regions used for summarising climate information are overlaid on a map of the nine regions treated in Part B.
- *Other aspects of the climate system*, such as the cryosphere, oceans, sea level, and atmospheric composition, especially given the importance of regional changes, for example, in sea ice cover for navigation, in land movements and local ocean currents that may counter or reinforce global sea level rise, or in air pollution that can be a major regional driver of atmospheric radiative forcing as well as having a confounding effect (often localised) on plant and human health.
- *Climate change impacts* on natural resource sectors, such as agriculture, forestry, ecosystems, water resources and fisheries, which often require a classification of regional types to distinguish contrasting environmental conditions, and the livelihoods and human interventions that accompany them. Here, it is common to classify regions according to biogeographical characteristics (e.g. biomes, climatic zones, physiographic features like mountains, river basins or deltas, or combinations of these).
- *Adaptive capacity*, which is a measure of society's ability to adjust to the potential impacts of climate change, sometimes characterised in relation to social vulnerability (Füssel, 2010),, and typically represented through the use of socio-economic indicators. The regional dimensions of adaptive capacity are often displayed as maps contrasting statistical data collected, modelled or aggregated at the scale of a given administrative unit (national maps with municipal comparisons – O'Brien *et al.*, 2006; e.g., global maps showing national comparisons – Füssel, 2010´).
- *Emissions* of greenhouse gases and aerosols and their cycling through the Earth system have a crucial regional expression that requires combining socio-economic data on human activities responsible for anthropogenic emissions with biogeochemical monitoring of material and gas fluxes worldwide. Since these activities are known to be responsible for anthropogenic climate change, and given that national and international policies are being designed to modify human activities, the regional units of most relevance for governments are those that provide comparison between political and economic regional groupings worldwide.
- *Global scenarios* of the major socio-economic, technological and land use drivers that affect anthropogenic emissions as well as influencing societal vulnerability to the impacts of climate change, rely heavily on integrated assessment models (IAMs) of the global energy–environment–socioeconomic system. Quantitative scenarios derived from such models need to be aggregated into regional units of relevance to stakeholders wishing to interpret and apply such scenarios. SRES was the most comprehensive scenario development exercise conducted to date to serve the climate change community, though the scenarios themselves are provided in common only for four world regions. New scenarios are under development by the global research community, and these are being designed to have more regional detail than SRES (Moss *et al.*, 2010 – see Box 21-1).
- Finally, *human responses to climate change through mitigation and adaptation* demand both global and regional approaches, as emphasised in the Articles of the UNFCCC and manifest in international financing to support climate policy (not only through UNFCCC-related financial mechanisms, but also via bilateral development agencies and multilateral development banks). However, governments require access to

> useable knowledge that can be applied at national and local scales. That is a regional challenge beyond the scope of an IPCC report alone, but for which these assessments should provide the appropriate context.

These give a flavour of the different approaches that are commonly employed in specifying regional units of analysis. Detailed examples of these will be referred to throughout this chapter and the regional chapters that follow. Some of the more important international political groupings of countries and territories are described and catalogued in supplementary material.

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Box 21-1. A New Framework of Global Scenarios for Regional Assessment

The major socio-economic driving factors of future emissions and their effects on the global climate system were characterized in the TAR and AR4 using scenarios derived from the IPCC Special Report on Emissions Scenarios (SRES – IPCC, 2000). Scenarios were developed in a linear process, whereby socio-economic scenarios were constructed to represent key drivers of emissions, model estimates of emissions were converted to atmospheric concentrations of greenhouse gases and aerosols that in turn were used as input to climate models for simulating the climate response to the forcings. Finally, IAV assessments were conducted using combinations of the socio-economic, atmospheric composition, climate and related projections such as land cover and sea level, downscaled to the region of interest. More recently a new approach to developing climate and socio-economic scenarios has been adopted in which atmospheric concentrations were developed first (Representative Concentration Pathways or RCPs – Moss et al., 2010), thereby allowing climate modeling work to proceed much earlier in the process. Different possible Shared Socio-economic Pathways (SSPs) were to be determined later, recognizing that more than one socio-economic pathway can lead to the same concentrations of greenhouse gases and aerosols.

Four different RCPs were developed, corresponding to four different levels of radiative forcing of the atmosphere by 2100 relative to pre-industrial levels, expressed in units of Wm^{-2}: RCP 8.5, 6.0, 4.5, and 2.6 (van Vuuren et al., 2012). These embrace the range of scenarios found in the literature, and all except RCP 8.5 also include explicit stabilization strategies, which were missing from the SRES set.

In addition, five SSPs have been proposed, representing a wide range of possible development pathways (van Vuuren et al., submitted). An inverse approach is applied, whereby the SSPs are constructed in terms of outcomes most relevant to IAV and mitigation analysis, depicted as challenges to mitigation and adaptation (Chapter 19, Figure 19-x). Narrative storylines for the SSPs have been outlined (O'Neill et al., submitted) and preliminary quantifications of the socio-economic variables are underway (O'Neill et al., 2012). Priority has been given to a set of *basic* SSPs with the minimum detail and comprehensiveness needed to provide inputs to IAV and integrated assessment models, primarily at global or large regional scales. Building on the basic SSPs, a second stage will construct *extended* SSPs, designed for finer-scale regional and sectoral applications (O'Neill et al., submitted).

An overall scenario architecture has been designed for integrating RCPs and SSPs (Kriegler et al., 2012; van Vuuren et al., submitted; van Vuuren et al., 2012), for considering mitigation and adaptation policies using Shared Policy Assumptions (SPAs – Kriegler et al., submitted) and for providing relevant socio-economic information at the scales required for IAV analysis (van Ruijven et al., submitted). Additional information on these scenarios can be found in other chapters of this report (Chapter 1, Section 1.1.3, Chapter 19, Box 19-3) and elsewhere in the assessment (Blanco et al., in prep.; Collins et al., in prep.; Kunreuther et al., in prep.). However, due to the time lags that still exist between the generation of RCP-based climate change scenarios, and the development of SSPs, few of the IAV studies assessed in WG II actively use these scenarios. Instead, most of the scenario-related studies in the assessed literature still rely on the SRES. As such, for purposes of comparison it can be instructive to attempt an approximate mapping of the SRES scenarios onto the new scenario framework (see Figure 1 – Carter et al., submitted). On the horizontal axis, SRES socio-economic characteristics are matched to those of SSPs grouped according to low, medium or high challenges for adaptation (O'Neill et al., submitted; van Vuuren et al., 2012). On the vertical axis, mapping of SRES onto the RCPs is based on radiative forcing by 2100 (chapter 1, this volume). Cells in the matrix indicate SRES mappings that coincide on both axes. Note that no SRES scenarios result in forcing as low as RCP

2.6, though SRES mitigation scenarios have been applied in a few climate model experiments (e.g. the E1 scenario – Johns et al., 2011).

[INSERT BOX 21-1 FIGURE HERE
Box 21-1 Figure Caption: Approximate mappings of the SRES scenarios onto the new SSP/RCP framework (for details, see text). After Carter et al. (submitted).]

_____ END BOX 21-1 HERE _____

21.2.3. Introduction to Methods and Information

There has been significant debate about the definitions of key terms (Janssen and Ostrom, 2006), such as vulnerability (Adger, 2006), adaptation (Stafford Smith et al,. 2011), adaptive capacity (Smit and Wandel, 2006) and resilience (Klein et al., 2003). One explanation is that the terms are not independent concepts, but defined by each other, thus making it impossible to remove the confusion around the definitions (Hinkel 2011). The differences in the definitions is based on the different entry points for looking at climate change risk (IPCC, 2012). Figure 21-2 shows four possible entry points to adaptation science, policy and practice (based on Hinkel et al, submitted). Each of these attracts a separate set of actors and researchers and relies on different sets of methods and tools.

[INSERT FIGURE 21-2 HERE
Figure 21-2: Entry points for adaptation science, policy, and practice (based on Hinkel et al, submitted).]

Table 21-3 shows two ways to think about vulnerability, demonstrating that different objectives (e.g., improving well being and livelihoods or reducing climate change impacts) lead to different sets of questions being asked. This results in the selection of different methods to arrive at the answers. The two approaches portrayed in the middle and right hand columns of Table 21-3 have also been characterised in terms of top-down (middle column) and bottom-up (right column) perspectives, with the former identifying physical vulnerability and the latter social vulnerability (Dessai and Hulme 2004). In the middle column, the development context is the starting point (i.e., social vulnerability), on top of which climate change occurs. The task is then to identify what changes are needed in the development pathways in order to reduce vulnerability to climate change. On the right, the climate change impacts are the starting point for the analysis, revealing that people and/or ecosystems are vulnerable to climate change. One of the differences is a difference in time-frames, where a climate change focussed approach tends to look to the future to see how to adjust to expected changes, whereas a vulnerability focussed approach is centred on addressing the drivers of current vulnerability. A similar approach is described by McGray et al (2009).

[INSERT TABLE 21-3 HERE
Table 21-3: Two possible entry points for thinking about vulnerability to climate change (adapted from Füssel 2007).]

The information assessed in this chapter stems from different entry points, framings and conceptual frameworks for thinking about risk. They merge social and natural science perspectives with transdisciplinary ones. There is no single ‘best’ conceptual model: the approaches change as scientific thinking evolves. The IPCC itself is an example of this: IPCC SREX presented an approach that has been adjusted and adapted in Chapter 19 of this volume. Chapter 2 describes other conceptual models for decision making in the context of risk. While this diversity in approaches enriches our understanding of climate change, it can also create difficulties in comparisons. For instance, findings that are described as vulnerabilities in some studies may be classified as impacts in others; lack of adaptive capacity in one setting might be described as social vulnerability in another.

21.3. Synthesis of Key Regional Issues

This section highlights regional distributions of key issues and briefly considers related methodological issues. It focuses on material contained in the regional chapters of this volume, and considers the advantages or disadvantages of analysing information about vulnerability, impacts and adaptation at a global or large-region scale. The value of taking a regional and global approach to vulnerability, impacts and adaptation is the ability to compare and contrast sub-regions. For example, regionally distributed impacts information can be assessed in conjunction with examinations of regional political economies to provide a context for understanding implications of impacts. Underpinning such analyses is an appreciation of ongoing and projected regional changes in the physical climate system.

Determining what belongs to a region or sub-region is addressed in 21.2, but deserves mention in the context of how to represent causal links of a geographical nature across regions and within them. Although climate change will affect different places in different ways, there will be spillover effects from one location to the next (Government Office for Science, 2011). For instance, a spillover effect occurs when there is a significant drought in a food-exporting country leading to food scarcity or insecurity in other countries (Sasson, 2012).

An examination of the nine regional chapters included in this volume of AR5 indicates that there is diversity in knowledge about climate change and its vulnerabilities, impacts and adaptation responses among and within different regions of the world. Research findings available for different global regions vary in terms of robustness, quantity, scope, and regional representativeness. With a substantial component of climate research devoted to global modelling, large scale aspects of regional climate are gradually becoming better understood over time. However, advances in knowledge about the finer details of regional climate change and its manifestations, have been more uneven, due in part to regional differences in data availability, resources and capacity.

Most regions have been conducting impacts studies for longer than they have been concerned with adaptation, so there is more region-specific information available on impacts. Some of the general issues that can be identified include the generality of much adaptation knowledge, and the limited amount of region-generated knowledge; differences in knowledge about social versus ecological vulnerability and impacts; and the difficulty of making general statements about regions that have high variability in terms of national poverty levels and adaptive capacity, such as Asia. The review below is limited to the literature that has been assessed by the regional chapters, and aims to highlight key issues to demonstrate either similarities or differences among regions. When regional chapters have omitted to describe these issues in their chapters, the assumption is that insufficient literature exists to provide evidence for any statement, but the information could also have been omitted for lack of space or because other issues are more relevant.

Aside from analyses that are conducted purely out of academic interest, most of the IAV studies assessed in this volume have been undertaken to serve a specific target audience. Thus, they can be regarded as providing information that might potentially be useful for decision-makers operating across a variety of sectors and levels of organisation (cf. Table 21-1). Here, an attempt is made to organise this information according to the broad research approach applied, distinguishing impacts and vulnerability approaches from adaptation approaches. Studies are then categorised according to scales of application ranging from global to local, which in turn helps to define the types of target audience intended. Table 21-4 has been constructed using these criteria, and is populated with examples of IAV studies drawn from other chapters in the volume as well as from a broader literature. This configuration then allows for an approximate matching of items in this Table with some of the dimensions of decision-making depicted in Table 21-1.

[INSERT TABLE 21-4 HERE
Table 21-4: Dimensions of assessments of impacts and vulnerability and of adaptation drawn upon to serve different target audiences (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to the original studies and to the chapters in which they are cited. Aspects of some of the studies in this table are also alluded to in section 21.5.]

The following sub-sections offer a brief synopsis of the approaches being reported in the different regional chapters, starting with impacts and vulnerability studies and then moving to adaptation studies. Table 21-4 serves as a rough template for organsing this discussion. Section 21-3-3 then provides an analysis of advances in understanding of the physical climate system for the different regions covered in chapters 22-30, introducing new regional information to complement the large-scale and process-oriented findings presented by Working Group I.

21.3.1. Vulnerabilities and Impacts

21.3.1.1. Observed Impacts

The first step taken by many researchers undertaking climate change impact assessments, before attempting to estimate future impacts, is to investigate how past and ongoing variations in climate may have affected a given exposure unit. This is also the approach adopted in many of the regional chapters in this volume, and there is also a separate chapter in Part A of the volume (chapter 18) dedicated to this topic

The evidence linking observed impacts on biological, physical and (increasingly) human systems to recent and ongoing regional climate changes has become more compelling since the AR4 (see chapter 18). One reason for this is the improved reporting of published studies from hitherto under-represented regions of the world, especially in the tropics (Rosenzweig and Neofotis, 2013). That said, the disparity is still large between the copious evidence being presented from Europe and North America, as well as good quality data emerging from Australasia, polar regions, many ocean areas and some parts of Asia and South America, compared to the much sparser coverage of studies from Africa, large parts of Asia, central and South America and many small islands. On the other hand, as the time series of well-calibrated satellite observations become longer in duration, and hence statistically more robust, these are increasingly providing a near global coverage of changes in surface characteristics such as vegetation, hydrology, and snow and ice conditions that can usefully complement or substitute for surface observations (see Table 21-2 and chapter 18 for examples). Changes in climate variables other than temperature, such as precipitation. evapotranspiration and CO_2 concentration, are also being related to observed impacts in a growing number of studies (Rosenzweig and Neofotis, 2013). For example, ecosystem responses would be expected to follow closely any long-term trends in precipitation and water availability in some tropical and sub-tropical regions, and although trends are often confounded by modes of climatic variability such as ENSO, some evidence for precipitation-related impacts is reported from Australia (in chapter 26) and southern South America [chapter 27).

Other regional differences in observed changes worth pointing out include trends in relative sea level, which is rising on average globally (Church *et al*., in prep.), but displays large regional variations in magnitude, or even sign, due to a combination of influences ranging from El Niño/La Nina cycles to local tectonic activity, making general conclusions about ongoing and future risks of sea level change very difficult to draw across diverse regional groupings such as small islands (see chapter 29). There are also regional variations in another ongoing effect of rising CO_2 concentration – ocean acidification, due to temperature dependence of the carbon flux to the ocean, with cooler, high latitude oceans experiencing the most rapid fluxes (chapter 30). Calcifying organisms are expected to show responses to these trends in future, though few recent trends are apparent that can be attributed to acidification effects alone. Finally, although problematic to disentangle from other potential explanatory factors, there is also mounting evidence that human adaptation is occurring as an autonomous response to ongoing climate change in some regions (e.g. draining glacial lakes to ameliorate the risk of flash flooding triggered by accelerated melting, sowing crops earlier in the spring to exploit warmer conditions, or changing reservoir operations to mitigate floods). These issues are touched on in chapters 18, 23, 25.

21.3.1.2. Future Impacts and Vulnerability

21.3.1.2.1. Impact models

The long-term monitoring of environmental variables, as well as serving a critical role in the detection and attribution of observed impacts, also provides basic calibration material used for the development and testing of impact models. These include process-based or statistical models used to simulate the biophysical impacts of climate on outcomes such as crop yield, forest productivity, river runoff, coastal inundation or human mortality and morbidity (see chapters 2-7; 11). They also encompass various types of economic models that can be applied to evaluate the costs incurred by biophysical impacts (see, for example, chapters 10 and 17). There are also integrated assessment models (IAMs), Earth System Models, and other more loosely linked integrated model frameworks that might incorporate several different biophysical impacts as well as economic and perhaps other processes (e.g. climate, land use change, global trade) and the various interactions and feedbacks between them. For descriptions of these, see chapter 17 and (Flato *et al.*, in prep.).

21.3.1.2.2. Vulnerability mapping

A second approach to projecting potential future impacts, is to construct vulnerability maps. These usually combine information on three components: exposure to a hazard – commonly defined by the magnitude of climate change, sensitivity to that hazard -- the magnitude of response for a given level of climate change, and adaptive capacity – describing the social and economic means to withstand the impacts of climate change (IPCC, 2001). Key indicators are selected to represent each of the three components, which are typically combined into a single index of vulnerability. Indicators are usually measured quantities taken from statistical sources (e.g. income, population), or have been modelled separately (e.g. key climate variables). Vulnerability indices have received close scrutiny in several recent reviews (Füssel, 2010; Hinkel, 2011; Malone and Engle, 2011; Preston *et al.*, 2011), and a number of global studies have been critiqued by Füssel (2010).

A variant of vulnerability mapping is risk mapping. This commonly identifies a single indicator of hazard (e.g. a level of flood expected with a given return period), which can be mapped accurately to define those regions at risk from such an event (e.g. in a flood plain). Combined with information on changing return periods of such events under a changing climate would enable some estimate of altered risk to be determined.

21.3.1.2.3. Experiments

A final approach for gaining insights on potential future impacts, concerns physical experiments designed to simulate future altered environments of climate (e.g. temperature, humidity and moisture), and atmospheric composition (e.g. CO_2, surface ozone and sulphur dioxide concentrations). These are typically conducted to study responses of crop plants, trees and natural vegetation,. using open top chambers, greenhouses or free air gas release systems (Craufurd *et al.*, 2013).

21.3.1.2.4. Scale issues

Impact models operate at a range of spatial and temporal resolutions, and while their outputs are sometimes presented as fine resolution maps, key model findings are rarely produced at the finest resolution of the simulations (i.e. they are commonly aggregated to political or topographic units of interest to the target audience, e.g. watershed, municipality, national or even global). Aggregation of data to coarse-scale units is also essential for allowing comparison of outputs from models operating at different resolutions, but it also means that sometimes quite useful detail may be overlooked when model outputs are presented at the scale of the coarsest common denominator. Conversely, if outputs from impact models are required as inputs to other models, the outputs may need to be harmonized to a finer grid than the original data. In such cases, downscaling methods are commonly applied. This was the case, for example, when providing spatially explicit projections of future land use from different IAMs for climate modellers to apply in the CMIP-5 process (see Box 21-1 – Hurtt *et al.*, 2011). It is also a common procedure used in matching climate model outputs to impact models designed to be applied locally (e.g. over a river basin or an urban area).

Even if the same metrics are being used to compare aggregate model results (e.g. developed versus developing country income under a given future scenario) estimates may have been obtained using completely different types of models operating at different resolutions. Moreover, many models that have a large-scale coverage (e.g. continental or global) may nonetheless simulate processes at a relatively fine spatial resolution, offering a potentially useful source of spatially explicit information that is unfamiliar to analysts working in specific regions, who may defer to models more commonly applied at the regional scale. Examples include comparison of hydrological models with a global and regional scope (Todd *et al*., 2011) and bioclimatic models of vascular plant distributions with a European and local scope (Trivedi *et al*., 2008). Vulnerability mapping exercises can also be undermined by the inappropriate merging of indicator datasets that resolve information to a different level of precision (e.g. Tzanopoulos *et al*., 2013). There is scope for considerably enhanced cross-scale model intercomparison work in the future, and projects such as AgMIP (Rosenzweig *et al*., 2013) and ISI-MIP (Schiermeier, 2012, – see section 21.5) have provision for just such exercises.

21.3.2. Adaptation

Although a large portion of adaptation knowledge, for instance, is based on conclusions from case studies in specific locations, the conceptual findings are typically applied globally. Much of this theory on adaptation guides understandings in the different regions. This is especially the case for developing regions. Thus, regional approaches to adaptation vary in their degree of generality. One of the most striking differences between regions in terms of adaptation is the extent to which it has been studied and implemented. Australia and Europe have invested heavily in research on adaptation, and the result is a rich body of literature published by local scientists. The ability to advance in adaptation knowledge may be related to the amount and quality of reliable climate information, the lack of which has been identified as a constraint to developing adaptation measures in Africa. Many case studies, especially of community-based adaptation, stem from Asia and Africa, but the majority of this work has been undertaken and authored by international non-governmental organisations, frequently featuring their own project work, as well as by non-local researchers. In Africa, most adaptation work is considered to be pilot, and seen as part of learning about adaptation, although there has been significant progress since the AR4.

Most regional chapters report lags in policy work on adaptation. While most European countries have adaptation strategies, few have been implemented. Lack of implementation of plans is also the case for Africa. In North, Central and South America, adaptation plans are in place for some cities. In Australasia, there are few adaptation plans. At the same time, civil society and local communities have the opportunity to play a role in decision making about adaptation in Europe and Asia. In Africa, social learning and collective action are used to promote adaptation. Adaptation is observed as mostly autonomous (spontaneous) in Africa, although socio-ecological changes are creating constraints for autonomous adaptation. There is a disconnect in most parts of Africa between policy and planning levels. In the case of UNFCCC-supported activities, such as National Adaptation Programmes of Action, few projects from the African and Asian least developed countries have been funded, thus limiting the effectiveness of these investments. Several chapters (Africa, Europe, North America, Central and South America and Small Islands) explicitly point out that climate change is only one of multiple factors that affect societies and ecosystems and drives vulnerability or challenges adaptation.

Some chapters (Polar Regions, North America, Australasia) emphasise the challenges faced by indigenous peoples and communities in dealing with climate change. Although they are described as having some degree of adaptive capacity to deal with climate variability, shifts in lifestyles combined with a loss of traditional knowledge leave many groups more vulnerable to climate change. Also, traditional responses have been found to be maladaptive because they are unable to adjust to the rate of change, or the broader context in which the change is taking place, as seen in the Arctic. In response to changing environmental conditions, people are taking on maladaptive behaviour – for instance, by going further to hunt because of changed fish-stocks and thus exposing themselves to greater risk, or changing to different species and depleting stocks. The limits to traditional approaches for responding to changing conditions has also been observed in several Small Island States.

Most populated regions have experience with adaptation strategies in agriculture, where exposure to the impacts of climate variability over centuries provides a starting point for making adjustments to new changes in climate. Water and land use management strategies stand out in the literature in common across all of the main continental regions.

The link between adaptation and development is explicit in Africa, where livelihood diversification has been key to reducing vulnerability. At the same time, there is evidence that many short-term development initiatives have been responsible for increasing vulnerability. Other chapters mention constraints or barriers to adaptation in their regions.

For example, the low priority accorded to adaptation in parts of Asia, compared to more pressing issues of employment and education, is attributed in part to a lack of awareness of the potential impacts of climate change and the need to adapt, a feature common to many regions. All developing regions cite insufficient financial resources for implementing adaptation as a significant limitation.

21.3.3. Regional Aspects of the Physical Climate System

This section is intended to provide a summary assessment of regional climate information, particularly regarding cross regional aspects and new emerging knowledge since the AR4, to place the regional chapters in a broader context. It is not intended to provide a detailed region-by-region assessment of information, which can be found in the WGI Chapter 14, the WGI Atlas and the WGII regional chapters. Also, as noted in 21.2.2 there are many different ways in which regions can be defined. However, many of these regional definitions are relevant to decision making and so generating climate change information for such regions is relevant to climate policy. This issue is explored using the example of African economic regions in Box 21-2. Similarly some emphasis is also given to material deriving from dynamical and statistical downscaling work which is often of greater direct relevance for IAV applications than coarser resolution global climate model data.

_____ START BOX 21-2 HERE _____

Box 21-2. Developing Regional Climate Information Relevant to Political and Economic Regions

In most world regions, countries form political and/or economic groupings and coordinate activities within these groups with stated aims such as furthering the interests of the constituent nations and their peoples. Such groupings provide a natural forum for coordinating action on transboundary issues within their region or responding to influences external to it. Climate is an important factor in the economies of many nations and the lives of their peoples and is well understood to have both transboundary dimensions and to involve remote influences. This has long been recognised, with national and regional weather-forecasting being highly dependent on globally coordinated activities, more recently with the advent of the WMO-sponsored Regional Climate Outlook Forums (Ogallo et al., 2010) and Global Framework for Climate Services (Hewitt et al., 2012). These links are also being made regionally. For example, the Intergovernmental Authority on Development (IGAD) of the countries of the Greater Horn of Africa (GHA) recognizes that the region is prone to extreme climate events such as droughts and floods which have severe negative impacts on key socio-economic sectors in all its countries. In response it has set up the IGAD Climate Prediction and Applications Centre (ICPAC) to provide and support application of early warning and related climate information for the management of climate-related risks (for more details see http://www.icpac.net/). As socio-economic factors are important contributors to both the vulnerability and adaptability of human and natural systems, it clearly makes sense to summarise and assess available climate and climate change information for these regions as it will be relevant to policy decisions taken within these groupings on their responses to climate change.

The accompanying figure presents summary climate change information for 5 political/economic regions covering much of Africa. These are the Common Market for Eastern and Southern Africa (COMESA6), the Economic Community of Central African States (ECCAS), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC) and the Arab Maghreb Union (UMA). Each graph shows observed7 and simulated variations in past and projected future annual average temperature and precipitation. Generally the observed regional temperature variations reflect global changes, with warming from 1901 to 1940, followed by a relatively stable period until 1970 and then steady warming thereafter. Consistent with simulations available for the AR4 (Christensen et al. 2007), the observed warming is contained within the envelope of the simulations of global climate models driven with observed changes in all known external drivers (pink band) in all five regions. The 1901-1940 warming in these simulations is partly distinguishable from what would have been expected if anthropogenic activities had not interfered with the climate, as estimated by simulations with observed changes in natural external drivers only (blue band). In all five regions there is a distinct difference by the beginning of the 21st century, which is projected to continue to widen if emissions broadly follow the RCP4.5 or RCP 8.5 emissions pathways (light blue and red bands). In contrast, precipitation has generally remained steady, relative to its year-to-year variability, without major changes driven by anthropogenic emissions in either the past or future as estimated from the climate model simulations. Exceptions are an observed drying over ECOWAS between the 1960s and 80s (Greene et al. 2009, Hoerling et al. 2006) and a simulated drying of about 15% over the 150-year period over UMA. It should also be noted that, unlike temperature, observed precipitation variability sometimes lies outside the envelope of the simulations from the models, which is consistent with the simulations representing precipitation effectively averaged over larger areas than is represented by the sparse station data underpinning the observed estimates.

[INSERT BOX 21-2 FIGURE HERE
Box 21-2 Figure Caption: Observed and simulated variations in past and projected future annual average precipitation and temperature over five African regions, Common Market for Eastern and Southern Africa (COMESA), the Economic Community of Central African States (ECCAS), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC) and the Arab Maghreb Union (UMA). Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations, taken from the CMIP5 archive (Taylor et al. 2012), driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30) and by two of the RCM emissions/ concentrations scenarios (van Vuuren et al., 2011), "RCP4.5" (68) and "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. The regions are described in Chapter 22 (section 22.1.2) but the COMESA region labelled here covers COMESA north and includes Rwanda, Uganda, and Kenya. Precipitation is included for land territories only, while temperature is included for both land and exclusive economic zone territories. The observational datasets used are GISTEMP (Hansen et al. 2010), HadCRUT3 (Brohan et al. 2006), and MLOST (Smith et al. 2008) for temperature, and CMAP (Xie and Arkin 1997), CRU TS 3.10 (Mitchell and Jones 2005), GPCP v2.2 (Adler et al. 2003), and PRECL (Chen et al. 2002) for precipitation. These suffer in some areas from sparse monitoring coverage.]

The information presented here is illustrative of an approach to presenting a simple summary of observed and projected or predicted climate changes for political/economic regions. The graphs convey important information on the ability of the models to reproduce the observed trends in temperature, that they simulate significantly lower temperatures without the anthropogenic forcings and how future temperatures under typical business as usual emissions paths will continue to rise. The main messages on precipitation are that for most regions the models project that future variations in the annual average will be similar to those simulated for the past and that the models may not capture all of the observed precipitation variability. Without further refinement, this information would suggest that future precipitation scenarios should be significantly informed by the past observed variability. However, at least two additional factors should be taken into account. The first is that these results do not convey information on trends or projected changes in precipitation on seasonal or shorter time-scales . Secondly, theoretical and model evidence indicates that it is not unreasonable to expect that in a warming climate many regions could experience changes in precipitation variability and extremes even with no changes in the average (Allen and Ingram, 2002).

_____ END BOX 21-2 HERE _____

Understanding the confidence that can be placed in climate information used in assessing climate vulnerability and impacts and decision making on adaptation is of crucial importance. This information is relevant and used over a very wide range of scales and it comes with a similarly wide range of confidence. Using a similar classification of spatial scales to that presented in Table 21-4, Table 21-5 provides a summary overview of the levels of confidence that are seen in two of the basic climate variables of relevance, surface temperature and precipitation. This information is drawn from the extensive assessment and supporting literature from the IPCC SREX report, the AR5 WG1 report and some discussion of relevant methodologies and related issues and results are also presented in section 21.5.

[INSERT TABLE 21-5 HERE
Table 21-5: Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to

Very Low (VL). Reliability of information on past climate depends on the availability and quality of observations and in general is higher for temperature as it is easier to observe and a temperature observation at a given location is more representative of temperatures in the surrounding areas than a precipitation observation. In the case of future climate change, which relies on using models of the climate system run into the future, reliability depends on the ability of these models to simulate well the processes that lead to these changes. Again, information on temperature is generally more reliable but this is due to there being more confidence in our ability to simulate the past changes in temperature and our understanding of the processes that cause these changes than is the case for precipitation.

There are significant variations in the reliability of past and future climate information at different temporal and spatial scales, in general at finer scales the information tends to be less reliable given the need for either a greater density observations or models maintaining accuracy at high resolutions. Also, there are significant geographical variations, again the root cause being different for information on past climate than on future climate change. For past climate observation availability and quality is again key and in many regions, especially for precipitation, there are issues with either or both. For future climate change, data availability is less of an issue with the advent of large ensembles of climate model projections but quality can be a significant problem in some regions where the models perform poorly and there is little confidence that the processes driving the projected changes are accurately captured. [Table is an incomplete placeholder pending more complete information from WG1 and other sources]]

In a regional context, the results developed by the AR5 WG1 Chapter 14, Regional Phenomena, are particularly relevant including their evaluation of confidence in models' ability to simulate temperature, precipitation and phenomena together with an assessed implication for the general level of confidence in projections for 2080-2099 of regional temperature and precipitation (Table 21-6).

[INSERT TABLE 21-6 HERE
Table 21-6: Placeholder for a table to be derived from the AR5 WG1 Ch14 table (still in development by WG1) evaluating confidence in GCM simulations and projections of temperature and precipitation and linked regional climate phenomena currently being finalised for the final draft of that chapter.]

21.3.3.1. Atmosphere and Land Surface

21.3.3.1.1. Observed changes and attribution of causes

New estimates of global surface air temperatures for the period of 1901-2010 give an estimated warming of about 0.8 C, and about 0.5 C for the period 1979-2010, when estimated by a linear trend, while the warming for the period 1986-2005 (reference period) compared to 1886-1905 is 0.66 +/- 0.06. Positive annual temperature trends are found over most land areas, particularly since 1979, except regions of central-northern Australia and central western South America (WGI Chapter 2). Relatively large trends have occurred over Europe, the Sahara and middle East, central and northern Asia.

Confidence in global precipitation estimates is low to medium due to incompleteness of data, however when all land areas are filled in using reconstruction methods, land precipitation shows little change since 1900, in contrast to the AR4 assessment of a small increasing trend. The NH mid to high latitudes show an increasing trend, although confidence is also low due to incompleteness of data. Observed precipitation trends show a high degree of spatial and temporal variability, with the occurrence of both positive and negative values (WGI Chapter 2).

Improved detection and attribution methods have shown that it is *extremely likely* that human activities have caused most of the global warming (more than 50%) since the 1950s and that this warming is not due to internal variability alone. The human influence on warming is *likely* over every inhabited continent (there are insufficient data to make an assessment over Antarctica). It is also *likely* that the human influence has altered sea level pressure patterns and related circulations. Attribution of changes in hydrological variables is less confident due to the lack of data though a human influence on zonal patterns of global and on high northern latitude precipitation changes has been detected (WGI Chapter 10).

21.3.3.1.2. Long-term projections

Analyses of the CMIP5 ensembles have shown that, in general, the mean temperature and precipitation change patterns are similar to those found for CMIP3, with a pattern correlation between CMIP5 and CMIP3 ensemble mean late 21st century change greater than 0.9 for temperature and greater than 0.8 for precipitation (WGI Chapter 12). This implies that the regional characteristics of change in the CMIP5 ensemble lead to conclusions generally consistent with those found in the AR4. Given the increased comprehensiveness and higher resolution of the CMIP5 models this adds an element of robustness to the projected changes.

Some of the main characteristics of the projected late 21st century temperature and precipitation changes derived from the CMIP5 ensemble can be broadly summarized as follows (from WGI Chapter 12 and the Atlas) with further details provided in Box 21-3 and accompanying supplementary material.

Temperature

Global-mean surface temperatures for 2081–2100 (relative to 1986–2005) will *likely* be (5–95% range of the CMIP5 models) : 0.2–1.8°C (RCP2.6), 1.0–2.6°C (RCP4.5), 1.3–3.2°C (RCP6.0), 2.6–4.8°C (RCP8.5).

Changes in global land surface air temperature exceed changes in global mean surface air temperature with continental interiors show the largest changes (Figure 21-3). Regions that exhibit relatively high temperature changes (often 50% or more larger than the global mean) are high latitude NH land areas and the Arctic (especially in DJF), Central North America, portions of the Amazon, Mediterranean, and Central Asia in JJA.

[INSERT FIGURE 21-3 HERE
Figure 21-3. CMIP5 ensemble median ratio of local:global average temperature change in the period 2070-2100 relative to 1961-90 under the RCP8.5 emissions/concentrations scenario. The values are displayed on a common 2.5°x3.75° grid onto which each models' data were regridded and they were calculated as follows: (i) for each model calculate the local change between 1961-90 and 2070-2100 at each grid cell and divide by the global average change over the same period; (ii) identify the median value across the ensemble at each grid cell.]

Precipitation

Changes in precipitation are regionally highly variable, with many areas projected to experience positive change and others exhibiting negative changes (Box21-3). The high latitudes will *very likely* experience greater amounts of precipitation, many mid-latitude arid and semi-arid regions will *likely* experience reduced precipitation, many moist mid-latitude regions will *likely* experience increased precipitation (AR5 WG1 Ch 12).

Basic information on observed historical changes and projected 21st century changes by the CMIP5 ensemble is presented in each of the following regional chapters, and Box 21-3 provides a description of this material.

_____ START BOX 21-3 HERE _____

Box 21-3. Summary Regional Climate Projection Information

To provide some context on observed and future climate changes relevant to the risks associated with climate change vulnerability and impacts and the decision-making on adaptations being planned and implemented in response to these risks summary figures on observed and projected changes in temperature and precipitation are presented in the following regional chapters. These figures show observed changes in annual average surface air temperature and precipitation over the inhabited continental regions for 1986-2005 compared to 1906-1925 and then projections of these annual average variables under two future emissions/concentrations scenarios (RCP 4.5 and 8.5) and two time periods (2046-2065 and 2081-2100, compared to 1986-2005). An example of one of these figures is given below for Africa (Figure 1). Observed changes are displayed when significant (see details in figure caption below)

[INSERT BOX 21-3 FIGURE 1 HERE
Box 21-3 Figure 1 Caption: Observed and projected changes in annual average temperature and precipitation over Africa. The observations are taken from the CRU TS 3.1 dataset (Harris et al., 2012) and the projections from the CMIP5 multi-model archive (Taylor et al. 2012). Projected changes are shown for the mid-21st century (2046-2065) and the late-21st century (2081-2100) from a baseline period of 1986-2005 under the RCP 4.5 and 8.5 emissions/ concentrations scenarios (van Vuuren et al., 2011). For the observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through to 1925. For the CMIP5 projections, four classes of results are displayed:

1) White indicates areas where for >66% of models the change in annual average precipitation is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986 through 2005. Thus in these regions more than 2/3 of models show no significant change (using this measure of significance) in annual average precipitation. However, note that this does not imply no significant change in precipitation averaged over seasonal or shorter time-scales such as months to days.
2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation but less than 2/3 agree on whether annual average precipitation will increase or decrease.
3) Colors with circles indicate the change in annual average precipitation averaged over all models in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation and more than 2/3 agree (but less than 90%) agree on whether annual average precipitation will increase or decrease.
4) Colors without circles indicate the change in annual average precipitation averaged over all models in areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether annual average precipitation will increase or decrease.

For models which have provided multiple realizations for the climate of the recent past and the future, results from each realisation are first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated.]

These figures provide a very broad overview of the projected regional climate changes but in dealing with only annual averages they are not able to convey any information about projected changes in seasonal or shorter timescales. In addition, they are derived solely from the CMIP5 GCMs and do not display any information from the CMIP3 database which is still very relevant to the IPCC WG2 as CMIP3 data are widely used in many of the studies assessed within the AR5 WG2 report. To provide extra context on projected future climate changes which deals with these issues two additional sets of example figures are presented here which display temperature and precipitation changes at the seasonal and daily timescale.

Projected seasonal changes are displayed as area averages over the regions defined in the IPCC SREX report, “Managing the risks of extreme events and disasters to advance climate change adaptation” (IPCC 2012), and compare these for the four RCP scenarios and three of the SRES scenarios (Figure 2). In this example provided for the SREX regions which lie in Central and South America (see Figure 21.1 for their geographical ranges), regional average changes in temperature and precipitation for the period 2071-2100 compared to a baseline of 1961-1990 are plotted for the four standard three months seasons with each CMIP3 or CMIP5 projected change represented by a symbol. (Thirty year periods were chosen for consistency with the figures displayed below showing changes in daily temperatures and precipitation.) Symbols showing the CMIP3 model projections are all grey but differ in shape depending on the driving SRES concentrations scenario and those showing the CMIP5 projections differ in colour depending on the driving RCP emissions/concentrations scenario (see figure legend for details). Figures presenting similar information for the SREX regions contained in the other inhabited continents are presented in supplementary figures S-Box21-CMIP5-boxplots.

[INSERT BOX 21-3 FIGURE 2 HERE
Box 21-3 Figure 2 Caption: Regional average change in seasonal mean temperature and precipitation over five regions covering South and Central America for the period 2070-2100 relative to 1961-90 in GCM projections from the CMIP5 ensemble under four RCP scenarios (van Vuuren et al., 2011) compared with GCM projections from the CMIP3 ensemble under three SRES scenarios (IPCC, 2000). Regional averaged are based on SREX region definitions (see Figure 21-RegAmplFac). Temperature changes are given in ºC and precipitation changes in mm/day with axes scaled relative to the maximum changes projected across the range of models.]

Projected changes in daily temperature and precipitation are presented for two example indices, the 90th percentiles of the daily maximum temperature and daily precipitation amounts on wet days (a wet day is defined as a day when more than 1mm of rain falls and defining the statistic of interest for wet days only allows data from regions with only a few rainy days per year to be easily included in the calculations). Due to concerns over the number of events that need to be sampled to generate robust statistics on changes in extremes (Kendon et. al, 2008) changes in these indices were calculated over 30 year periods (1961-1990 for the baseline and two future periods, 2041-2070 and 2071-2100) and the analysis was focused on the less extreme daily events. For consistency with the example summary regional figure, Figure 1, projected changes were calculated for RCPs 4.5 and 8.5 and the results are displayed as a map for a given continental region and also regional averages over the SREX regions within that continent. Two examples are provided, for temperature changes over N America (Figure 3) and precipitation changes over Asia (Figure 4), and a full set can be found in supplementary figures S-Box21-CMIP5-dailychanges.

[INSERT BOX 21-3 FIGURE 3 HERE
Box 21-3 Figure 3 Caption: The frequency of 'hot days' (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961-1990) projected for the 2071-2100 period by the CMIP5 GCMs for North America. Top: Ensemble median frequency of 'hot days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'hot-day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘Hot days’of 10% is represented on the graphs by the dashed line.
[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]]

[INSERT BOX 21-3 FIGURE 4 HERE
Box 21-3 Figure 4 Caption: The frequency of 'very wet days' (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961-1990 with wet days defined as days with 1mm of precipitation or more) projected for the 2071-2100 period by the CMIP5 GCMs. Top: Ensemble median frequency of 'very wet days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'very wet day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘Very wet days’ of 10% is represented on the graphs by the dashed line.
[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]]

_____ END BOX 21-3 HERE _____

Studies have also attempted to obtain regional information based on pattern scaling techniques in which regional temperature and precipitation changes are derived as a function of global temperature change. For example, in a recent paper Harris et al. (2012) used a Bayesian method complemented by pattern scaling and performance-based model weighting to calculate Probability Density Functions (PDFs) of temperature and precipitation change over sub-continental scale regions (Figure 21.4) under the A1B emission scenario based on an ensemble of simulations constrained to observations for the late 21st century. Although most impact studies might need local rather than sub-continental scale information, Figure 21.4 illustrates how the identification of the evolution of different percentiles of the distribution might be especially useful for risk assessment studies. Pattern scaling is indeed a valuable tool to estimate mean regional changes and associated uncertainty. It was for example used to calculate PDFs of temperature and precipitation change over different regions by Watterson (2008), Watterson and Whetton (2011), Watterson (2011), and Giorgi (2008).

[INSERT FIGURE 21-4 HERE
Figure 21-4: Evolution of the 5%, 17%, 33%, 50%, 66%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (upper panel) and annual precipitation (lower panel) for the Giorgi-Francisco (2000) regions and the globe with the A1B forcing scenario. Twenty year means relative to the 1961-1990 baseline are plotted in decadal steps using a common y-axis scale. The 5%, 50% and 95% percentile values for the period 2080-2099 are displayed for each region. (From Harris et al. 2012)]

21.3.3.1.3. Near-term decadal predictability

Compared to CMIP3, CMIP5 has an additional emphasis on near-term climate change, including intitialized experiments aimed at assessing decadal predictability. The uncertainty in near term projections is dominated by internal variability of the climate system, initial ocean conditions and inter-model response, rather than GHG forcing, and in fact the internal variability grows in importance at smaller spatial and temporal scales (Hawkins and Sutton 2009, 2010). Conversely, GHG forcing uncertainty becomes increasingly important on longer time scales, especially for surface air temperature (Hawkins and Sutton, 2009, 2010). Global warming for the period of 2016-2035 compared to 1986-2005 based on the CMIP5 multi model ensemble is *likely* of 0.4-1.0ºC, *more likely than not* closer to the lower end 0.4 C, and spatial patterns of near term warming are generally consistent with the AR4 (WGI Chapter 11). Differences across RCPs are small and about 50% of the warming is understood as the committed response to past emissions (WGI Chapter11). In terms of precipitation change patterns, it is more *likely than not that* in the next decade's precipitation will increase in regions of high precipitation and decrease in relatively dry regions (WGI Chapter 11).

The CMIP5 ensemble includes a new set of multidecadal near term prediction experiments (up to 2035) with initialized ocean state (WGI Chapter 11). Results from these experiments and analyses of un-initialized simulations show that there is a medium amount of evidence of the predictability of yearly to decadal averages of temperature both for the global average and for some geographical regions. Multi-model results for precipitation indicate a generally low level of predictability, except for some regions at higher northern latitudes and longer timescales. There is medium evidence that the Atlantic Multidecadal Variability (AMV) and Pacific Decadal Variability (PDV) patterns of climate variation exhibit predictability on timescales up to a decade (WGI Chapter 11). It is also shown that indices of global-mean temperature and Atlantic multi-decadal variability have statistically significant positive correlation with observations for most forecast periods (i.e., four-year averages ranging from 1–4 to 6–10 years) considered. At the regional scale, the retrospective prediction experiments for forecast periods of 1 to 10 years have statistically significant correlations with the observations (greater than 0.6, significant at the 95% confidence level) over much of the globe for temperature and over several regions for precipitation. [Section 11.2.2]. The correlation is improved by the ocean initialization over the North Atlantic, regions of the South Pacific and small continental areas of the Northern Hemisphere for temperature, while the effect of initialization for precipitation is negligible.

21.3.3.1.4. Changes in hydroclimate and extreme events

Changes in the characteristics of surface hydroclimatology, and especially extremes, are fundamental for an assessment of related impacts. Based on an analysis of observations, global and regional climate model simulations, Giorgi et al. (2011) defined an index of hydroclimatic intensity (HY-INT) incorporating a combined measure of precipitation intensity and mean dry spell length. They found that a ubiquitous global and regional increase in HY-INT was a strong hydroclimatic signature in model projections consistent with observations for the late decades of the 20th century, suggesting that HY-INT may be an important hydroclimatic indicator of global warming for use in detection/attribution and impact studies. The increase in intensity of precipitation (and thus risk of flood) and summer drought occurrence over mid-continental land areas is a robust signature of global warming, both in observations for recent decades and in model projections (Trenberth 2011).

CMIP5 projections of temperature extremes essentially confirm results from the CMIP3, namely a decrease in the frequency of cold days and nights, an increase in the frequency of warm days and nights, an increase in the duration of heat waves and an increase in the frequency and intensity of high precipitation events, both in the near term and far future (SREX Report, WGI Chapter 12). Some relevant summary statistics on CMIP5 projections of changes in daily temperature and precipitation extremes over the main continents and the SREX regions (Figure 21.1) are introduced in Box 21-3 and accompanying supplementary material.

Concerning tropical cyclones, there is still little confidence in past trends and near term projections of tropical cyclone frequency and intensity (Senevirante et al 2012; SREX Report). The global tropical cyclone frequency is projected to either not change or decrease and show different responses at the basin scale (Knutson et al. 2010). Concurrently, a *likely* overall increase in maximum wind speed and precipitation is expected, but region-specific conclusions are still uncertain (Knutson et al. 2010).

Regional circulations, such as the monsoon, are expected to change. Seth et al. (2011) and Sobel and Camargo (2011) found in the CMIP3 ensemble of 21st century projections a redistribution of precipitation from spring (early monsoon phase) to summer, mature phase in both northern (North America, West Africa and Southeast Asia) and southern (South America, Southern Africa) hemisphere monsoon regions. More generally, model projections indicate a prevailing decrease of the intensity of monsoon circulation, but an increase of monsoon rain due to the greater water-holding capacity of the atmosphere along with later monsoon onset leading to longer monsoon seasons (WGI Chapter 14).

21.3.3.1.5. Major modes of variability

ENSO is the mode of variability that has received most attention from a climate impacts point of view with significant effects on human and natural systems (http://iri.columbia.edu/climate/ENSO/societal/index.html). Seasonal forecasting of El Nińo behavior has significant skill (AR4-WG1 Chapter 8) and is used to providing advanced warnings of its impacts worldwide. Recent research has underscored the complexity of the ENSO system and provided some explanation for this, such as the non-symmetric amplitude between El Nino and La Nina (An, 2005, WGI Chapter 14). While we do not have definitve answers regarding the effect of anthropogenic forcing on ENSO, we know that it experiences decadal and longer term modulations that occur with relatively small changes in the mean climate state of the tropical Pacific. Model improvements in the reproduction of ENSO are evident in some of the models used for the CMIP5 simulations. For example CCSM4 shows good performance in reproducing the asymmetry between El Nino and La Nina durations (Deser et al., 2011). Although model projections indicate that ENSO remains a major mode of tropical variability, there is little evidence to indicate changes forced by GHG warming which are outside the natural modulation of ENSO occurrences.

The North Atlantic Oscillation (NAO) is a major model of variability for the northern Hemisphere mid-latitude climate. Model projections indicate that the NAO phase is *likely* to become slightly more positive (WGI Chapter 14) due to GHG forcing, but the NAO will be dominated by its large natural fluctuations. Model projections indicate that the Southern Annular Mode (SAM), a major model of variability for the southern hemisphere, is *likely* going to weaken as ozone concentrations recover through the mid-21st century (WGI Chapter 14).

21.3.3.1.6. Results from dynamical and statistical downscaling experiments

Dynamical and statistical downscaling techniques have been increasingly applied to regional climate change simulations, often as part of multi-model intercomparison projects. In this regard a new international program has been implemented, the COordinated Regional Downscaling Experiment (CORDEX, Giorgi et al. 2009), that will provide a framework for the assessment of dynamical and statistical downscaling techniques and the production of a new generation of climate projections over regions worldwide for use in impact and adaptation work. A few papers have already become available describing the first CORDEX experiments over different domains, and it is expected that CORDEX will in fact become a reference framework for downscaling experiments in the same way that CMIP5 is for global model experiments.

A large number of RCM-based climate projections for the European region were produced as part of the European projects PRUDENCE (Christensen et al. 2007; Deque et al. 2007) and ENSEMBLES (Hewitt 2005; Deque and

Somot 2010) where multiple RCMs have been run as driven by different GCMs for various scenarios . They all provide a generally consistent picture of seasonally and latitudinally varying patterns of change, which Giorgi and Coppola (2007) summarized with the term “European Climate Change Oscillation (ECO)”, consisting of a dipole pattern of precipitation change, with decreased precipitation to the south (Mediterranean) and increased to the north (Northern Europe) following a latitudinal/seasonal oscillation centered over the Mediterranean in winter and moving northward to central Europe in summer. As a result, the Mediterranean region is projected to be much drier and hotter than today in the warm seasons (Giorgi and Lionello 2008), and central/northern Europe much warmer and wetter in the cold seasons (Kjellstrom and Ruosteenoja, 2007). An increase of interannual variability of precipitation and summer temperature is also projected throughout Europe, with a decrease in winter temperature variability over Northern Europe (Schar et al. 2004; Giorgi and Coppola 2007; Lenderink et al. 2007). The broad patterns of change in regional model simulations generally follow those of the driving global models (Christensen and Christensen 2007; Deque et al. 2007), however fine scale differences related to local topographical, land use and coastline features are produced. For example, east-west winter precipitation change dipoles are projected across the Appenine chain as a result of the effect of this mountain system (Gao et al. 2006; Coppola and Giorgi 2010). These RCM simulations also projected an increase in a broad range of climate extremes (Beniston et al. 2007), such as heat waves, maximum drought length and number of hot days, especially over Central and Southeastern Europe and the Mediterranean (Gao et al. 2006; Beniston et al. 2007; Kjellstrom et al., 2007; Diffenbaugh et al., 2007), precipitation intensity and extremes especially over Central, Western and Northern Europe (Frei et al. 2006; Beniston et al. 2007, Buonuomo et al. 2007; Fowler et al. 2007; May 2008; Fowler and Ekstrom 2009; Kysely and Beranova, 2009; Kendon et al. 2010; Hanel and Buishand 2011; Kysely et al. 2011). Studies have also consistently shown that the distribution of seasonal temperature anomalies in the future is expected to be broader than today, particularly over central and southern Europe. This will lead, along with a shift of the distribution, to a higher frequency and intensity of extreme hot and dry summers (e.g. Schar et al. 2004; Seneviratne et al. 2006; Beniston et al. 2007; Coppola and Giorgi 2010), for which a substantial contribution is given by land-atmosphere feedbacks (Seneviratne et al. 2006; Fischer et al. 2007; Seneviratne et al. 2010; Hirschi et al. 2011; Jaeger and Seneviratne 2011). In general, the Mediterranean region is consistently projected to be much more arid than today (Rowell and Jones 2006; De Castro et al. 2007; Giorgi and Lionello, 2008; Gao and Giorgi 2008; Onol and Semazzi 2009; Trnka et al. 2011), and coupled atmosphere-ocean RCM simulations indicate that ocean feedbacks can significantly amplify the regional climate change signal over different regions of Europe (Somot et al. 2008). Concerning storminess projections , some studies based on ensembles of RCM simulations indicate a prevailing increase in winter mean daily and peak wind speed over Northern Europe (Rockel and Woth 2007; Albrecht et al. 2010, Bengtsson et al. 2009, Ulbrich et al. 2009), while more mixed results are found over the Mediterranean (Lionello et al. 2008; Giorgi and Lionello 2008). Recently, the first set of high resolution (dx = 12.5 km) projections over the EURO-CORDEX domain have been completed (Jacob et al. 2013). Both for the RCP8.5 and RCP4.5 scenarios the temperature and precipitation change patterns are generally consistent with those found for the ENSEMBLES project, further strengthening the robustness of those results.

As part of the ENSEMBLES and AMMA projects, 9 RCMs were run for the period 1990-2050 (A1B scenario) over domains encompassing the West Africa region with lateral boundary conditions from different GCMs. The RCM-simulated West Africa monsoon showed a wide range of response in the projections, even when the models were driven by the same GCMs (Paeth et al. 2011) (Figure 21.5). Although at least some of the response patterns may be within the natural variability, this result along with the fact that the model biases were not strongly tied to the driving GCMs suggests that for Africa, and probably more generally the tropical regions, local processes and how they are represented in models play a key factor in determining the precipitation change signal. Similar conclusions were found for an all-Africa RCM simulation of 1980-2100 (A1B scenario) by Mariotti et al. (2011) as well as a climate change projection over South Africa with a variable resolution model (Engelbrecht et al. 2009). Diallo et al. (2012) showed that ensemble averaging of RCM simulations tends to compensate systematic errors from the individual models and provide more consistent results. They found a prevailing decrease in peak monsoon rainfall over the western Sahel for the early decades of the 21st century in an ensemble of 4 RCM simulations driven by different GCMs. These results indicate that uncertainties in projections of the hydrologic cycle of Africa remain high and need large ensembles of model simulations in order to be fully characterized.

Statistical downscaling techniques have also been applied to the Africa region (Hewitson and Crane 2006; McKellar et al. 2007; Lumsden et al. 2009; Steynor et al. 2009). In general, methodological developments since the AR4 have been limited (see, for example reviews in Paeth et al., 2011, and Brown et al., 2008) and activities have focused more on the applications (e.g. Mukheibir, 2007, Nawaz et al, 2007, Gerbaux et al, 2009) for regional specific activities in the context of IAV work. Some promising developments relate to combining dynamical and statistical approaches, as for example in Paeth and Diederich (2010), who use an extended weather generator to optimize inputs to a hydrological model for application in west Africa. New work is also emerging that is not specific to Africa, but inclusive of all terrestrial regions. For example, Benestad (2011) developed a global downscaled product for station locations across all continents based on CMIP3, and draws a range of conclusions for regions including Africa, although the robustness of the statistical downscaling relationship for a number of locations is weak. Other activities are underway for similar globally extensive downscaling based on new CMIP5 GCMs with the purpose of producing gridded products (Ref to be eventually added here). However, the majority of statistical downscaling has been related to application of existing data products and is mostly not reported in the peer reviewed scientific literature, being found instead in the grey literature of project and institutional reports.

[INSERT FIGURE 21-5 HERE
Figure 21-5: Linear changes (i.e. changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001-2050 period from 10 individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land cover changes (see Paeth et al. 2011 for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 5% level are marked by black dots. (From Paeth et al. 2011)]

Several RCM experiments have been conducted for the South America continent, also as part of the CLARIS project (Menendez et al. 2010; Nunez et al. 2009; Sorensson et al. 2010; Marengo et al. 2009, 2010), and time-slice high resolution GCMs have been analyzed over the continent (Kitoh et al. 2011). In addition, pattern scaling was used to produce climate change scenarios over Southern South America (Cabre et al. 2010). Overall these studies revealed varied patterns of temperature and precipitation change, depending on the global and regional models used, however a consistent change found in many of these studies was an increase in both precipitation intensity and extremes, especially in areas where mean precipitation was projected to also increase.

The Central American region has emerged as a prominent climate change hot-spot since the AR4, especially in terms of a consistent decrease of precipitation projected by most models. Regional model studies focusing specifically on Central America projections are however still sparse. For example Campbell et al. (2010) performed a downscaling study on two GCMs finding some robust precipitation changes, such as a general drying in June-October, which is consistent with the more general analysis of CMIP3 results by Rauscher et al. (2008) and Rauscher et al. (2011) who however found that most of the precipitation reduction there occurred in June-July, just before the August mid-summer drought.

For both the South America and Central America regions, a first ensemble of RCM CORDEX projections were produced by Coppola et al. (2012), Fuentes-Franco et al. (2013) using different driving global models, different regional model configurations and the RCP8.5 and RCP4.5 scenarios. Preliminary analysis of the results showed that the change signals, especially for precipitation, were sensitive not only to the driving GCM fields, but also to the internal model physics, and in particular to the representation of land surface processes and feedbacks and the response of convection to SST forcing. This adds an element of uncertainty to the interpretation of fine scale change patterns that needs to be assessed with the use of large RCM ensemble. Diro et al. (2013) also showed that the simulation of tropical storms in the Atlantic and Pacific are sensitive to the convection scheme used. When using the better performing schemes, they found that the frequency of tropical cyclones decreased in the tropical Atlantic and eastern Pacific coastal areas while it increased over the central Pacific and northern Atlantic, with these changes being mostly driven by the changes in SST and wind shear. The experiments also shown a consistent increase in the frequency of intense and long lasting tropical storms.

Since the AR4 there has been considerable attention given to producing higher resolution future projections of climate change over North America through the application of RCMs and higher resolution global time slices. The North American Regional Climate Change Assessment Program (NARCCAP) has been a major multi-institutional effort using a number of different RCMs (with a resolution of 50 km) driven by different global climate models (GCMs) from the CMIP3 dataset, over the domain of most of North America (Mearns et al., 2009; 2012). Results indicate considerable variations in future climate based on the different RCMs, even when driven by the same GCM (Figure 21.6). In winter there tends to be more agreement across the GCMs and the RCMs for change in precipitation compared to in the summer, when the RCMs tend to depart more distinctly from the future projections of the GCMs (Mearns et al., 2013; De Elia and Cote 2010). This may indicate a lack of robustness in the projected precipitation changes in summer, but in-depth process level analysis will be necessary to determine this. There is also a tendency for the uncertainty across the driving GCMs to dominate for winter temperature and precipitation, but the uncertainty across the different RCMs dominates in the summer season. More detailed investigations of subregions of the NARCCAP domain have also been performed (e.g. Solowski and Pvelski 2012; Rawlins et al. 2012) Bukovsky et al. (2013) investigated the behavior of the NARCCAP models with regard to the North American Monsoon and was able to separate out the effects of the driving GCMs and the RCMs regarding error propagation. The GCM-RCM combinations that better produced the monsoon characteristics tended to indicate decreases in monsoon rainfall.

[INSERT FIGURE 21-6 HERE
Figure 21-6: Change in summer (JJA) average temperature (2041-2070 minus 1971-2000) from (top left) the NCAR CCSM3, (top right) the MM5 regional climate model driven by the CCSM3; (bottom left) the WRF model, driven by CCSM3, and (bottom right) the Canadian CRCM, driven by CCSM3. Temperature is in °C. Data from the NARCCAP program. (From Mearns et al., 2009, 2013)]

Other regional modeling efforts for sub-regions of North America include those of Hostetler (in preparation), Caya and Biner (2011) Subin et al. (2011), Salathé et al., (2008, 2010), Dominguez et al. (2010), De Elia et al. (submitted), Lofgren et al. (in preparation). In the realm of statistical downscaling and spatial disaggregation, considerable efforts have been devoted to applying techniques for the entire US and parts of Canada (e.g., Maurer et al., 2007; Hayhoe et al., 2010). These methods are particularly useful for driving impacts models, since they are produced at very high resolutions (e.g., 10 km), but usually only include temperature and precipitation. Comparisons among the spatial disaggregation techniques and dynamical downscaling are underway including the differential effects on impacts and adaptation planning (e.g., Barsugli et al., in progress).

Numerous high resolution RCM projections have been carried out over the East Asia continent, and some of these tend to produce results that are actually not in line with those from GCMs. For example, Ashfaq et al. (2009) used an RCM with 25 km grid spacing to find that enhanced greenhouse forcing resulted in a predominant suppression of South Asia summer monsoon precipitation, a delay in monsoon onset and a an increase in monsoon break periods, while most GCMs tend to produce increased South Asia monsoon precipitation (WGI Chapter 14). These were mostly attributed to a weakening of the monsoon flow and a suppression of the dominant intraseasonal oscillatory modes. As another example, Gao et al. (2011) completed a climate projection at 20 km grid spacing over East Asia and found that while the forcing GCM produced a prevailing increase in summer monsoon precipitation, in agreement with most GCM-based projections, the nested RCM showed large areas of decreased summer precipitation amounts in response to the high resolution topographical forcing of the Tibetan Plateau and other topographical complexes. Similarly a series of double nested RCM scenario simulations were performed for the Korea peninsula reaching a grid spacing of 20 km (Im et al. 2007a; 2008a,b; 2010; 2011a,b). They indicated a complex fine scale structure of the climate change signal, particularly for precipitation, also forced by local topographical features and a consistent increase in intense and extreme precipitation events. While it is difficult to clearly establish whether the RCM simulations are more credible, which would require large ensembles, all these high resolution RCM experiments do point out the importance of regional and local topographical forcings in modulating the response of regional circulations, e.g. the monsoon, and of local phenomena, e.g. tropical convection.

Both RCM and variable resolution model experiments have been conducted over the Australian continent or some of its sub-regions (Watterson et al. 2008; Nunez and Mc Gregor 2007; Song et al. 2008), showing that a local fine scale modulation of the large scale climate signal occurs in response to topographical and coastal forcings. Statistical downscaling has been applied for a number of focused studies over Australia. Timbal et al (2008) evaluate the consistency between statistical downscaling and projections from the GCMs using two different statistical downscaling methods. They find that along with the higher resolution of the downscaling, the downscaled and direct model projections are largely consistent across the 15 GCMs used, and averaged across the southwest of Western Australia, indicate a general decline of precipitation. More recently Yin et al (2010) focus on new methodological developments in downscaling, using an adapted Self Organizing Map procedure based on Hewitson and Crane (2006), and in common with other statistical downscaling studies finds the most notable challenge is downscaling precipitation in arid zones.

21.3.3.2. Oceans and Sea Level

Contributions to global sea level rise include thermal expansion, glacier and ice cap melting, Greenland ice sheet and Antarctic iceberg calving and ice sheet melting. Regional sea level change can be quite different from global sea level change due to changes in circulations and associated wind stress, changes to the geoid and crustal subsidence and rebound (WGI Chapter 3).

From paleo records there is evidence that during the last 3 million years global mean sea level (GMSL) was more than 6 m higher than present, with global mean temperatures being 2-3 C warmer than present. The rate of GMSL rise has increased in the last 200 years, to about 1.7 +/- 0.2 mm/year during the 20th century and 2.8-3.6 mm/year since 1993 (WGI Chapter 3). Since 1970 the greatest contributions to GMSL (combined 80%) rise have been from ocean warming/expansion and glacier melting, however the rate of the contributions from Greenland and Antarctica ice has been increasing since the 1990s. An important advance compared to the AR4 is the closure of the observations budget for recent decades due to an improved set of observations, in particular the GRACE satellite data. In addition, estimates of 20th century GMSL increase from AOGCM simulations are now much closer to observations due to better understanding and modeling of relevant processes (WGI Chapter 11). The mean regional pattern of sea surface salinity has been enhanced, with saline surface waters in the evaporation-dominated mid-latitudes becoming more saline, and relatively fresh surface waters in rainfall-dominated tropical and polar regions becoming fresher.

Evidence is strong that the biogeochemical state of the ocean has changed (WGI Chapter 3). The ocean inventory of anthropogenic carbon dioxide has increased, from 114 ± 22 PgC in 1994 to 151 ± 26 PgC in 2010 and this is in broad agreement with the expected change resulting from the increase in atmospheric CO2 concentrations and change in atmospheric O2/N2 ratios (WGI Chapter 3). The uptake of CO2 by the ocean has resulted in a gradual acidification of seawater, with observations showing declines in pH in the mixed layer between -0.0015 and -0.0024 yr^{-1}.

Concerning GMSL projections (WGI Chapter 13), under all the RCP scenarios, the time-mean rate of GMSL rise during the 21st century is *very likely* to exceed the rate observed during 1971–2010, with ocean thermal expansion and glacier melting *likely* to make the largest contributions to this rise. For the period 2081 to 2100 compared to 1986 to 2005, GMSL rise is *likely* to lie in the range 0.29–0.55 m for RCP2.6, 0.36–0.63 m for RCP4.5, 0.37-0.64 for RCP6.0, and 0.48–0.82 m for RCP8.5. The upper end of this range is higher than in the AR4, but the confidence in these estimates is still limited due to limited understanding of some key processes, such as rapid changes in ice sheet dynamics and the differences between estimates with semi-empirical and process-based models, with the former giving higher upper estimates (higher than 1.0 m).

Projections of regional sea level changes, both based on the CMIP3 and CMIP5 models, indicate a large regional variability of sea level rise (even more than 100% of the GMSL rise), with areas undergoing much larger or smaller rise than the global average in response to different regional processes (WGI Chapter 13). However, by the end of the 21st century it's *very likely* that over about 95% of the oceans will undergo sea level rise, with the remaining 5% experiencing a decline mostly in high latitude regions and 75-80% of coastlines experiencing a sea level rise within 20% of the GLSL one.

Regional sea level changes for the next decades will largely be dominated by internal dynamical variability of the climate system, while on longer time scales changes in regional sea level will likely be dominated by changes in ocean dynamics. Some preliminary analysis of the CMIP5 ensembles, for example, indicates area of maximum steric sea level rise in the Northern Atlantic, the northwestern Pacific off the East Asia coasts, the eastern coastal oceanic regions of the Bay of Bengal and the western coastal regions of the Arabian Sea (WGI Chapter 13).

Some analysis of the past decades indicate that the increase in storm surges and extreme sea level events is generally in line with the increase in mean sea level (Menendez and Woodworth 2010; Lowe et al. 2010; Woodworth et al. 2011). Dominant modes of variability, such as ENSO and the NAO, are also found to significantly affect extreme sea levels in a number of regions (Lowe et al. 2010). Some low lying areas, such as Venice (Carbognin et al. 2010) and the deltaic regions of the Bay of Bengal (Unnikrishnan and Shankar 2007), show trends in sea level much higher that the global average, also because eof subsidence in some cases (e.g. Venice). Positive wave height trends are found in many areas of the North Atlantic, North pacific, U.S. coasts and Southern ocean, with modulation associated with main modes of climate variability. Projections of storm surges in European coasts have used RCM-produced wind fields to force storm surge models, and prevailing increases in extreme storm surges were found (Debernard and Roed 2008; Wang et al. 2008). However changes in storm surges are tied to changes in atmospheric circulations, and may be highly regionally dependent. Increase of GMSL is likely to affect storm surges and increase the frequency of extreme sea level events.

Projections of changes in the Atlantic Meridional Overturning Circulation (AMOC) from the CMIP5 models indicate that it is *very likely* that the AMOC will weaken in the 21st century as a result of increased GHG concentrations (by 20-30% in the RCP4.5 scenario and 36-44% in the RCP8.5) but it is *very unlikely* that it will undergo an abrupt transition or collapse for the scenarios considered (WGI Chapter 12).

21.3.3.3. Air Quality

Changes in air pollutants such as near surface ozone and particulate material may have effects on human health, agriculture and natural ecosystems. These changes may depend on changes in emissions or changes in climatic and meteorological conditions affecting transport and removal of the pollutants. Therefore the issues of climate change and air quality are deeply interconnected (Giorgi et al. Meleux 2007).

Since the AR4 the interest in climate-air quality interactions has increased and more studies have become available addressing the issue of the effects of both climate and emission changes on air quality. Most of these studies focused on the continental United States and Europe, and utilized both global and regional climate and air quality models run in off-line or coupled mode. Regional modeling studies over the United States or some of its sub-regions include, for example, those of Hogrefe et al. (2004), Knowlton et al. (2004), Steiner et al. (2006), Dawson et al. (2006), Lin et al. (2008), Weaver et al. (2009), Zhang et al. (2008), while examples of global modeling studies include Murazaki and Hess (2006), Stevenson et al. (2006), Shindell et al. (2006), Doherty et al. (2006). Weaver et al. (2009) provide a synthesis of simulated effects of climate change on ozone concentrations in the U.S. using an ensemble of regional and global climate and air quality models. These studies indicate a predominant increase in near-surface ozone concentrations, particularly in the Eastern U.S. (Figure 21.7) mostly tied to higher temperatures and corresponding biogenic emissions. An even greater increase was found in the frequency and intensity of extreme ozone concentration events, which are the most dangerous for human health.

Examples of regional studies of air quality changes in response to climate change over Europe include Langner et al. (2005), Forkel and Knocke (2006) , Szopa and Hauglustaine (2007), and Meleux et al. (2007), Carvalho et al. (2010), Engartd et al. (2009), Andersson and Engardt (2010), Kruger et al. (2008), Athanassiadou et al. (2010). All these studies indicated the potential of large increases in near surface summer ozone concentrations especially in Central and Southern Europe due to much warmer and drier projected summer seasons (Figure 21-8).

[INSERT FIGURE 21-7 HERE
Figure 21-7: Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2081-2100 minus 1981-2000) MDA8 summer ozone concentrations across (left-hand panels) all 7 experiments (5 regional and 2 global) and, for comparison purposes (right-hand panels) not including the WSU experiment (which simulated July only conditions). (From Weaver et al. 2009)]

[INSERT FIGURE 21-8 HERE
Figure 21-8: Difference in average summer daily ozone mean (left panel) and peak (right panel) concentration over Europe due to climate change, (2071-2100 minus 1961-1990), A2 scenario. (From Meleux et al. 2007)]

In general, while a consistently predominant increase of ozone concentrations due to climate change was found in these experiments, results were more mixed and regionally/seasonally dependent for other pollutants such as PM, sulfur and nitrogen compounds. It should be mentioned that most studied addressed the issue of climate effects on ozone without changes in anthropogenic emission. However, these are likely to change as well, and thus modulate the climate-related signals.

21.3.3.4. Cryosphere

The cryosphere is one of the most sensitive components of the climate system to global warming, and this response, which has profound implications for changes in sea level rise and atmospheric circulations, is determined by very complex processes, some of which are still poorly understood (e.g. ice flow dynamics).

New and improved data have become available since the AR4 to evaluate changes in the cryosphere (WGI Chapter 4), most notably the GRACE satellite ones, which have allowed more accurate assessments of the ice sheet mass balance. These improved observations show that the retreat of Arctic ice in all seasons has continued, at a rate of 3.9% per decade annually and 12.2% per decade during the summer during the period 1979-2011. The thickness, concentration and volume of arctic ice have also decreased, with a decrease in mean winter thickness by 48% between 1980 and 2009. Conversely, the total extent of Antarctic ice has increased slightly (1.4% per decade) between 1979 and 2011, with strong regional differences.

Retreat of mountain glaciers is widespread, with varying rates across regions, and uncertainty about the global rate. In particular, increasing loss of glacier mass has been observed in recent decades over Central Europe, Alaska, the Canadian Arctic and the Southern Andes. Several hundred glaciers globally have completely disappeared in the last 30 years.

Because of better techniques and more data, confidence has increased in the measurements of Greenland and Antarctica ice sheets. These indicate that parts of the Antarctic and Greenland ice sheets have been losing mass over the last two decades and contribute to global sea level rise. During 1993-2012, Greenland lost on average 123 ± 22 Gt yr-1 (0.34 mm/year of SLE) and Antarctica lost 65 ± 33 Gt yr-1 (0.18 mm/year of SLE). In the GRACE period 2005–2010, the losses were higher, 228 ± 54 Gt yr-1 in Greenland and 112 ± 58 Gt yr-1 in Antarctica. These were mostly caused by changes in ice flow in Antarctica, and a mix of changes in ice flow and increases in snow/ice melt in Greenland. Ice shelves in the Antarctic peninsula are also continuing a long-term trend of retreat and partial collapse started some decades ago. In total global SLR due to the contributions of Greenland and Antarctic ice sheets was 1.2+/- 0.2 mm/year for 1993-2010 and 1.7 +/1 0.5 mm/year for 2005-2010 (WGI Chapter 4).

New data, both in situ and from satellite confirm a decrease in snow cover extent in most months, particularly in spring (8% in 1970-2010 compared to 1922-1970), with marked regional and seasonal variations and with a decline in the duration of northern hemisphere snow season of about 5.3 days per decade (WGI Chapter 4). During the past three decades, significant permafrost degradation occurred. Permafrost temperature has increased (up to 3°C since the late-1970s in some regions of the Arctic) and the areal extent of permafrost is declining. The thickness of seasonally frozen ground has decreased in the 20th century across the Russian European North and from 1960 to the present on the Qinghai-Xizang (Tibetan) Plateau. The thaw season has expanded by more than two weeks from 1988 through 2007 across central and eastern Asia.

Twenty first century projections of cryosphere changes based on the CMIP5 ensemble show long-term reductions in Northern Hemisphere sea ice areal coverage in both hemispheres, from 39% for RCP2.6 to 94% for RCP8.5 in September and from 9% to 35% in February by the end of the century (WGI Chapter 12). The models indicate a nearly ice-free Arctic at the end of summer for warming greater than 2C. The CMIP5 models also better capture the rapid decline in summer Arctic sea ice observed during the last decades than CMIP3 models. Future projections of

Southern Hemisphere sea ice remain comparatively more uncertain, with the CMIP5 multi-model ensemble projecting, for the end of the 21st century, a decrease in Southern Hemisphere sea ice extent from 14% for RCP2.6 to 57% for RCP8.5 in February and from 9% to 29% in September, and a large inter-model scatter. The models show no evidence of critical thresholds in the transition from perennial ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible. Projections of decrease in Northern Hemisphere spring snow covered area in the CMIP5 models are fairly coherent (decrease of about 7% in RCP2.6 and 25% RCP8.5 by 2100). Surface permafrost area is projected to decrease between 37% (RCP2.6) to 81% (RCP8.5) by 2100.

21.4. Cross-Regional Phenomena

Thus far, this chapter has covered climate change-related issues that have a regional expression in one part of the world or another. In principle, these issues can be studied and described, *in situ*, in the regions in which they occur. However, there is a separate class of issues that transcends regional boundaries and demands a different treatment. In order to understand such cross-regional phenomena, knowledge is required of critical but geographically remote associations and of dynamic cross-boundary flows. The following sections consider some examples of these phenomena, focusing on trade and financial flows and migration. Though these issues are treated in more detail in Part A of this report, they are restated here in Part B to stress the importance of a global perspective in appreciating climate change challenges and potential solutions at the regional scale.

21.4.1. Trade and Financial Flows

Global trade and international financial transactions are the motors of modern global economic activity, and are inextricably linked to climate change through a number of interrelated pathways: (i) as a direct or indirect cause of anthropogenic emissions, (ii) as a predisposing factor for regional vulnerability to the impacts of climate change, (iii) through their sensitivity to climate trends and extreme climate events, and (iv) as an instrument for implementing mitigation and adaptation policies.

21.4.1.1.International Trade and Emissions

The contemporary world is highly dependent on trading relationships between countries in the import and export of raw materials, food and fibre commodities and manufactured goods. A rapidly growing world population and expanded economic activity in many developing countries during the past two decades has fuelled increasing demand for imports. The engines of manufacturing are now located in developing countries with a young and relatively cheap workforce, with only high value products retaining competitiveness in the developed world. Even during a period of general recession since 2008, economic development in many emerging, export-led economies (e.g. China, India, Ghana and Brazil) succeeded in bucking the global trend (World Bank, 2012).

Bulk transport of these products, whether by air, sea or over land, is now a non-trivial contributor to emissions of greenhouse gases and aerosols. Furthermore, the relocation of manufacturing has transferred net emissions via international trade from developed to developing countries (see Figure 21-9), and most developed countries have increased their consumption-based emissions faster than their domestic (territorial) emissions (Peters *et al*., 2011). This regional transfer of emissions is commonly referred to in climate policy negotiations as "carbon leakage" (Barker *et al*., 2007), though only a very small portion of this can be attributed to climate policy ("strong carbon leakage"), a substantial majority being due to the effect of nonclimate policies on international trade ("weak carbon leakage" – Peters, 2010). A particular example of strong carbon leakage concerns the conversion of land use from the production of food to bioenergy crops. These crops sequester carbon otherwise extracted from the ground as fossil fuels, but in the process displace demand for food production to land in other regions, often inducing land clearance and hence an increase in emissions (Searchinger *et al*., 2008), though the empirical basis for this latter assertion is disputed (see Kline and Dale, 2008).

[INSERT FIGURE 21-9 HERE
Figure 21-9: Growth rates from 1990-2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macrovariables, all indexed to 1990 (Peters et al., 2011).]

21.4.1.2. Trade and Financial Flows as Factors Influencing Vulnerability

The increasingly international nature of trade and financial flows (commonly referred to as globalisation), while offering potential benefits for economic development and competitiveness in developing countries, also presents high exposure to climate-related risks for some of the populations already most vulnerable to climate change. Examples of these risks, explored further in Chapters 7-9, 12 and 13 of Part A, include:

- Severe impacts of food price spikes in many developing countries (including food riots and increased incidence of child malnutrition) such as occurred in 2008 following shortfalls in staple cereals, due to a coincidence of regional weather extremes (e.g. drought) in producer countries, the reallocation of food crops by some major exporters for use as biofuels (an outcome of climate policy – see previous section) and market speculation (Ziervogel and Ericksen, 2010). Prices subsequently fell back as the world economy went into recession, but spiked again in early 2011for many of the same reasons (Trostle *et al.*, 2011), with some commentators predicting a period of rising and volatile prices due to increasing demand and competition from biofuels (Godfray *et al.*, 2010).
- A growing dependence of the rural poor on supplementary income from seasonal urban employment by family members and/or on international financial remittances from migrant workers (Davies *et al.*, 2009). These workers are commonly the first to lose their jobs in times of economic recession, which automatically decreases the resilience of recipient communities in the event of adverse climate conditions.On the other hand, schemes to provide more effective communication with the diaspora in times of severe weather and other extreme events can provide rapid access to resources to aid recovery and reduce vulnerability (Downing, 2012).
- Some aspects of international disaster relief, especially the provision of emergency food aid over protracted periods, has been cited as an impediment to enhancing adaptive capacity to cope with climate-related hazards in many developing countries (Schipper and Pelling, 2006). Here, international intervention, while well-intentioned to relieve short-term stress, may actually be counter-productive in regard to the building of long-term resilience.

21.4.1.3. Sensitivity of International Trade to Climate

Climate trends and extreme climate events can have significant implications for regional resource exploitation and international trade flows. The clearest example of a major prospective impact of climate change concerns the opening of Arctic shipping routes as well as exploitation of mineral resources in the exclusive economic zones (EEZs) of Canada, Greenland/Denmark, Norway, Russia and the USA (Figure 21-10a, and see Chapter 28). For instance, the CCSM4 climate and sea ice model has been used to provide projections under RCP4.5, RCP6.0 and RCP8.5 forcing (see Box 21-1) of future accessibility for shipping to the sea ice hazard zone of the Arctic marine environment defined by the International Maritime Organization (Stephenson *et al.*, 2013 – Figure 25-10a). Results suggest that moderately ice-strengthened ships (Polar Class 6), which are estimated under baseline (1980-1999) conditions to be able to access annually about 36 % of the IMO zone, would increase this access to 45-48 % by 2011-2030, 58-69% by 2046-2065 and 68-93% by 2080-2099, with almost complete accessibility projected for summer (90-98% in July-October) by the end of the century (Stephenson *et al.*, 2013). Estimates are also presented for three major cross Arctic routes: the Northwest Passage, Northern Sea Route (which is part of the Northeast Passage), and Trans-Polar Route (Figure 21-10a). This could represent significant distance savings for trans-continental shipping currently using routes via the Panama and Suez Canals (Stephenson *et al.*, 2011). Indeed, in 2009 two ice-hardened cargo vessels – the Beluga Fraternity and Beluga Foresight – became the first to successfully traverse the Northeast Passage from South Korea to the Netherlands, a reduction of 5,500 km and 10 days compared to their traditional 20,000 km route via the Suez Canal, translating into an estimated saving of some $300,000 per ship, including the cost of standby icebreaker assistance (Smith, 2009; Det Norsk Veritas, Beluga). A projection using an earlier version of the sea ice model under the SRES A1B scenario, but offering similar results (with forcing comparable to RCP 6.0), is presented in Figure 21-11b, which also portrays winter transportation routes on frozen ground. These routes are heavily relied upon for supplying remote communities and for activities such as forestry and, in contrast to the shipping routes, are projected to decline in many regions (Figure 21-10b).

[INSERT FIGURE 21-10 HERE
Figure 21-10: (a) Marine exclusive environmental zones (EEZs – dashed lines) of Canada, Greenland/Denmark, Norway, Russia, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the IMO Guidelines Boundary for Arctic shipping (thick black border). After Stephenson (2013). (b) Projected change in accessibility of maritime and land-based transportation by mid-century (2045-2059 relative to 2000-2014) using the Arctic Transport Accessibility Model and CCSM3 climate and sea ice estimates assuming an SRES A1B scenario. Green areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).]

A second illustration of how the risk of adverse climate changes may have contributed to anticipatory adaptive actions affecting countries in other regions of the world and potentially influencing commodity markets, relates to the purchase or renting of large tracts of productive land in parts of Africa, Latin America, Central Asia and Southeast Asia by countries in Europe, Africa, the Gulf and South and East Asia (De Schutter, 2009; Cotula *et al.*, 2011; Zoomers, 2011). While there is clearly a profit motive in many of these purchases (i.e., cheap and fertile land and the opportunity to cultivate high value food or biofuel crops), there is also a concern that domestic agricultural production in some countries will be unable to keep pace with rapid growth in domestic demand and changing dietary preferences, especially in agricultural regions affected by frequent shortfalls due to droughts, floods and cyclones (Cotula *et al.*, 2011), or threatened by sea-level rise (Zoomers, 2011). Land acquisition on such a large scale raises a number of ethical issues relating to local access to food and the appropriate and sustainable management of the land (Deininger and Byerlee, 2012). These issues have led the UN Special Rapporteur on the right to food to recommend a list of eleven principles for ensuring informed participation of local communities, adequate benefit sharing and the respect of human rights (De Schutter, 2009). This issue is elaborated with respect to rural areas, in Chapter 9 and livelihoods and poverty, in Chapter 13.

Extreme climate phenomena that may be harbingers of similar and more frequent events in a warmer world, already exact devastating consequences in some regions that extend well beyond country boundaries. A recent event that disrupted international trade and commodity flows was the severe 2010/2011 flooding in eastern Australia (Giles, 2011; Queensland Floods Commission of Inquiry, 2012; and see Chapter 25), which combined with damaging cyclones in Queensland and Western Australia curtailed numerous mining operations and damaged transportation networks, leading to declines in both thermal and metallurgical coal exports (by 31% and 19%, respectively, relative to the previous quarter – ABARES, 2011) with a sharp rise in their monthly price between November 2010 and January 2011 (Index Mundi, Coal). The severe weather was the primary factor contributing to a fall in Australian GDP of 1.2% during January-March 2011 compared with a rise of 0.7% in the preceding three-month period (Australian Bureau of Statistics, Australian National). Other examples of how extreme climate events can affect international trade are reported by Oh and Reuveny (2010) and Handmer et al. (2012).

21.4.1.4. International Transactions as Instruments of Regional Climate Policy

International policies to curb climate change and to adapt to its impacts, are increasingly looking to cross-border mechanisms to encourage action (and see Chapters 14-17). The European Union Emissions Trading System (EU ETS) is the first and largest international scheme for the trading of greenhouse gas emission allowances, covering some 11,000 power stations and industrial plants in 30 countries and accounting for almost half of the EU's CO_2 emissions and 40% of its total greenhouse gas emissions (European Commission, 2012). The Clean Development Mechanism (CDM) allows industrialised countries (Annex B Parties, cf. Supplementary material) to invest in emission-reduction projects in developing countries, which earn certified emission reduction (CER) credits, each equivalent to one tonne of CO_2. These CERs can be traded and sold to meet part of the emission reduction targets of the Annex B Parties under the Kyoto Protocol.

21.4.2. Human Migration

There has been considerable debate in recent years around the postulate that anthropogenic climate change and environmental degradation could lead to mass migration (Perch-Nielsen *et al.*, 2008; Feng *et al.*, 2010; Warner, 2010; Black *et al.*, 2011; Government Office for Science, 2011; Assan and Rosenfeld, 2012). The issue is treated at length in Chapters 8, 9, 12 and 13 of Part A, so only a few aspects are touched on here, to highlight the growing significance of migration in all regions of the world.

Four possible pathways through which climate change could affect migration are suggested by (Martin, 2009):

1) Intensification of natural disasters
2) Increased warming and drought that affects agricultural production and access to clean water
3) Sea-level rise, which makes coastal areas and some island states increasingly uninhabitable
4) Competition over natural resources, leading to conflict and displacement of inhabitants.

Abundant historical evidence exists to suggest that changes in climatic conditions have been a contributory factor in migration, including large population displacements in the wake of severe events such as Hurricane Katrina in New Orleans, Louisiana in 2005 (Cutter *et al.*, 2012), Hurricane Mitch in Central America in 1998 and the northern Ethiopian famines of the 1980s (McLeman and Smit, 2006). However, the evidence is not clear cut (Black, 2001), with counter examples also available of migration being limited due to economic hardship (e.g. during the Sahel drought of the mid-1980s in Mali – Findley, 1994).

The spatial dimension of climate-related migration is most commonly internal to nations (e.g. from affected regions to safer zones – Naik, 2009). In this context it is also worth pointing out that internal migration for other (predominantly economic) reasons may actually expose populations to increased climate risk. For instance, there are large cities in developing countries in low elevation coastal zones that are vulnerable to sea level rise. Increased migration to these cities could exacerbate the problems with the migrants themselves being especially vulnerable (Nordås and Gleditsch, 2007; UNFPA, 2007).

Migration can also be international, though this is less common in response to extreme weather events, and where it does happen it usually occurs along well established routes. For example, emigration following Hurricane Mitch tripled from Honduras and increased from Nicaragua by 40%, mainly to the southern States of the US – already a traditional destination for migrants, and was aided by a relaxation of temporary residency requirements by the United States (Naik, 2009).

The causal chains and links between climate change and migration are complex and can be difficult to demonstrate (e.g., Perch-Nielsen *et al.*, 2008; Piguet, 2010; Tänzler *et al.*, 2010; ADB, 2012; Oliver-Smith, 2012), though useful insights can be gained from studying past abandonment of settlements (McLeman, 2011). Thus projecting future climate-related migration remains a challenging research topic (Feng *et al.*, 2010). There are also psychological, symbolic, cultural and emotional aspects to place attachment, which are well documented from other non-climate causes of forced migration, and are also applicable to cases of managed coastal retreat due to sea-level rise (e.g., Agyeman *et al.*, 2009). Furthermore, forced migration appears to be an emerging issue requiring more scrutiny by governments in organising development co-operation, and to be factored into international policy making as well as international refugee policies. For example, it has been suggested that the National Adaptation Plans of Action (NAPAs) under the UNFCCC, by ignoring transboundary issues (such as water scarcity), and propounding nationally-orientated adaptation actions (e.g. upstream river management, to the detriment of downstream users in neighbouring countries), could potentially be a trigger for conflict, with its inevitable human consequences. Moreover, currently there is no category in the United Nations High Commission for Refugees classification system for environmental refugees, but it is possible that this group of refugees will increase in the future and their needs and rights will need to be taken into consideration (Brown, 2008). The Nansen Initiative, put forward jointly by Norway and Switzerland at a 2011 ministerial meeting, pledges "to cooperate with interested states and relevant actors, including UNHCR, to obtain a better understanding of cross-border movements provoked by new factors such as climate change, identify best practices and develop a consensus on how best to protect and assist those affected ", and may eventually result in a soft law or policy framework (Kolmannskog, 2012 environmental). However, migration should not always be regarded as a problem; in certain circumstances where it contributes to adaptation (e.g. through remittances) it can be part of the solution (Laczko and Aghazarm, 2009).

21.4.3. Migration of Natural Ecosystems

One of the more obvious consequences of climate change, is the displacement of biogeographical zones and the natural migration of species (see Chapters 4 and 6). General warming of the climate can be expected to result in migration of ecosystems towards higher latitudes and upward into higher elevations. Species shifts are already occurring in response to recent climate changes in many parts of the world (Rosenzweig *et al*., 2008), with average poleward shifts in species' range boundaries of 6 km per decade being reported (Parmesan *et al*., 2011).

Study of the estimated shifts of climatic zones alone can provide insights into the types of climatic regimes to anticipate under projected future anthropogenic climate change. By grouping different combinations and levels of climatic variables, it is possible not only to track the shifts in the zones in which they occur, but also to identify newly emerging combinations of conditions not found at the present day (novel climates) as well as combinations that may not survive global climate change (disappearing climates – Williams *et al*., 2007). These analyses can help define what types of climatic niches may be available in the future and where they will be located. Such a spatial analogue approach (cf. Carter *et al*., 2007) can delimit those regions that might currently or potentially (in the future) be susceptible to invasion by undesirable aquatic (e.g., EPA, 2008) or terrestrial (e.g., Mainka and Howard, 2010) alien species or alternatively might be candidates for targetting translocation (assisted colonisation) of species endangered in their native habitats (e.g., Brooker *et al*., 2011; Thomas, 2011). However, there are many questions about the viability of such actions, including genetic implications (e.g., Weeks *et al*., 2011), inadvertent transport of pests or pathogens with the introduced stock (e.g., Brooker *et al*., 2011) and risk of invasiveness (e.g., Mueller and Hellmann, 2008).

The ability of species to migrate with climate change must next be judged, in the first instance, against the rate at which the climatic zones shift over space (e.g. Loarie *et al*., 2009 – Figure 21-11). For projecting potential future species shifts, this is the most straightforward part of the calculation. In contrast, the ecological capacity of species to migrate is a highly complex function of factors, including their ability to:

- Reproduce, propagate or disperse
- Compete for resources
- Adapt to different soils, terrain, water quality and daylength
- Overcome physical barriers (e.g. mountains, water/land obstacles)
- Contend with obstacles imposed by human activity (e.g. land use, pollution or dams).

[INSERT FIGURE 21-11 HERE
Figure 21-11: The velocity of shifting climatic zones due to climate change based on the average of 16 global climate models for an A1B emissions scenario and temporal gradients computed for 2050-2100. (Loarie et al., 2009).]

Conservation policy under a changing climate is largely a matter of promoting the natural adaptation of ecosystems, if this is even feasible for many species given the rapidity of projected climate change. Studies stress the risks of potential mismatching in responses of co-dependent species to climate change (e.g., Schweiger *et al*., 2012) as well as the importance of maintaining species diversity as insurance for the provision of basic ecosystem services (e.g., Traill *et al*., 2010; Isbell *et al*., 2011). Four priorities have been identified for conservation stakeholders to apply to climate change planning and adaptation (Heller and Zavaleta, 2009): (i) regional institutional coordination for reserve planning and management and to improve landscape connectivity; (ii) a broadening of spatial and temporal perspectives in management activities and practice, and actions to enhance system resilience; (iii) mainstreaming of climate change into all conservation planning and actions; and (iv) holistic treatment of multiple threats and global change drivers, also accounting for human communities and cultures. The regional aspects of conservation planning transcend political boundaries, again arguing for a regional (rather than exclusively national) approach to adaptation policy. This issue is elaborated in Chapters 4 and 14.

21.4.4. Hotspots

Hotspots is an approach that has been used to indicate locations that stand out in terms of impacts, vulnerability or adaptive capacity (or all three). The approach exists in many fields and the meaning and use of the term hotspots differs. The term typically relates to a geographical location, which emerges as a concern when multiple layers of information are compiled. For example, the Consultative Group on International Agricultural Research (CGIAR) Research Program on Climate Change Agriculture and Food Security (CCAFS) mapped hotspots of food insecurity and climate change in the tropics (Ericksen et al, 2011). Other studies look at how climate change can influence disease risk (de Wet et al 2001), extinctions of endemic species (Malcolm et al 2005), and disaster risk (Dilley 2006). The purpose of the hotspots is to set priorities for policy action and for further research (de Sherbinin, submitted; Dilley 2006, Ericksen et al 2011, see www.climatehotmap.org).

Hotspots generally refers to a geographical location, but could also be used to refer to a topic, such as a type of ecosystem or farming system (eg. biofuels), a style of armed conflict (eg. guerrilla warfare) or seasonally distributed diseases (eg. malaria). This bends the definition of ‘spot’ but reflects the same approach: that certain circumstances result in certain levels of exposure or sensitivity to climate change. Below are some ways in which hotspots are used:

Climate Change: A climate change hotspot can describe (a) a region for which potential climate change impacts on the environment or different activity sectors can be particularly pronounced or (b) a region whose climate is especially responsive to global change (Giorgi 2006). Since the AR4, a number of studies attempted to identify “Climate change Hotspots” at subcontinental scale following the latter definition. For example, Giorgi (2006), Diffenbaugh et al. (2008), Giorgi and Bi (2009), Xu et al. (2009) and Diffenbaugh and Scherer (2011) used different regional climate change indexes including changes in mean and interannual variability of temperature and precipitation to calculate late 21st century climate change “hot-spots” based on the CMIP3 ensemble accounting for multiple GCMs, scenarios and realizations. Among the most prominent hot-spots identified were the Mediterranean Basin, Central America, Central Africa, the Northern high latitude regions, the southwestern United States, Southeast Asia and the Tibetan Plateau. A new climate change hot-spot analysis of the CMIP5 ensemble was carried out by Diffenbaugh and Giorgi (2012), who extended the methodology of Giorgi (2006) and Diffenbaugh et al. (2008) by adding metrics of seasonal extremes and considering the temporal evolution and emergence of hotspots (Figure 21.12). They found that the Amazon, the Arctic, the Sahel and tropical West Africa, and the Tibetan Plateau are persistent regional climate change hotspots which emerge early in the 21st century of the RCP8.5 forcing pathway and persist throughout the rest of the century, suggesting that they are robust to varying levels of global warming. Areas of southern Africa, the Mediterranean, and Central America/western North America also emerged as prominent regional climate change hotspots but mostly in response to high levels of forcing. This contrasting persistence and emergence of hotspots in response to increasing radiative forcing highlights the relevance of regional climate heterogeneity for climate change mitigation and adaptation strategies. Others have defined climate change hotspots as locations where impacts of climate change are ‘well pronounced and well documented’ (UCS 2011). De Sherbinin (submitted) notes that because hotspots often overlay projections of climate change with current vulnerability, there is a disconnect in timescales.

[INSERT FIGURE 21-12 HERE
Figure 21-12: The relative aggregate climate change between the 1975-2005 period and the 2010-2039, 2040-2069 and 2070-2099 periods of RCP8.5. The aggregate climate change is calculated using the Standard Euclidean Distance (SED) across the 28-dimensional climate space formed by 7 climate variables in each of 4 seasons. The absolute values of change in each variable are normalized to the maximum global absolute value prior to calculating the SED. The SED values are then normalized to the maximum global SED value. Only land grid points north of 60˚S are used in the normalizations (From Diffenbaugh and Giorgi 2012).]

Biodiversity and Conservation: A biodiversity hotspot – the original use of this concept – is a recognised unit of analysis for guiding policy and investment decisions, developed by Meyers (1988). It refers to a region that is biologically diverse and typically under some sort of threat from human activity, climate change, or other drivers.

Health and Disease: Hotspots of disease can describe incidence rates, death rates, areas where certain viruses are likely to emerge, among other things. They can be coupled to climate change, biodiversity change, population growth, human-animal proximity, or to other drivers. A study on emerging infectious diseases (EIDs) identified hotspots as regions where new EIDs are likely to originate, in order to guide decisions makers where to allocate global resources to pre-empt, or combat, the first stages of disease emergence (Jones et al 2008).

Disasters: Disasters hotspots are identified as geographic areas that are most vulnerable to hazards (Dilley et al 2006). The purpose of disasters hotspots is to encourage development agencies and policy makers to incorporate disaster risk management into investment plans and decisions (Arnold et al 2005).

Food production, Food security: Areas of food production that are affected by pressures such as urbanisation, environmental degradation, water scarcity or climate change can be identified as hotspots of food insecurity, such as by CGIAR CCAFS (Ericksen et al 2011). Similarly, adverse implications of agriculture on environment have been described as ‘agri-environmental hotspots’. FAO (2010) defines agri-environmental hotspots as ‘locations where human activities are detrimental to the sustainability of an ecosystem or the human activities depending on it’. The rationale for identifying such hotspots is that ‘they may gradually evolve into extremely tense socio-economic situations associated with a severe degradation of the natural resources base and food security’ (FAO 2010). Fraser et al (2013) combine hydrological modelling with quantitatively modelled adaptive capacity (defined as the inverse of sensitivity to drought) to identify vulnerability hotspots for wheat and maize.

21.5. Critical Analysis of Approaches to Regional Impacts, Adaptation, and Vulnerability Studies and Their Uncertainties

Assessing climate vulnerability or options for adapting to climate impacts in human and natural systems requires an understanding of all factors influencing the system and how change may be effected within the system or applied to one or more of the external influencing factors. This implies the need, in general, for a wide range of climate and non-climate information and then determining how this may be used to enhance the resilience of the system. Previous sections have defined the context in which these systems operate, synthesized key regional and cross-regional knowledge and issues. This section focuses on advances in the methods and information that underpin these findings, initially examining methods to study vulnerability and adaptation and assess impacts. This is followed by assessments of new information on, and thinking related to: (a) baseline and recent trends in factors needed to assess vulnerability and define impacts baselines; and (b) future scenarios used to assess impacts, changes in vulnerability and options for adaptation; and then assessment of the credibility of the various types of information presented.

21.5.1. Vulnerability and Adaptation Analyses

Multiple methodologies exist for assessing vulnerability and adaptive capacity (Schipper et al 2010, UNFCCC 2008) and many have now become well-established approaches. Choice of method is influenced by objective and starting point (see Table 21-3) as well as the type of information available. Qualitative assessments require different inputs from quantitative assessments. Qualitative information cannot always be translated to quantitative information, and vice versa, yet both qualitative and quantitative approaches can be used to answer the same questions.

The comparison of vulnerability and adaptive capacity across regions requires some common baseline from which to judge relative levels of vulnerability and adaptive capacity – a type of measurement. Measuring adaptive capacity has not been explored in the same way, and often adaptive capacity is assumed to be a component of vulnerability (based on the vulnerability definition in IPCC 2001). Qualitative and quantitative studies are used to identify why people are vulnerable and how, and are typically the basis for determining strategies for reducing vulnerability and adapting to climate change. Indicators have been used to make this comparison. This section reflects briefly on indicators.

Several attempts at developing vulnerability indicators and indices have been made (Birkmann et al. 2011; Chen et al. 2011; Barr et al 2010; Cardona, 2007; Luers et al 2003; Lawrence *et al.,* 2003, Villa and McLeod, 2002, Downing *et al.* 2001, Atkins *et al.,* 2000; Moss *et al.* 1999). Representation of vulnerability on a map or through an index is the most common way to show global vulnerability information and requires quantification of selected variables in order to measure them against a selected baseline, even though quantification of some qualitative information may not be possible (Hinkel, 2011; Edwards et al, 2007; Luers et al 2003,). Maps of vulnerabilities where hazards or projected climate change impacts are overlain with population density suggests that everyone has an equal probability of being affected by a hazard or by climate change impacts, ie. that everyone is equally at risk. Vulnerability is differentiated according to factors such as gender, age, livelihood or access to social networks (Cardona et al 2012; Wisner et al 2005), which can be a challenge to incorporate into indicators, and therefore choice of indicators of or proxies for vulnerability will determine what the result looks like. One approach that is used to create regional comparisons is an index approach that measures different variables to create indicators of vulnerability. The index is the composite of several normalised indicators (Rygel et al 2006, Adger et al 2004). The approach has been critiqued extensively because giving different weights to the indicators depends on expert opinion and this can result in different countries appearing more or less vulnerable, as Fuessel (2010) found in reviewing different vulnerability maps. Lack of full understanding of what drives vulnerability means that indicators can give misleading or incorrect information about vulnerability (Böhringer and Jochem, 2007).

Luers et al (2003) propose the idea of ex-post measure of vulnerability, using the number of people killed in a storm as an indicator that they were vulnerable. A deductive analysis of the situation would suggest that they were killed because (a) they were exposed to the storm, (b) they were sensitive to the storm, (c) they had low capacity to escape the storm or (d) the storm had a very high impact. However, a low impact storm could also result in deaths if the people were especially sensitive or exposed. Their deaths could also simply be explained by being in the wrong place at the wrong time, which suggests that ex-post analysis can indicate only the state of vulnerability of the people killed at the moment they were killed, and not anything else. Conversely, an ex-ante analysis of vulnerability to a storm might suggest that old people, people who will not want to evacuate their houses because they do not want to risk losing their assets (such as livestock) or people who have a lack of knowledge of where to go and what to do in an emergency, would be the most sensitive and exposed. Even with these characteristics, the outcome does not necessarily lead to death, since they could also be rescued, their area could be unaffected by the storm, or they could survive anyway. In other words, identifying a single characteristic or even several may not give a sufficient picture of vulnerability for decision making, even on a local level.

Vulnerability indicators developed to date have been unable to reflect the dynamic nature of the various variables used as indicators. This is illustrated in the case of the (in)ability to characterise how the selected indicators contribute to determining vulnerability over time. Importantly, the relative importance of the indicator may change from season-to-season (eg, access to irrigation water) or gradually or rapidly become obsolete. Hinkel's (2011) review of literature on vulnerability indicators suggests that vulnerability has been confused as a proxy for unsustainable or insufficient development, which means that simple measurements are seen as sufficient to tell a story about vulnerability. Hinkel (2011) suggests that the simplification of information to create vulnerability indicators is what limits the utility of vulnerability indicators.

Adaptation is considered to be tightly linked with development (Adger et al 2003b, Schipper 2007) and a significant portion of adaptation approaches emerge from activities in developing countries. The metrics of adaptation is a topic of considerable interest for the purpose of funding prioritisation, monitoring progress in adjusting to climate change and identifying suitable adaptation options (IGES 2008).

Adaptation assessment as a process is described more extensively in chapters 2, 14, 15, and 17, and this section addresses the usefulness of indicators for understanding adaptation at a regional and global level. Most adaptation assessments rely on assessing adaptive capacity (Yohe and Tol 2002), based on some variables that are often transformed into indicators, success of implementation of adaptation projects (often also based on a set of indicators) or 'functions' that countries should follow to attain resilience (WRI 2009).

As a way of understanding adaptive capacity further, numerous types of indicator systems have been developed. These are used both to measure adaptive capacity as well as to identify entry points for enhancing it (Adaptation

Sub-Committee, 2011; Lioubimtseva and Henebry, 2009; Swanson et al., 2007; Adger and Vincent, 2005; Eriksen and Kelly, 2007) For example, the Global Adaptation Index, developed by the Global Adaptation Alliance (GAIN, n.d.) uses a national approach to assess vulnerability to climate change and other global challenges and compare this with a country's 'Readiness to improve resilience' (GAIN, n.d.) for the purpose of assisting public and private sectors to prioritise financial investments in adaptation activities.

Indicators can be a useful starting point for a discussion on what qualifies as an appropriate proxy for capacity, in order to determine what sort of factors act as barriers and drivers. When rooted in the poverty and livelihoods discourse on vulnerability (Chambers, 1989; Swift, 1989), proxies for capacity look very similar to indicators of development, despite the significant argument about the causal structure of vulnerability, which underscores that vulnerability is not the same as poverty (Chambers, 1989; Ribot, 1996). Resources may be for enhancing 'the capacity and endurance of the affected people to cope with adversities' (Ahmed and Ahmad 2000: 100), but equating vulnerability with poverty creates a false association between lack of development and lack of capacity (Magnan, 2010).

A special case of the use of indicators concerns the identification of hotspots. This is a concept used in numerous fields to describe locations that stand out as important for the analytical lens that is being applied (see section 21.4.4, above). The purpose of doing hotspot analysis varies across different fields, but they are typically the outcome of the combination of different sets of variables with a geographical reference. In climate change, hotspots are being used with increasing frequency to help distinguish priority locations for funding (de Sherbinin, submitted). The presentation of hotspots differs according to multiple factors, including the scale of analysis (from specific houses to entire ecosystems), the number of variables examined (two or more), whether the information refers to measured or projected hotspots. Hotspots can contrast with "cool spots", where the inverse situation can be found, and can be ranked when they are derived from numerical values (e.g., number of crimes committed). Hotspots are another way of comparing regions, and the subjective nature of ranking locations as more urgent for climate change investment than others is controversial and can be considered politically-motivated (Klein 2009). In part, this is also because the identification of hotspots raises important methodological issues, discussed earlier in this section, with regard to the limitation of using indicators to give an illustration that integrates impacts with qualitative dimensions of vulnerability. De Sherbinin (submitted) points out that hotspot maps are commonly used as communications tools, but the tentative nature and the on-going process of knowledge generation that they represent is frequently not understood by the audience, who see the maps as a description of how things are or will be.

Certain areas are considered hotspots because of their regional or global importance. These can be defined by population size and growth rate, contributions to regional or global economies, productive significance (e.g., food production) as well as by disaster frequency and magnitude, and projected climate change impacts. Variables identified to represent these issues can be controversial, and relationships between variables may not always be fully understood. For instance, the CCAFS hotspot map introduced in section 21.4.4 uses stunted growth as a proxy for food insecurity (Ericksen et al 2011), but other variables could also have been selected, and could have resulted in different locations being identified as hotspots (Füssel, 2009). Scale matters in representing hotspots and will look differently on a global scale than on a finer scale (Arnold et al., 2006).

21.5.2. Impacts Analyses

In recent years, as adaptation considerations have risen up the policy agenda, there has been increased scrutiny of the methods and tools applied in impact assessment, especially quantitative models that are used to project the biophysical and socio-economic impacts of future climate change (see chapter 2), but also encompassing qualitative methods, including studies of indigenous knowledge (Galloway McLean, 2010, and see chapter 12). In an advance from previous assessments, different types of impact models are now being applied for the first time in many regions of the world. This is largely due to burgeoning international development support for climate change vulnerability and adaptation studies (Fankhauser, 2010). It is also related to a surge of interest in regional economic assessments in the wake of the Stern review (Stern, 2007) as well as to the evolution of climate models into earth system models that incorporate a more realistic representation of land surface processes (Flato *et al.*, in prep.) and their increased application to study hydrological (chapter 3), ecophysiological (chapter 4) and cryological (chapter 28) impacts.

21.5.2.1. Framing of Impact Studies

Potential impacts have been simulated for single as well as multiple sectors, at spatial scales ranging from site or household to global, and over a range of temporal scales and time horizons (Table 21.3). A majority of impact studies still follow the conventional approach described in section 21.2.3 (left hand side in Table 21-3), whereupon future impacts are modelled based on a set of assumptions (scenarios) about future climate and socioeconomic conditions. However, an increasing number of impact studies are being undertaken that follow a "socio-institutional" approach to adaptation planning (Downing, 2012) as reflected on the right hand side of Table 21-3, which emphasises adaptive flexibility and climate resilience as an acknowledgement of the often intractable, "deep" uncertainties implicit in many projections of future change (e.g., Donley *et al.*, 2012; Garrett *et al.*, 2013; Gersonius *et al.*, 2013).

Adaptation assessment is addressed in section 21.5.1, but it should be noted that impact modelling studies commonly treat aspects of adaptation as well, either explicitly as modelled options, or implicitly as built-in autonomous responses (Dickinson, 2007; White *et al.*, 2011). Furthermore, with an anthropogenic signature being attributed to ongoing climate changes in many regions (Bindoff *et al.*, in prep.), and with growing evidence that these changes are having impacts on natural and human systems in many more regions of the world than reported in the AR4 (chapter 18, and see Rosenzweig and Neofotis, in press), there is now a real possibility in some regions and sectors to test the projections of impact models against the observed impacts of recent climate change (e.g., Araújo *et al.*, 2005; Barnett *et al.*, 2008; Lobell *et al.*, 2011), which is also an essential element in the attribution of observed impacts (see chapter 18).

21.5.2.2. Uncertainties Attributable to Future Climate Projections

Much of the literature regarding uncertainty in impacts analyses has focused on the uncertainties in impacts that result from the uncertainties in future climate (Mearns et al., 2001a; Carter et al., 2007), and this literature continues to grow since AR4, particularly in the realm of agriculture and water resources (e.g., Wetterhall et al., 20011; Ferrise et al., 2011; Ficklin et al., 2012; Littell et al., 2011, Osborne et al., 2013), but also in other areas such as flood risk (Ward et al., 2013). Furthermore, research has moved forward to establish which uncertainties about future climate are most important to the resultant uncertainties about crop yields (e.g., Lobell and Burke, 2008). These uncertainties regarding future resources have now been applied to adaptation studies as well (Howden et al., 2007).

The use of a greater number of climate scenarios either from global or regional models is now found in many more studies. For example, in the area of impacts of climate change on water resources a number of studies have used more global models (Gosling et al., 2010; Bae et al., 2011; Arnell, 2011) or ensembles of regional climate models (Olsson et al., 2011), and thus present estimates of impact for between 10-25 different climates for a given emissions scenario. The use of probabilistic quantification of climate uncertainties has produced estimates of probabilities of changes in future resources such as agriculture and water (e.g., Watterson and Whetton, 2011; Tebaldi and Lobell, 2008). Some studies have developed probability distributions of future impacts by combining results from multiple climate projections and, sometimes, different emissions scenarios, making different assumptions about the relative weight to give to each scenario (Brekke et al., 2009).

Nobrega et al. (2011) apply a number of pattern-scaled GCMs to study the impacts of climate change on water resources in the Rio Grande Basin in Brazil. They used 6 different GCMs and 4 different SRES emissions scenarios and applied them to a large-scale hydrologic model, and found that choice of GCM was the major source of uncertainty in terms of river discharge. Through the CLARIS project (Menendez et al., 2010) multi-regional model climate change scenarios over South America will soon be used for a wide range of climate change impacts studies (e.g., Dengue fever, Degallier et al., 2010).

21.5.2.3. Uncertainties Attributable to Impact Models

With an ever-increasing number of projections of future climate change impacts appearing in the literature, and considering the unprecedented rate and magnitude of climate change projected for many regions, some authors have begun to question both the robustness of the models being applied (e.g., Heikkinen *et al*., 2006; Fitzpatrick and Hargrove, 2009; Watkiss, 2011a) as well as the methods used to represent key uncertainties in model projections (e.g., Arnell, 2011; Rötter *et al*., 2011; White *et al*., 2011). This may reflect a relative low level of co-ordinated activity in the testing and intercomparison of impact models since the mid-1990s, following earlier efforts in the International Geosphere Biosphere Programme (e.g., Kabat *et al*., 1995; VEMAP Members, 1995; Jamieson *et al*., 1998) and other notable exceptions (e.g., Mearns et al., 2001b; Tebaldi and Lobell, 2008). However, in recent years there has been a strong resurgence of interest and activity, with several prominent international research efforts initiated, including the Agricultural Model Intercomparison and Improvement Project, involving crop and economic models at different scales (AgMIP – Rosenzweig *et al*., 2013), the Carbon Cycle Model Intercomparison Project (C^4MIP) and its follow up (Friedlingstein *et al*., 2006; Sitch *et al*., 2008; Arora *et al*., 2013) and the Water Model Intercomparison Project (WaterMIP – Haddeland *et al*., 2011). Modelling groups from these projects are also participating in the Inter-Sectoral Impact Model Intercomparison Project, which is focusing initially on intercomparing global impact models for agriculture, ecosystems, water resources, health and coasts under RCP- and SSP-based scenarios (see Box 21-1), but will also consider regional models in a second phase of work (ISI-MIP – Schiermeier, 2012).

For example, in AgMIP preliminary results looking at five different wheat models at a site in Mexico indicate that the results for projections of yield to the mid-21st century are more sensitive to the differences in the crop models than to the differences among the different global climate models used (Rosenzweig et al., 2013). WaterMIP compared five global hydrologic and six land surface models to determine the uncertainty across these models in a climate change context for hydrological variables such as runoff and evapotranspiration. Results comparing the models for an observed period indicated substantial differences in the models' estimates in these key parameters (Haddelenad et al., 2011).

21.5.2.4. Effect of Combined Uncertainties

As is standard practice in climate modelling, a growing number of researchers are now applying multiple impact model and perturbed parameter ensemble approaches to future projections (e.g., Araújo and New, 2007; Jiang *et al*., 2007; Palosuo *et al*., 2011), usually in combination with ensemble climate projections treated discretely(e.g., New *et al*., 2007; Graux *et al*., 2013; Tao and Zhang, 2013) or probabilistically (e.g., Luo *et al*., 2007; Fronzek *et al*., 2009; Børgesen and Olesen, 2011; Ferrise *et al*., 2011; Wetterhall *et al*., 2011).

21.5.2.5. Evaluating the Robustness of Impact Models

Drawing inspiration from more than two decades of internationally co-ordinated efforts by climate modellers in the Atmospheric (AMIP) and then Coupled (CMIP) Model Intercomparison Projects (Gates *et al*., 1998; Meehl *et al*., 2005; Taylor *et al*., 2012), these new impact MIPs, and other initiatives like them, have the common purpose of mobilising the research community to address some of the long-recognised but pervasive problems commonly encountered in climate change impact modelling. A sample of recent papers illustrate the variety of issues being highlighted, including forest model typology and comparison (Medlyn *et al*., 2011), crop pest and disease modelling and evaluation (Sutherst *et al*., 2011; Garrett *et al*., 2013), modelling responses to extreme weather events (Lobell *et al*., 2010; Asseng *et al*., submitted), field experimentation for model calibration and testing (Long *et al*., 2006; Craufurd *et al*., 2013) and data quality considerations for model input and calibration (Lobell, 2013). Greater attention is also being paid to methods of economic evaluation of the costs of impacts and adaptation. Cost estimates have been reported at scales ranging from global (e.g., UNFCCC, 2007; Nelson *et al*., 2009; Parry *et al*., 2009; Fankhauser, 2010; Füssel, 2010; Patt *et al*., 2010), through regional (e.g., EEA, 2007; World Bank, 2010; Ciscar *et al*., 2011; Watkiss, 2011b), to national (SEI, 2009; GCAP, 2011) and local level (e.g., Perrels *et al*., 2010).

21.5.3. Scenario Development and Application

21.5.3.1.Baseline Information and Context – Current State and Recent Trends

This section deals with defining baseline information relevant to the assessment of climate change vulnerability, climate change impacts and adaptation to climate change. Baseline here means the reference state or behaviour of a system, e.g. the current biodiversity of an ecosystem, or the reference state of factors (such as climate elements or agricultural activity) which influence that system (see also Glossary entry). In the pure climate context, the phrase pre-industrial baselines is used to define the (reference state of the) climate prior to changes in the atmospheric composition (from its baseline pre-industrial state), for example when the UNFCCC defines a reference for measuring global average temperature rises. An historical baseline refers to climate of a particular period, e.g. a WMO climate normal period such as 1961-1990 as a reference to define climate changes in recent decades, and if derived from a climate model then the model would include consistent changes in atmospheric composition. In an adaptation context, a baseline could be the impacts on a system under a given amount of climate change prior to changes in non-climate factors (e.g. improved early warning systems, modified infrastructure) aimed at reducing the impacts. This section does not consider methods for calculating baselines involved in assessing vulnerability of, impacts in and adaptations to systems – but methods for deriving the information on climatic and non-climatic factors used to calculate these baselines.

There are several important properties of baselines to consider when assessing methods to derive relevant information. Defining a reference state sufficiently well that it provides for a good measure of a system’s vulnerability or for testing whether significant changes have taken place often requires that much of the variability of the system needs to be captured. Thus the information used to establish this reference state must account for the variability of the factors influencing the system; in the case of climate factors often this requires 30 years of data and sometimes substantially more (e.g. Kendon et al., 2008). Also the temporal and spatial properties of the system under investigation will influence the information required to establish a reliable baseline. Many systems operate at or depend on high resolution information, for example the high spatial resolution of urban drainage systems or organisms within an ecosystem sensitive to temperature extremes require information at the sub-daily time-scale.

Clearly, in defining baselines for assessing climate change impacts, vulnerability or adaptation, a wide range of information will be required as the systems being studies generally comprise interacting physical and human components influenced by climatic and non-climatic factors. For example the assessment of options to respond to river flooding will require information on some or all of the following: past and future rainfall/river flow sequencing and river channel modifications; likelihood of riverside development; viability of property insurance; regional or national finances; effectiveness of relevant institutions. In this case information is required on climate and other physical aspects of the system as well as social and economic factors, and this will generally be so. The rest of this section then assesses methods to derive climatic and then non-climatic information relevant to establishing these baselines and the reliability of this information.

21.5.3.1.1 Climate baselines and their credibility

Fundamental to the study of climate change impacts is to establish an “impact baseline”, the behaviour of the system under a reference climate. The baseline information defining this reference climate may be derived from either or a combination of observations or models, with the spatial and temporal resolution generally prescribed by the source, and the choices generally depending on the application. For example Challinor et al. (2004) use observed weather inputs at the daily timescale and coarse spatial resolution with a crop model to demonstrate its ability to simulate a realistic range of yields under historical climate variability to motivate using the model to estimate quantitatively the effect on yields of perturbed climates (e.g. Challinor et al., 2006). Arnell et al. (2003) used a range of climate baselines to study the effect of different choices on the characteristics and ranges the impacts (and paid less attention to the validation of the impacts baselines). In a further example Bell et al., (2009) use high quality observed data at daily timescale and 5 km resolution to demonstrate the ability of a river flow model to simulate an accurate baseline over a 1km river network in order to establish confidence in the impacts model. This is then used with less accurate climate model-derived baselines that are then compared with results when using climate-model derived futures (Bell et al., 2012). In this case the impacts model is being used with plausible time-series of climate variables to derive realistic (though not necessarily accurate) high resolution baseline and future river flows and thus ranges of climate change impacts which can be considered realistic responses to the imposed climate perturbations. In a more comprehensive study of impacts of climate change in selected UK rivers, Kay and Jones (2012) used different baselines from the UKCP09 scenarios (Murphy et al., 2009) and noted that the changes were similar when using either weather generator or RCM baseline information. However, a greater range of projected changes resulted when using high time-resolution (daily rather than monthly) information (Figure 21-13), underscoring the importance of including the full spectrum of climate variability when assessing climate impacts.

[INSERT FIGURE 21-13 HERE
Figure 21-13: The range of percentage change in flood peaks for nine UK catchments at the a) 2-year and b) 20-year return period. Box-and-whisker plots are used to summarise results when using 10,000 UKCP09 Sampled Data (Murphy et al. 2009) change factors (red) and 100 sets of UKCP09 current and future Weather Generator time-series (cyan). Also plotted, are the results when using 11 sets of RCM-derived change factors (red crosses) and when using 11 sets of RCM current and future times-series (green rectangles). The box delineates the 25th-75th percentile range and the whiskers the 10th-90th percentile range, with the median (50th percentile) shown by the line dividing the box. Additional markers outside the whiskers indicate the minima and maxima, if within the plotted range of -50 to +100. The points derived from the RCM results are joined for the corresponding members of the RCM ensemble (grey lines), and the medians for these methods are shown by black horizontal bars.]

These examples show that a good description of the baseline climate, i.e. in general including information on its variability on timescales of days to decades, is important for developing the reference state or behaviour of a climate-sensitive system for determining impacts on or the vulnerability of the system. This has motivated significant efforts to enhance the quality, length and homogeneity of observed climate records (also important for monitoring, detecting and attributing observed climate change, AR5-WG1 Chapter 2-5 and 10)) and to make these data more easily available. This has included derivation of new observational datasets such as APHRODITE (a gridded rain-gauge based dataset for Asia, Yatagai, et al., 2012), coordinated analysis of regional climate indices and extremes by CLIVAR's ETCCDI (http://www.clivar.org/organization/etccdi, see e.g. Zhang et al., 2011) and data rescue work typified by the ACRE initiative (Allen et al., 2011) which has resulted in analysis and digitization of many daily or sub-daily weather records from all over the world. For some datasets error estimates have been developed (e.g. Morice et al., 2012 for the HadCRUT near-surface temperature record) and for others such as precipitation, increased focus on improving existing datasets such as GPCC (Rudolf et al., 2011) and developing new ones (e.g. TRMM (Huffman et al., 2010) or APHRODITE, Yatagi et al.; 2012) enables observational uncertainty to be estimated. This allows us to more accurately quantify the amplitude of natural variability important for detecting trends or establishing impacts or vulnerability baselines.

Another area of significant progress has been in the development of improved and new global reanalyses. These use weather forecast models constrained by observations from across the globe and available through a period of time to reconstruct the evolution of the weather over the globe. A significant new development in this field has been the use of digitized surface pressure data from ACRE by the 20th Century Reanalysis (20CR) project (Compo et al., 2011) to reconstruct the global evolution of the weather from 1871 to present day. 20CR provides the basis for, at any location, estimating historical climate variability from the sub-daily to the multi-decadal timescale (Figure 21-14) and hence developing robust estimates of the baseline sensitivity of a system to the climate and addressing related issues such as establishing links between historical climate events and their impacts. Other advances include new reanalyses (http://reanalyses.org/) with a focus on developing higher quality reconstructions for the more recent period. They include a new European Centre for Medium Range Weather Forecasts (ECMWF) Reanalyses (ERA) dataset, ERA-Interim (Dee et al., 2011) for the period 1979-2011, the NASA Modern Era Reanalysis for Research and Applications (MERRA), 1979-present (Rienecker et al., 2011), the NCEP Climate Forecast System Reanalysis (CFSR), 1979-Jan 2010 (Saha et al., 2010) and regional reanalyses such as the North American Regional Reanalysis (NARR) (Mesinger et al., 2006) and EURO4M (http://www.euro4m.eu/).

Variables from the first generation of reanalyses often contained discontinuities in time (often resulting from changes in the observations they used) thus clearly were not suitable for defining trends (Thorne and Vose, 2010) and needed to be used with caution to define climate baselines. In addition, reanalyses combine observations, generally with global coverage, with models and thus those outputs less directly constrained by the observations are subject to model error. For example, precipitation derived from the ECMWF's ERA15 and ERA-40 reanalyses did contain significant biases which have been much reduced in the more recent ERA-Interim dataset (Dee et al., 2011). As with recent efforts on observational datasets, the production of several reanalyses from different international centres (AR5-WG1 Box 2.3) means that the uncertainty in their of climate baselines can be estimated. In the case of 20CR (Compo et al., 2011) a 56 member ensemble of reconstructions was calculated. This is useful in assessing the credibility of the reanalysis in the regions in the early part of the 140-year reconstruction where there were sparse (or no) observations and also to give an estimate of the inherent uncertainty in detail provided by these reanalyses even where there are good observations.

[INSERT FIGURE 21-14 HERE
Figure 21-14: Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann etal. (2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis and model sources: statistical reconstructions of the PWC, the PNA and the NAO, see Brönnimann et al. (2009) for details, (all cyan); 20CR (pink); NCEP–NCAR reanalyses (NNR; dark blue); ERA-40 (green); ERA-Interim (orange). The dark-grey dashed line and grey shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed seas-surface temperatures and sea-ice from the HadISST dataset (Rayner et al. 2003), see Brönnimann etal. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea-surface temperature and sea-ice alone and demonstrate that the reanalyses have significantly higher skill in reproduces these modes of variability.]

As noted in the introduction, the scale of the system being investigated often implies the need for high temporal and spatial resolution climate information, either observed or simulated, to calculate its baseline or reference behaviour. Observed high-resolution climate baselines are not available in many regions or for all variables required (e.g. Washington et al. 2006, World Weather Watch 2005). Even when datasets exist, they often only provide monthly mean data and thus lack temporal variability and often lack sufficient spatial resolution. The recent reanalyses provide globally complete and temporally detailed reconstructions of the climate of the recent past but generally lack the spatial resolution which would enable them to represent the fine details of weather events often important when modeling the response of systems sensitive to climate. However, they can be combined with either statistical or dynamical downscaling (see e.g. Maraun et al., 2010, AR5-WG1 Chapter 9) to provide higher resolution simulations of the variables required consistent with the (usually reasonably accurate estimate of the) large-scale drivers from the reanalyis. Available observations can then be used to estimate the error in the downscaled simulation.

An example of this methodology is given by Duryan et al., 2010 for West Africa who analyse results from nine regional climate models driven by ERA-Interim for the period 1990-2007 for a region encompassing West and much of Central Africa. Many models show significant biases (Figure 21-15) and thus may not be considered sufficiently accurate to provide the required additional detail on the climate baselines for the region. Advances in this area should be expected through the WCRP-sponsored Coordinated Regional Downscaling Experiment (CORDEX) project (http://wcrp.ipsl.jussieu.fr/SF_RCD_CORDEX.html and see Giorgi et al., 2009) with the initial experiment recommended being to apply the downscaling methods to the ERA-Interim over all land and enclosed sea areas using common domains for dynamical downscaling.

[INSERT FIGURE 21-15 HERE
Figure 21-15: Observed 1990-2007 annual precipitation climatology from GPCC (Rudolf et al., 2011), top left, and, in the remaining panels, related systematic errors in 9 individual regional climate model simulations driven by the ERA-Interim reanalyses (Dee et al., 2011) and in the multi-model ensemble mean (Duryan et al., 2010).]

Climate baseline information can also be derived directly from climate models, either global models or via downscaling of their outputs. Significant international activity on establishing the credibility of the climate simulations of these models is enabled through the coordination activities of the Coupled Model Intercomparison

Project (e.g. CMIP5, Taylor et al., 2009) and has shown improvements in the quality of this information since AR4 (AR5-WG1 Chapter 9). The issue raised above of credibility of climate information from a spatial resolution perspective is relevant here, though there has been some improvement since CMIP3/AR4 with many of the models now running at 100-150km resolutions. Again, this may be addressed by downscaling these simulations (which has been facilitated by improved data capture from the CMIP5 models for CORDEX, Giorgi et al., 2009) and the credibility of this information can be established by similar validation procedures (AR5-WG1 Chapter 9). In theory, one would expect that validation of a reanalysis downscaling should provide a more accurate picture of a models performance though this can be complicated by reanalysis errors (Cerezo-Mota et al., 2010) or differences between reanalyses (Mearns et al., 2012).

With downscaling providing climate baselines at high temporal and spatial resolutions, these can be used directly to assess the impacts of the projected high-resolution climate changes. Historically, the more usual approach has been to use observed baselines and then add climate changes derived from climate projections to these and then calculate the impact using this perturbation of the observed baselines. This was the only viable approach to take when high resolution input data were required to assess impacts or vulnerability and only coarse resolution GCM-based projections were available. Now high-resolution projections are becoming increasingly available both direct and perturbed baseline approaches can be used (see e.g. Kay and Jones, 2011). The direct approach has the disadvantage that the baseline climate will often contain significant errors and their influence on the calculated impact will need to be addressed. The perturbed baseline approach has the disadvantage that in order to calculate a plausible future climate accounting for the full detail of projected climate change the perturbations applied should account for changes in those aspects of climate variability that the system being studied is sensitive to (see e.g. Hawkins et al., 2013). Thus it is important to consider not just the quality of the baseline but what influence the choice of baseline may have on the assessment of vulnerability or the calculation of climate change impacts.

21.5.3.1.2. Non-climatic baselines and their credibility

Given the diversity of non-climatic influences on many climate-sensitive systems baseline information on a wide range of factors will often be required. For example agriculture, water resources, ecosystems and health are all affected by a diverse range of (non-climatic) physical factors and socio-economic influences. Example of physical factor are availability of irrigation systems for agriculture, effectiveness of disease prevention, atmospheric composition (e.g. affecting air quality or CO_2 availability for plant growth) and land-cover/use (e.g. defining the urban environment or availability of agricultural land). Relevant socio-economic factors include demography, level of social, educational and economic development, political/governance background and available technology. Thus to provide a comprehensive assessment of how or whether a climate-sensitive system can adapt to climate change it is necessary to assess its vulnerability in respect of all non-climatic factors that may influence it and information is required on the baseline state of these factors to enable the reference behaviour of a system to be established. (See also TAR WG2 Chapter 13 and AR4 WG2 Chapter 2.)

Significant work has been undertaken to collect and make this information available. For the socio-economic factors, local and national governments and international agencies (e.g. UN agencies, World Bank - http://data.worldbank.org/data-catalog) have been collecting data on the human-related factors for many decades and similarly information on technological developments is widely available. In some situations these factors are evolving quickly and the baseline is taken as the reference state at a particular point in time rather than aggregated over a longer period. In the case of the physical factors, information on many of these have been refined and updated as they are critical inputs to deriving the climate forcings in the Representative Concentration Pathways (RCPs, van Vuuren et al., 2011) used in the CMIP5 (Taylor et al., 2009) experiments. For example these included updated information on land-use change (Hurtt et al., 2011), atmospheric composition (Meinshausen et al., 2010) and aerosols (Grainer et al., 2011, Lamarque et al., 2011). Other aspects of the physical environment in many areas have been well-studied and detailed records are available (e.g. through improved satellite observations and observational processing or via research by international bodies e.g. FAO assessing agriculture and forestry systems). However, much like with climate observations, there are still areas of the world which are less well-observed where rescuing and/or making available old records of the physical environment is of significant value as is making new or more detailed observations.

Given the multi-stressor environment in which assessments of climate change vulnerability and adaptivity are being made, there needs to be consideration of multiple plausible non-climate futures. In this situation a future baseline can be defined, e.g. a given socio-economic scenario, to establish, along with future climate scenarios, a reference state of future vulnerability or adaptive capacity. This then allows the impact of alternative socio-economic futures, such as the story-lines associated with the Special Report on Emissions Scenarios (SRES, IPCC, 2000) and the new Shared Socio-economic Pathways (SSPs), on future vulnerability or adaptation options to be assessed.

A key step in assessing adaptation to climate change in a system is defining information on the non-climatic factors which influence its vulnerability: i.e. the importance of the non-climatic baseline information being assessed here is how it defines the baseline vulnerability of the system and so how changes in these factors can allow it to adapt to climate change, i.e. compensate for/take advantage of increased/reduced climate vulnerability. Given the diversity of climate-sensitive systems as explained above, it is not possible to assess methods for deriving all non-climatic baselines relevant to vulnerability and adaptation studies.

In some cases, this information will be able to be derived from available data sources and in other cases it will be deficient (e.g. in resolution) or missing. The rest of this section will concentrate on presenting several studies which demonstrate some of these cases as a guide to the importance of relevant non-climatic baselines and how they can be derived and interpreted.

The issue of establishing an appropriate non-climatic baseline, in this case in the physical environment, is illustrated in the example of a study of climate change impacts on flow in the River Thames in the UK. Despite increases in temperature and a major change in the seasonal partitioning of rainfall over the Thames basin there is no long-term trend in annual maximum flows over a 126 year series (Marsh 2004). In the 19th century summer rainfall was on average greater than in winter, a situation reversed by the end of the 20th century due to respectively negative and positive precipitation trends which would be expected to have influenced maximum flows. An investigation of the physical environment found that it had been significantly modified as part of river management activities with increases in channel capacity of 30% over 70 years leading to fewer floods in the lower Thames. In this case, establishing the current level of vulnerability of the Thames to flooding required a detailed investigation to determine the appropriate baseline for the physical factor (river channel capacity) influencing this vulnerability.

Another example involves a study of the potential for adaptation in response to projected climate change impacts on crop yields (Challinor et al., 2009). The relevant non-climatic factor in this case was technological, the availability of alternative crop varieties. Detailed field studies demonstrated that the current germplasm included varieties with a wide range of tolerance to higher temperatures (Badigannavar et al., 2002). This established an agricultural technology baseline which demonstrated the potential to reduce vulnerability in the system to compensate for the projected climate change impact.

The relevance of future baselines is demonstrated in the assessment of the economics of climate change as presented in the report of the same name, also known as the Stern report (Stern 2007). For example, a baseline of technological improvement was assumed in determining the costs of mitigation. Also, as noted by Mendelsohn (2007), it makes assumptions (i.e. defines a baseline) about future economic growth in order to establish the costs of projected impacts or damages. In such cases, applying variations from these baselines allows the sensitivity of the findings of such studies to the proposed future baselines to be tested.

21.5.3.2. Development of Scenarios and Projections

Since the AR4 there have been several new developments in the realm of scenarios and projections: 1) a new approach to the construction of global scenarios for use in climate change analysis, initiated with the development of representative concentration pathways (RCPs); 2) the development and application of a greater number of higher resolution climate scenarios from regional climate model simulations; and 3) further use of multiple scenario elements as opposed to use of climate change scenarios only and greater focus on multiple stressors. Scenarios of land-use change are also deserving of more attention and are also discussed below.

21.5.3.2.1. New approach to scenario development

For both the TAR and AR4, the main socio-economic and emissions scenarios used were derived from SRES (Nakicenovic et al., 2000). More recently a new approach to developing climate and socio-economic scenarios was adopted. This new approach changed the familiar linear structure, wherein socio-economic scenarios were constructed, these were used to calculate emissions through application of Integrated Assessment Models (IAMs), and from the concentration of greenhouse gasses and aerosols, climate models would simulate the climate response to the forcings. In the new approach, concentrations of greenhouse gases were developed first (Representative Concentration Pathways, Moss et al., 2010), which allowed the climate modeling work to proceed much earlier in the process. Different possible socio-economic pathways were to be determined later, and it was recognized that more than one socio-economic pathway could lead to the same concentrations of greenhouse gases and aerosols. The process of determining the socio-economic scenarios is ongoing (US NAS, 2010). Four different RCPs were developed, corresponding to 4 different levels of forcing (by 2100) based on watts/m2: RCP 8.5, 6.0, 4.5, and 2.6. These embrace the range of scenarios found in the literature, and they also include explicit stabilization strategies, which were missing from the SRES set. In addition, a set of Shared Socio-economic Pathways (SSPs) is being developed that would characterize a wide range of possible development pathways. More information on these scenarios may be found in Chapter 19 (Box 19-3) of WG2, the WG3 Report, and WG1, Chapter 12, section 12.3.1.3, and Box 21-1 in this chapter. However, due to the time lags that still exist between the generation of the climate change scenarios, and completion of the development of the related socio-economic scenarios, few of the impacts/adaptation studies assessed in WG2 actively use these scenarios. Most of the assessed literature is still based on the SRES climate and socio-economic scenarios

21.5.3.2.2. High-resolution scenarios

There have been large numbers of new simulations with regional climate models (see section 21.4.1.1), e.g., over Europe (ENSEMBLES), over North America (NARCCAP), over Asia (RMIP), over South America (CLARIS and Marengo et al. 2011), over India (HIGHNOON), and these are now being used in impacts and adaptation studies (e.g., Miles et al., 2010, Morse et al., 2009). The CORDEX program (Giorgi et al. 2009) is providing an international coordination of high resolution dynamical downscaling of the CMIP5 global models for all regions of the world. The continent of Africa has been the point of departure for the program, but as indicated in section 21.4.1.1, a number of simulations over Europe, and other continents have also already been produced.

There have also been applications of simpler downscaling techniques (e.g., the delta method, Mearns et al., 2001; and the Bias Correction Spatial Disaggregation method, BCSD, Maurer et al., 2002, 2007). The desire for higher resolution information is largely assumed to result from the needs for impacts and adaptation, but of course, particularly with regard to dynamical downscaling, the purpose is often to produce superior simulations that take into account higher resolution forcings, such as complex topography (e.g., Salathé et al., 2010) or more details in land-atmosphere feedbacks such as in West Africa (Taylor et al. 2011). Applications of some of these new higher resolution results are discussed in the section below. It must be noted that the different means of attaining high resolution climate information for use in impacts and adaptation studies have been noted for a long time (e.g., Giorgi and Mearns, 1991; Giorgi et al, 2001) but there remains many uncertainties on the relative merits of these different techniques, and particularly a paucity of information on when to use what method.

Application of high-resolution climate information

There are now a number of studies that have used dynamically downscaled information of impacts and adaptation planning. A rather complete analysis of climate impacts including possible adaptations in the Pacific North West of North America was recently conducted (Miles et al., 2010) that used both simple downscaling of the global climate model simulations from CMIP3 (Mote and Salathé, 2010) but also two different dynamically downscaled scenarios (Salathé et al., 2010). The dynamically downscaled scenarios were particularly useful for the assessment of effects of climate change on storm water infrastructure (Rosenberg et al., 2010). Other aspects of the future aside from climate change were used in some of the sectoral analyses, such as population increase to 2025 for effects of climate on energy resources (Hamlet et al., 2010) and climate change along with air pollution scenarios for effects on human health (Jackson et al., 2010 The European PESETA program (Christensen et al. 2012) employed several RCM climate change simulations from the PRUDENCE program to investigate the impacts of climate change over Europe for agriculture, river flooding, human health, and tourism.

The ENSEMBLES project (Christensen et al., 2010) and its suite of high resolution climate projections have spawned a number of impacts studies, such as the effect of climate change on potential energy demand for heating and cooling in the Mediterranean, forest fire risk in Fennoscandia, property damage due to wind storms, crop yields and water resources in Poland, and risk of wheat yield shortfall in the Mediterranean region (Morse et al., 2009). Means of assessing risks of impacts using probabilistic information formed part of many of these projects.

The ENSEMBLES project and AMMA project (Polcher et al., 2011) developed a strong collaboration in order to provide new regional climate scenarios for use in impacts studies for West Africa. Moreover, large inter-comparison initiatives favoured the evaluation of model components relevant for impact studies, such as land-surface and chemistry models (Ruti et al., 2011).

The United Kingdom Climate Program (UKCP09) has used a combination of parameter permutation experiments (PPEs) based on the HadCM3 global climate model and multi-model ensembles (MMEs), as well as regional climate model results to develop probabilities of changes in temperature and precipitation at a 25 km resolution (Murphy et al., 2009) for all of the UK. This information is being used to determine probabilities of different impacts of climate change and possible adaptations. Results of individual regional climate model simulations are also available. A number of case studies using the UKCP09 scenarios have been developed. For example, Bell et al., (2011) used the results from 11 RCM simulations to determine potential changes in river flows throughout the UK for the A1B emissions scenario.

While the majority of articles published based on the NARCCAP suite of simulations over North America has been on climate analysis, a growing number of articles on climate impacts is appearing including impacts of climate change on available wind energy (Pryor and Barthelmie, 2011; Rasmussen et al., 2011), road safety (Hambly et al., 2012), hydrology (Burger et al., 2011; Shrestha et al., 2011), forest drought (Williams et al., 2012), and human health (Li et al., 2012).

21.5.3.2.3. Use of multiple scenario elements and focus on multiple stressors

Many more impacts and adaptation studies now use multiple scenario elements, as opposed to climate change scenarios alone. Some of the most common types of study that uses multiple scenario elements are those concerned with world hunger, where population change, land use, and economic conditions in various parts of the world make up important elements in addition to climate change (e.g., Parry et al., 2004). Arnell (2004) also used multiple aspects of the SRES scenarios in a study of global water resources, another context where population changes and future economic conditions would be critical to the study. Another type of study that commonly makes use of multiple aspects of scenarios are urban heat island and climate change studies concerned with human health (e.g., Knowlton et al., 2008; Rosenzweig et al., 2009). Recently, McCarthy et al. (2010) considered population increase up to 2050, as well as expanded urban areas to determine effects of climate change on urban heat islands. In the European Impacts Program PRESETA multiple aspects of the SRES scenarios (e.g., population and socio-economic conditions) were considered for some of the impacts areas such as human health (Watkiss and Hunt, 2012). The use of multiple scenario elements is associated with the issue of multiple stressors, which is discussed below.

One of the issues that remain somewhat unresolved is that of downscaling scenario elements. The SRES scenarios have been downscaled for Europe, for example (van Vuuren and O'Neil, 2006), but such downscaling has not been accomplished for all areas. The economic activity information in the SSP's (see above) has also been downscaled to 0.5 degree grids in some cases, but not all. This information, however, has not yet been examined carefully in the impacts and vulnerability literature (Ebi et al., submitted). (See van Vuuren et al., 2010 for a review of issues related to downscaling of socioeconomic data). Moreover, vulnerability studies often consider other scenario elements on very local scales, and tend to use other, local sources for these scenario elements, which may or may not be consistent with the larger scale scenario elements. See the discussion of credibility of scenario elements in section 21.5.3.3.2 below.

The recognition of the importance of viewing climate change in the context of multiple stressors has increased over time. In AR4 this topic was, naturally, discussed in terms of sustainability (Chapter 20) and adaptation (Chapter 17). In the AR5 the issue of multiple stressors is incorporated into most regional and sectoral chapters, and those related to adaptation. Multiple stressors can have independent, synergistic, or antagonistic effects on particular impact areas. Typical stressors, aside from climate change, include changes in population, migration, land use, economic factors (particularly affecting adaptive capacity), technological development, social capital, air pollution, and governance structures, among others. Magrin, Marengo et al. (2011) clearly identify land-use change and shifts in major socio-economic conditions as stressors of equal importance to climate change in considering future conditions in Latin America. In the new chapter on ocean systems Portner, Karl et al. (2011) indicate the central importance of numerous changes in addition to climate (e.g., changes in nutrients), that are strongly affecting ocean ecosystem health. Hijioka, Lin et al. (2011) identify rapid urbanization, industrialization and economic development as major multiple stressors that will likely be compounded by climate change in Asia. The importance of simultaneous changes of frequency in excessive heat events and increases in air pollution have been well documented in the context of human health (Jackson et al., 2010). Human health studies in general tend to require a multiple stressor approach (Morello-Frosch, et al., 2011).

Many of the multiple stressor studies are regional or local in scope. For example Ziervogel and Taylor (2008) examined multiple stressors in South Africa, taking a survey approach. They examined two different villages in Sekhukune and found that a suite of stressors are present in the two villages, such as high unemployment, health status (e.g., increased concern about AIDs), and access to education. Concerns about climate change were only present in the context of other impacts such as availability of water. In a study on the Great Lakes region, additional stressors included land use change, population increase, and point source pollution (Danz et al., 2007). They proposed an integrated measure of multiple stresses for the region. Mawdesly et al. (2009) in considering wildlife management and biodiversity conservation note that reducing pressure from stressors other than climate change can maximize flexibility for adaptation to climate change. Stressors in this area are many, including invasion of non-native species, land-use change, and human population increases and shifts. Baker et al. (2008) note the importance of multiple stressors in the case of coral bleaching; these include sedimentation, turbidity, and nutrient loading in addition to shifts in climate. Nelson and Palmer (2007) discuss the effect of the stressors of increased watershed imperviousness, reduction in riparian vegetation, and increased siltation on water temperatures of streams, which in turn affects their suitability as a habitat. Shifts to warm-water species will result. Eakin and Wehber (2009) consider the effects of changes in demographic factors such as age structure and education level in two agricultural case studies in Latin America.

This increased focus on multiple stressors obviously increases the need for a much wider range of data and wider range of projections for the wide range of stressors, across multiple spatial scales.

21.5.3.2.4. Projections of land-use change

Land-cover and land-use are related in multiple ways to the regional distribution of vulnerabilities, both because they are intrinsically part of the distribution of natural resources and of goods and services from ecosystems (e.g. Scholes et al 2005, Janetos et al 2005), but also because they are changing rapidly as a consequence of both societal demands for those goods and services, and because of variability in the climate system. While documenting global patterns of land-cover change has been a focus for observational research for many years in particular ecosystem types (e.g. forests in Lepers et al. 2005, Hansen et al.), the projections of land-use and land-cover change have typically either focused on human-driven changes (Rindfuss 2008) or on the sensitivity of ecosystems to climate variability, but rarely both. Land-use and land-cover histories have been harmonized for use in future simulations as part of the RCP process (Hurtt et al 2011).

More recent literature begins to address new aspects of land-use and land-cover change as those processes relate to greenhouse gas mitigation actions. Meinshausen et al (in press), Van Vuuren et al. (2011), Thomson et al. (2010), and Wise et al. (2009) present scenarios of land-use and land-cover change that have focused on how those changes are also consequences of decisions about greenhouse gas mitigation, especially the potential for expansion of purpose-grown bioenergy crops. The extent and rapidity of spread of purpose-grown bioenergy crops in these studies using integrated assessment models is largely a function of economic behavior- specifically, whether a price is associated with terrestrial carbon as well as fossil fuel emissions, or whether a price is only associated with fossil fuel emissions. In some models, (Thomson et al 2010, Wise et al 2009), bioenergy crops are used for electricity generation when coupled with geological capture and sequestration. This is not a general result, however, as all integrated assessment models do not represent that particular combination of technologies. In model results that have large expansions of purpose-grown bioenergy crops, there is also a larger expansion of cropland for food production to satisfy the demand for food from growing human populations. This result is due to the fact that the competition for arable land forces agriculture onto less suitable lands and lowers their per hectare productivity. However, while the interaction between land-use, bioenergy crops, and agricultural productivity is beginning to be investigated, the interaction with the climate system itself is still largely unexplored, so our understanding of these interactions is still in a very preliminary stage. Hibbard et al (2010) present an analysis of the major uncertainties and research gaps in addressing this interaction.

21.5.3.3. Uncertainties and Credibility of Projections and Scenarios

21.5.3.3.1. Uncertainties and credibility regarding future climate

From the viewpoint of developing projections of long-term climate change, there are primarily three sources of uncertainty. This section discusses these three sources, comments on how the uncertainty has been quantified (if it has been), indicates how credible current estimates are and indicates whether we can reasonably expect reductions in these sources of uncertainty.

Future emissions and concentrations of greenhouse gases and aerosols

Future climate forcing (derived from emissions and concentrations) will be shaped primarily by: emissions of greenhouse gases, aerosols, and short-lived species into the atmosphere; and processes that control the composition of the atmosphere, such as atmospheric chemistry, terrestrial and marine components of the carbon cycle, and nitrogen cycles. Factors that influence the scale of future anthropogenic emissions include the scale of economic activity, the technologies with which human societies generate and use energy, and the public policy environment in which human activities are conducted. Hence, predicting emissions of GHG and aerosols requires being able to predict how the entire human world will develop in the future, a truly daunting task fraught with multiple profound uncertainties. This would also include determining future populations, gross domestic product (GDP), and the development of future technologies. There is not much chance of reducing these uncertainties for the long-term future. There has been an understandable reluctance to quantify the uncertainty in the emissions of greenhouse gases and aerosols, although some elements contributing to final emissions estimates have been quantified, for example, of population (also see section 21.5.3.3.2 below). Nevertheless, future emissions have mainly been presented as scenarios having equal plausibility (Parson et al., 2007). This was the case with the SRES scenarios, and is presently the case with the RCPs and SSPs (van Vuuren et al 2012, Adger et al 2011). See section 21.5.3.3.2 below for a more thorough discussion of the credibility of the elements of socio-economic scenarios.

Climate system response to forcing

Climate system uncertainty is explored through the application of global and regional climate models. While most of these models are carefully constructed to incorporate many climate-related processes and are carefully evaluated, they do not necessarily respond in the same way to a given future forcing scenario. These differences are due to scientific uncertainties about how the climate system works, differences in the way various subsystems are modeled (e.g., land surface processes) and differences in how unresolved processes are parameterized (e.g., convection). These uncertainties are explored and characterized by analyzing the results of different types of ensembles of climate model simulations. The most common is the multi-model ensemble (MME) based on simulations with different climate models that are subjected to the same future radiative forcing. These MMEs play a central role in the analyses that contribute to the various IPCC assessments (e.g, sets of simulations from CMIP3 and CMIP5 for the AR5 Reports). There are also ensembles developed from a single climate model whose parameters are varied in systematic ways, which are referred to variously as Parameter Permutation Experiments or Perturbed Physics Ensembles (PPE) (e.g., Murphy et al., 2007).

While the climate models used to generate simulations for the AR5 are more complete than ever before (Chapter 9 WG1) (e.g., most now have fully closed carbon and nitrogen cycles, thus reducing the uncertainty regarding final concentrations in the atmosphere), there are still processes that are known to be important but are not incorporated due to incomplete understanding of the process or difficulty in modeling the process. For example, most of the CMIP5 models still do not include the explicit modeling of glacier and ice sheet dynamics (see WG 1 Chapter 9, section 9.1.3.2.8). Hence, projections of sea level rise from such models are bound to be incomplete and therefore limited. (However, better estimates are made in the AR5 using offline land ice sheet models). Other such missing processes include possible occurrence of catastrophic events such as the collapse of the Greenland Ice Sheet. Another example is that the global climate models are still limited in terms of resolution which can be important for capturing relevant processes as demonstrated in a recent study with improved vertical resolution allowing better representation of the stratosphere which then significantly influenced the projected changes in the climate over Europe (Scaife et al. 2011).

Obtaining robust predictions of climate change (i.e. at least a clear understanding of the direction of change of precipitation preferably with a level of uncertainty quantification), requires combining the projections with detailed analysis and understanding of the drivers of the changes. The most successful example of this is the application of the attribution of observed global and regional temperature changes using global models incorporating known natural and anthropogenic climate forcing factors (AR4 WG1). The global model's ability to reproduce the observed variations in temperature, the quantification of the influence of the different forcings factors and how well these influences are captured in the models provide for:

- Confidence that models capture correctly the physical processes driving the changes and thus in their ability to project future changes;
- A method of quantifying the range of sensitivities of the climate system to the different forcings factors and thus how it is likely to respond to scenarios of changes in these forcing factors.

In this situation, a robust message was derived due to having a clear understanding of the drivers of observed changes and all models reproducing these along with the direction and, to a reasonable degree of accuracy, the magnitude of the change.

Through a careful analysis of the drivers of projected changes, similar robust messages can be derived for precipitation change. Rowell and Jones (2006) performed a detailed analysis of the drivers of projected European drying in summer and concluded this signal to be robust as the dominant processes were driven by warming. In a similar analysis Kendon et al. (2010) concluded that the signal of increased daily precipitation in Europe in winter was also robust.

IPCC AR4 stated clearly that temperatures and sea-level are predicted to increase (i.e. providing quantified levels of confidence in the range in which these increases are expected to lie) and thus this information has high credibility. This is due to model simulations reproducing observed trends in these variables, an understanding of the physical drivers of these trends and that the models represent these well.

In some cases, for example precipitation on a regional scale, the sign of the change may differ from one model to another. However, it is important to note that in many cases, the difference in direction of change in precipitation simulated by, for example, two different models, indicates a lack of significant change in the precipitation compared to the natural variability in a particular region (Tebaldi et al. 2011).

Yet, it is also the case that some contrasts in direction of change are significant. In some situations, future projections may go in opposite directions to each other with neither possibility able to be excluded on the basis of our physical understanding of the drivers of these changes. For example, McSweeney et al., (2011) found that in an ensemble of GCM projections over south-east Asia, all models simulated the important monsoon processes and rainfall well but projected both positive and negative changes in monsoon precipitation and significantly different patterns of change. In this case no information on observed trends or more detailed process understanding was available but there has been little effort to analyse trends and projected changes in south-east Asia and thus the current issue of contradictory projections could be clarified with some targeted research.

Model projections may also be less consistent or inconsistent with available observations. In these cases, the projected information is less credible as explained in the following examples:

- In some cases drivers of historical change are not known so there is a lack of physically based understanding of the past to use in the assessment of confidence in the models' ability to simulate regional climate change. An example of this is the reason for the significant drying trend seen in the Sahel from the 1960s to the 1990s. Whereas statistical analysis has demonstrated the role of sea-surface temperatures (SSTs) in driving Sahel rainfall variability, and some relevant mechanisms identified, models driven by observed SSTs fail to capture the full magnitude of the drying trend (e.g. Held et al. 2005). Thus our understanding of the system and its drivers is incomplete which complicates the interpretation of future projected changes in this region (e.g. Biasutti et al., 2009, Druyan, 2010). This implies that other processes are important and thus research is required to identify these and ensure that they are correctly represented in the models. Without knowing what these processes are and thus that the models are representing all relevant processes, projections of rainfall changes over this region cannot be considered reliable.
- A more extreme case is where future projections all go in the opposite direction to the observed changes and an example of this is seen over part of the continental US which has seen cooling trends in past few decades (AR4 WG1) though the projected changes indicate a warming. This is not necessarily a contradiction though the lack of similar cooling trends in many climate models again indicates there is a process that is not being captured in the models and needs to be identified and included in the future. Then the influence of the process in projections of future climate change needs to be assessed in order to provide confidence in the sign and magnitude of any changes.

In these cases where future projections differ significantly or go in opposite directions, it is still important to provide information on the range of changes. The likelihood that temperatures (and sea-level) will continue to rise in the future is sufficient to motivate a response to these predicted changes and, in general, information on other climate variables will also be required. Thus it is important to be able to characterize the range of plausible changes in these other variables.

One approach is to use a Bayesian probabilistic framework to combine the range of information that may include differences in direction of change in precipitation in a global climate model (e.g. Tebaldi and Knutti, 2007, Harriss et al., 2012) or in a global model and then a regional model driven by the global model (e.g., Déqué and Somot (2010). Another is to identify a subset of available models whose response characterises the range of projected futures (e.g. McSweeney et al., 2011).

It is expected that with model improvements (e.g., including more important processes and modeling processes more completely) that the uncertainty due to climate (model) response will be reduced over time in certain ways. However, this does not necessarily mean that all metrics of uncertainty will be reduced at once. It is quite possible that improving the representation of processes will not immediately result in reduction of uncertainties regarding the likely range of temperature change in central Kansas in 2050, for example (Mearns, 2010). One of the FAQs presented in Chapter 1 of WG1 discusses this issue in more detail.

Internal variability

Long-term projections of climate change are subject to uncertainty resulting from the internal variability of the climate system. The relative role of this type of uncertainty compared to the other sources of uncertainty (climate model response uncertainty and forcing uncertainty), are a function of the future time horizon being considered and the spatial scale of analysis (Hawkins and Sutton, 2009; 2011). Here we use the term natural or internal variability to refer to unforced variability internal to the climate system. Hence this definition does not include variability related to the occurrence of natural phenomenon, such as volcanoes. Internal variability is usually explored by running sets of climate model simulations (ensembles) using different initial conditions for each simulation. Traditionally the number of ensemble members has not been large (e.g., around 3 in the CMIP3 data set), but the number has increased in the CMIP5 set of simulations to about 7. However, some recent research has explored larger numbers of ensemble members (e.g., Deser et al., 2010) and has thus come up with improved measures of natural variability. In this case 40 different members were produced, which represent how much the climate can vary based on random internal variations. The variations across ensemble members can be considerable on various spatial scales, and there is considerable evidence that this kind of uncertainty may not be particularly reducible (Deser et al. 2012). The issue of internal variability is more thoroughly discussed in WG1 Chapter 12, section 12.1.1.2.

21.5.3.3.2. Credibility and uncertainties regarding socioeconomic scenario elements

Credibility

The fact that scenarios serve both as tools of investigation for the scientific community and as the basis of information on possible futures for decision-makers introduces additional demands for the credibility of scenarios beyond that typically required of other scientific studies (van Ruijven et al. forthcoming).

Cash et al. (2003) distinguish three criteria for effectively linking scientific knowledge to policy action: credibility, salience, and legitimacy. Credibility refers to the scientific adequacy of a policy-relevant study. Salience refers to the relevance of a study's findings to the needs of decision-makers, while legitimacy refers to the perception that the study was produced in a manner that is respectful of divergent values and beliefs. Cash et al. (2003) find these attributes to be tightly coupled and suggest that efforts to enhance one criterion normally introduce tradeoffs for the others. Studies examining the performance of scenarios in climate change research across all three of these criteria are rare, but a general conclusion has been that most effort has been expended on credibility with much less attention to salience and legitimacy (Hulme and Dessai 2008, Garb et al. 2008, Girod et al. 2009).

Perhaps partially in recognition of the limitations that scenarios have had historically with salience and legitimacy, new scenarios for future climate change research will have a dramatically new structure. Under the parallel process (Moss et al. 2010), research streams that developed independently around climate scenarios (inspired by representative concentration pathways, or RCPs; see van Vuuren et al. 2011) and socioeconomic scenarios (shared socioeconomic pathways, or SSPs; see O'Neill at al. forthcoming) will be brought together to enable integrated analyses of mitigation, adaptation, and residual impacts. (See Box 21-1 for an overview of the new scenarios). RCPs aim to be the concept that coheres climate and socioeconomic elements together for reference scenarios (i.e. alternative futures assuming no new climate policy; see Ebi et al. forthcoming and van Vuuren et al. forthcoming). In principle, such coherence is possible, as RCPs can serve as both inputs to climate modeling and as target outputs to IA modeling. Additionally, one of the main conclusions of the SRES (Nakicenovic et al. 2000) supports this aspect of the new scenario design, as fairly different socioeconomic conditions could give rise to similar emissions trajectories. Subsequent studies have arrived at similar results (van Vuuren et al. 2008).

However, heeding the warning of tradeoffs from Cash et al. (2003), it remains to be seen if enhancements to scenario salience may result in diminished scientific credibility. It is unclear how difficult it will be to bring independently developed climate and socioeconomic scenarios together in an internally consistent manner during the integration phase (O'Neill and Schweizer 2011). Additionally, the SSP framework (O'Neill et al., forthcoming) introduces another layer of complexity by labeling SSPs describing globally aggregated trends as "basic" versions, while more elaborate SSPs, which will be geared toward sector-specific or more regional and localized analyses, will contain additional socioeconomic detail and are called "extended" SSPs. The possibility that additional details in extended versions of the SSPs could upset the internal consistency of the basic SSPs cannot be dismissed, and such problems will only be uncovered as the SSPs are further developed and used.

In this regard, recent scholarship has suggested that the exclusion of some socioeconomic details in socioeconomic scenario studies can affect the internal consistency, and therefore the credibility, of a study overall. This is due to the common practice of Story and Simulation (SAS; Alcamo 2008) for scenarios, where narrative descriptions of alternative futures serve as the inspiration for socioeconomic simulations. At the initial stage of story development, the first internal consistency test is that these stories be plausible. Thereafter, integrated assessment (IA) models attempt to replicate qualities of these stories. The ability of the IA model to simulate the story is viewed as a more rigorous test for internal consistency. Conventional wisdom is that so long as IA models are able to simulate the conditions described in the story, the story (and hence its assumed combinations of socioeconomic elements) has been demonstrated as internally consistent and therefore credible. Thus, a strength of SAS is that it marries the malleability of stories to the rigors of simulation (Raskin et al. 2005). As noted in the AR4, stories in SAS can offer a point of entry for multi-scalar scenario analyses (Lebel et al., 2005; Kämäri et al., 2006). Despite these benefits, some scholars have pointed out a potentially serious deficiency in the practice of SAS, as stories often include details that make them plausible which IA models do not include (Kok 2009, Schweizer and Kriegler 2012, Schweizer and O'Neill forthcoming). The exclusion of some details in IA models may affect the determination of whether a story is plausible (Lloyd and Schweizer, forthcoming) let alone internally consistent. For example, one of the findings of Schweizer and Kriegler (2012), who employed a systematic method for assessing the internal consistency of the qualitative aspects of scenarios, is that assumptions regarding social priorities (e.g. contrasting hypothetical worlds that are economically versus environmentally focused) can make the difference between marginal and strong internal consistency for SRES scenarios with the lowest emissions profiles.

Along with the new research opportunities that will be made possible under the new scenario process, the scientific community must also revisit what credibility means across extended SSPs, basic SSPs, and SSP+RCP scenario combinations. Scholarship on environmental scenario exercises crossing geographical scales suggests that linkages between scenarios at different scales can be hard or soft (Zurek and Heinrichs 2007), where downscaling would be an example of a hard linkage while other similarities between scenarios would be soft linkages. In the context of the new scenario framework, some thought has been given to the circumstances under which strong internal consistency should be retained (e.g. global SSP+RCP scenarios) and when it may be relaxed (e.g. the internal consistency of a provincial vulnerability assessment, based on extended SSPs + regional RCP climate projections, with global SSP+RCP scenarios) (van Vuuren et al. 2012). Nevertheless, how to apply flexible interpretations of scientific adequacy and maintain scenario credibility is relatively uncharted territory for scenario-based environmental change assessments. There will be a need for studies to document best practices in this respect and for the scientific and policy communities to move toward consensus.

In conclusion, we find that few studies have assessed the performance of scenarios and their reception by decision-makers, whether focusing on credibility (e.g. internal consistency) or also considering salience and legitimacy. The new scenario process will also introduce new complexities for scenarios, and attention should be paid to what these complexities may mean for scenario credibility.

Quantifications of uncertainties of scenario elements and scenarios

Since AR4, little has changed over the controversy for whether probability density functions (pdfs) should be assigned to emissions pathways or other socioeconomic scenario elements (e.g. population growth, income growth) (Parson et al., 2007). Where studies have incorporated probabilities, they have done so in a variety of ways. Some propose or have demonstrated probabilistic estimates for socioeconomic scenario elements. A study by van Vuuren et al. (2008) applied conditional probabilistic estimates for socioeconomic scenario elements that would be consistent with alternative SRES storylines. Van Vuuren et al. (2008) were careful to comment that the purpose of such conditional probabilities is not to evaluate the likelihood of the underlying storylines but to explore other topics such as the ranges of emissions for different storylines. In contrast, Morgan and Keith (2008) have proposed that likelihoods for scenarios could be obtained through a subjectivist approach, where probabilities are obtained from experts. In this vein, some expert elicitation studies regarding technological change (Curtright et al. 2008, Anadon et al. 2011), including those combined with economic modeling (Böhringer et al. 2009, Baker et al. 2009), have further demonstrated that experts could assign subjective probability judgments to alternative future outcomes. Other examples of uncertainty quantification include probability estimates for the feasibility of achieving temperature or concentration targets (Keppo et al. 2007, O'Neill et al. 2009). In these latter cases, socioeconomic elements in emissions scenarios are not treated probabilistically; instead, assumptions about climate sensitivity or perfect foresight are adjusted, and an IA model is run multiple times. The frequency of the model runs in the ensemble that achieve the temperature or concentration targets provide probabilistic estimates for achieving the policy targets.

Because there are multiple ways to quantify uncertainties in scenarios, the new parallel design for socioeconomic and climate scenarios may or may not pose challenges for further uncertainty quantification. Although decoupled socioeconomic and climate scenarios may make it difficult to determine probabilities for climate scenarios based on a probabilistic analysis of socioeconomic scenarios alone, other opportunities for probabilistic analyses will be retained. For example, it would be possible to do conditional probabilistic studies with socioeconomic scenarios independently and determine probabilistic ranges for emissions. If subjective probabilities for socioeconomic scenario elements were also introduced, it would be possible to conclude conditions under which particular emissions scenarios would be expected to be more likely. In the latter case, likelihood judgments for emissions scenarios may be translatable to likelihood judgments for RCPs, and therefore, related climate projections.

21.6. Knowledge Gaps and Research Needs

The issues of the regional context of climate change are arguably the thematic area most in need of attention to advance adaptation response, policy, and decision making. The needs range from the practical questions requiring applied research, to more fundamental theoretical questions. Table 21.4 identifies leading foci that currently constrain the adaptation community, and where a solid advance of knowledge advance would contribute to substantial value for the broad adaptation community.

[INSERT TABLE 21-7 HERE
Table 21-7: Leading knowledge gaps and related research needs.]

Frequently Asked Questions

FAQ 21.1: Should we be concerned about impacts of climate change in other parts of the world?

Short answer: *Regional impacts of climate change, both adverse and beneficial, may have ramifications in other parts of the world. Different types of impacts can be of importance to a variety of interest groups. Cross-regional concerns about four types of impacts can be distinguished: 1) Concerns about large-scale geophysical impacts, 2) Concerns about socio-economic and geopolitical impacts, 3) Concerns about social instability due to rapid-onset events, and 4) Concerns internationally about impacts occurring locally. Some illustrations of these are provided below, along with the types of groups who might show interest.*

Long answer: Climate change is a global phenomenon, but the expression of that change and its impacts on natural systems and society varies enormously from place to place and over different time scales. Some impacts may be gradual responses to long-term trends, sometimes referred to as "slow-onset" impacts. More prominent, though also more difficult to attribute to a changing climate, are "rapid-onset" impacts of extreme weather events[1] such as droughts, floods or storms. In both cases, regional climate change has direct impacts on systems and communities that are exposed to that change in the same region. However, such impacts can also have implications much farther afield, sometimes in completely different parts of the world. The reasons for this relate to key regional interdependencies that are present both in the global physical climate system as well as in economic, social and political systems that are themselves becoming increasingly globalised. Cross-regional concerns about four types of impacts can be distinguished:

1) *Concerns about large-scale geophysical impacts*. Some types of geophysical impact can have large-scale repercussions well beyond the regions in which they occur. A well-known example of this is the melting of land-based ice, which is contributing to sea-level rise (and adding to the effects of thermal expansion of the oceans), with implications for low-lying areas far beyond the polar and mountain regions where the melting is taking place. These impacts are ongoing and are projected to take centuries or millennia to slow down or

halt, which would require that climate change stabilisation be achieved first. The types of actors with an interest in these impacts include policy-makers involved in discussions about reducing global greenhouse gas emissions in order to stabilise the climate, decision-makers needing to formulate strategies for coastal management and flood protection under rising sea levels, or insurers offering coverage for flooding, erosion and related risks.

2) *Concerns about socio-economic and geopolitical impacts*. Local, slow-onset impacts of climate change may also trigger higher-order responses that have wider social, economic and geopolitical implications. For example, there has been much debate in recent years on the question of environmental refugees, where the argument has been put forward that climate change is degrading environments in some regions to such an extent that the livelihoods of local populations have or will become unsustainable, and they are forced to migrate to other regions. While there is evidence of international migration in the wake of extreme events such as hurricanes (e.g. population displacement from central America to the United States following Hurricane Mitch in 1998), the evidence for longer-term climatic causes of migration is disputed, and is also confounded by the growing phenomenon of economic migration. Nonetheless, geopolitically this is an issue of increasing importance to national and international policy makers.

   A second example of a regional impact of climate change with socio-economic and security implications is the accelerated shrinkage of Arctic sea ice that has been observed in recent years. This is projected to continue into the future under sustained regional warming, opening Arctic shipping routes as well as providing access to valuable mineral resources in the exclusive economic zones of countries bordering the Arctic. For example, under some scenarios, it is estimated that moderately ice-strengthened ships could have almost complete summer access to Arctic routes such as the Northwest Passage, Northern Sea Route and Trans-Polar Route by the end of the 21st century, representing significant savings for trans-continental shipping currently using routes via the Panama and Suez Canals. On the other hand, there are also numerous risks that would accompany such commercial exploitation, including shipping accidents, pollution, threats to livelihoods among indigenous communities, and general degradation of an already fragile environment. National governments, representatives of indigenous peoples, international freight carriers, resource extraction industries and environmental agencies are among the parties having a stake in these future developments.

3) *Concerns about social instability due to rapid-onset events*. A third class of local impacts with global ramifications, are those that are caused by rapid-onset, extreme weather events, which may curtail production of some key commodities that are traded internationally, leading to shortages of supply and hence increased prices to consumers. For instance, there are recent examples of price spikes in some basic food commodities that caused local unrest among consumers in some parts of the developing world. Though these price rises were triggered by weather-related crop failures in exporting regions, the underlying causes of reduced food supply are more complex, and include reallocation of food crops by some major exporters for use as biofuels, national trade protection policies, as well as market speculation. Some key actors with an interest in such events might include bodies regulating international commodities trading, national governments, regional trading blocs, public law and order authorities, and aid agencies.

4) *Concerns internationally about impacts occurring locally*. Some impacts are local and may have little or no immediate effect outside the regions in which they occur. Nonetheless, they may be of concern to actors outside that region for a range of reasons, including: (i) disaster relief (e.g., to ameliorate the impacts of malnutrition or disease brought on by weather-related events), (ii) environmental protection (e.g., conservation of locally threatened and valued species), (iii) enhancing adaptive capacity (e.g. through capacity building and other development projects that enhance resilience to climate change), or (iv) exploiting potential opportunities (e.g. through foreign investment in agricultural production in regions where future climate change impacts may be beneficial for productivity). Here, some key actors who might wish to consider such impacts include national and international development agencies, humanitarian organisations, multi-national corporations, and environmental organisations.

[FOOTNOTE 1: Although extreme weather events on their own can be very difficult to attribute to anthropogenic climate change, long-term trends in such events are projected by climate models (Cross reference?), and in some cases are already being observed (see FAQ 2.2, Chapter 2, WG I).]

FAQ 21.2: Is the highest resolution projection the best to use? [placeholder draft]

Short answer: *A common perception is that higher resolution equates to more information. Unfortunately data does not equal information, and more high resolution data does not necessarily equal more information. Hence, while there are many methods that can increase resolution, it is not a given that there will be more skill in the final product. For example, simple approaches such as interpolation or perturbing observed data fields with GCM information increase the resolution but add no high resolution climate change information. Using downscaling methods will add a high resolution component but there will be an extra error associated with the additional method applied which needs to be considered. More importantly, if downscaling is applied to only one or two GCMs then the resulting high resolution scenarios are unlikely to span the full range of projected changes that a large GCM ensemble would indicate are plausible futures. Thus for many applications, such as understanding the full envelope of possible impacts resulting from our current best estimates of plausible change in a regional climate system, lower resolution data can be more informative. At the end of the day, no one data set is best, and it is through the integration of multiple sources of information that robust understanding of change is developed.*

Long answer: placeholder pending a support graphic/cartoon being developed

FAQ 21.3: Are earlier assessments still valid? [placeholder draft]

Short answer: [to be drafted]

Long answer: The IPCC has conducted four major Assessments, starting in 1990, and each has included the equivalent of a Working Group 2 Report. The current report represents the fifth assessment. The reports through time have increased in length, scope, and complexity. But the essential goal of the reports has a core commonality. In the first report, it is stated that the ‘responsibility of Working Group II is to describe the environmental and socioeconomic implications of possible climate changes over the next decades caused by increasing concentrations of greenhouse gases’ (IPCC 1990). By the Third and Fourth Assessments, the WG2 Assessments had expanded to explicitly consider vulnerability and adaptation, in addition to impacts. In the second report both mitigation and adaptation were considered in WG2, but the sections on adaptation were very basic. So we see that the organization of the Working Groups, including their remits, has changed over time. But our concern in this FAQ is whether the content of the earlier reports are still valid, not whether the structure of the reports has significantly changed. Within the Second Report (SAR) concerns regarding vulnerability and adaptation were already present, as were many concepts that received more intensive coverage in the later reports, such as multiple stressors, adaptive capacity, and vulnerability. But the earlier reports (IPCC 1990, 1995) tended to be much less quantitative than later reports, and provided less detail on a regional scale. Yet many of the concerns expressed in later reports (2001, 2007, 2014) are already adumbrated in the earlier ones (e.g., negative impacts on human health from increased heat waves, decreased water resources and strains on cropping systems, changes in ecosystem composition). By the 2001 Report, much more detailed regional analysis was taken on, and the structure of a sectoral section and a regional section came into being, along with a detailed chapter on adaptation. Also greater attention was placed on how uncertainties are expressed and quantified. By the 2007 report, the major new theme of assessment of observed changes and responses in natural and managed systems became a subject of its own, although it was introduced in the Third Assessment Report (TAR). Also by the time of the TAR, greater emphasis was placed on the concept of sustainability as a broader framework through which climate change impacts should be viewed.

[Placeholder for figure of different IPCC assessments, and the new elements that emerged with each report]

The overall message of this FAQ would be that yes, in a general sense, the earlier assessments are still valid, but the assessments have become much more complete over time, evolving from making very simple, general statements about sectoral impacts, through greater concern with regions regarding impacts and vulnerabilities, through to greater emphasis on sustainability, equity, and deeper examination of adaptation options. Finally in the current report (IPCC 2014) we see four chapter on adaptation, and a much more explicit treatment of the challenges of decision-making. The progression of the reports reflects tremendous scientific progress and deep learning from one report to the next. Obviously one can learn the most about impacts, vulnerability, and adaptation in the context of climate change by looking at the most recent report. It is certainly much more complex and complete in its treatment of defining societies challenges in the face of climate change, possible adaptation, and how to maintain a sustainable world even with the challenges of climate change. So, the earlier reports are for the most part valid, but they appear incomplete and somewhat naïve compared to our most recent efforts. Observing the progress represented by each new report is a validating experience in and of itself.

FAQ 21.4: What information should I take into account for climate risk management for the 20-year time horizon?

Short answer: *For climate-affected decisions that play out over the coming 20 years, it is important to be aware that the climate is changing. Climate trends over the recent past may provide guidance on what is expected in the near future if the reasons for these trends are known and are expected to intensify. Also, any climate model projections in which there is confidence for climate variables of importance are potentially useful. However, climate trends and model projections will at most provide only some relevant information for managing risk for the 20-year time horizon. To effectively manage these risks, it is important to (i) properly characterize the decision-making context, including trends in vulnerability and exposure to climate and weather phenomena (ii) understand the natural variability in the key climate variables as well as any robust predictions of changes; (iii) where relevant, make use of forecasting on shorter timescales if early-warning systems are or could be important in managing the risks involved.*

Long answer: How to manage risks for decisions with a 20-year time horizon clearly depends on the specific decision-making context. It is essential to first characterize the vulnerability to climate conditions of the issue being addressed, and to determine how climate conditions interact with other factors, which may be changing more rapidly than the climate itself. For example, if the issue is design of contingency plans for disasters in a rapidly growing city, vulnerability will depend on the people and assets at risk in a particular location, including the types of buildings and land use. If the issue is agriculture investments (say, a switch of crops), vulnerability will also depend, for instance, on market conditions, the availability of credit and insurance.

A second element that clearly depends on a good understanding of the decision-making context, is to assess which climate variables matter most. If the issue is design of contingency plans for disasters, it is clearly the extremes that matter most; in the case of agriculture it may be average seasonal rainfall, but also seasonal onset, or maximum daily rainfall.

Thirdly, once that decision-making context, and the climate variables that matter most to the risks being addressed, are clear, it is important to recognize that the climate of today, and of the next 20 years, is already different from the past climate. Basic statistics based on historical records may not provide the best guess for the climate will look like in the next 20 years.

On the other hand, on their own, the changes in climate conditions as projected by climate models for the period between now and the middle or even the end of the century, may not provide the best guidance, either. Taken over just 20 years, the long-term trends are often relatively small compared to the natural variability in the climate system. And while so-called decadal predictions, based on climate models that are initialized using current climate system observations, are improving, their skill is still low.

In simple terms, for many decisions to be taken with a 20-year time horizon, climate change primarily means that uncertainty about the precise conditions to expect is increasing. For some variables, such as average temperature, the trends may be pretty clear: there is a higher chance of higher average temperatures, and of high temperature extremes. For others, such as rainfall and particularly rainfall extremes for instance, the uncertainty is much higher.

So what climate information can be used to manage risks under these circumstances?

First of all, it is essential to properly characterize historical climate variability: how has the climate varied in the past (including extremes, and looking at seasonal, annual and decadal variability). Assessing possible risk management options for robustness under that range of conditions is often a very important first step (and most often much more important than simply focusing on the projected trend due to climate change).

Secondly, for many climate variables, forecasting on shorter timescales, such as regular weather forecasts, and in some regions seasonal forecasts, may provide good indications of what to expect in the relatively near term, which also helps manage some of these risks, including the rising uncertainties.

Thirdly, it is important to be aware of observed trends to get a sense of how the climate may already have been changing. This can be a challenge, somewhat depending on the climate variables of interest, and particularly in regions with more limited data, in terms of coverage and timespan. For instance, if only a 20 years of observational data is available, it will not be possible to confidently interpret, let alone extrapolate a trend.

For some climate variables, climate models may provide additional guidance on how things may already have changed, and what to expect for the coming 20 years. Rather than interpreting these results as a prediction of the precise conditions that will happen, they are often best used as a guide for the direction of change, and thus of the wider envelope of conditions that should be taken into account when making decisions that will be more robust in the conditions to expect in the coming 20 years.

In order to assess the confidence that should be attached to these model projections, it is often important to cross-compare different models, and to know how well these models have performed in simulating the same variables in the same region in the past. This often requires expert judgment. Regional assessments of observed and projected changes in some key climate variables, such as summarized in IPCC reports [include specific chapter references], may provide a rough indication of the direction of change, or the uncertainties, that should be taken into account to aim for more robust decisions in a changing climate.

Finally, decisions with an apparent 20-year time horizon may actually have long-term consequences. For instance, as an investment decision to build a coastal tourist resort with an economic lifetime of 20-years, may actually have severe long-term implications, in this example by changing ecosystems and coastal morphology, but also by triggering different settlement patterns and infrastructure in the surrounding areas. It is becoming increasingly important to take account of such longer-term dimensions of risk in shorter-term decisions, and avoid maladaptation.

FAQ 21.5: How do I find out how vulnerable my region is (am I a hot spot)?

PLACEHOLDER

Cross-Chapter Box

Box CC-RC. Regional Climate Summary Figures

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

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

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

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

The four classifications depicted in the regional climate figures are:

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

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

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

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

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

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

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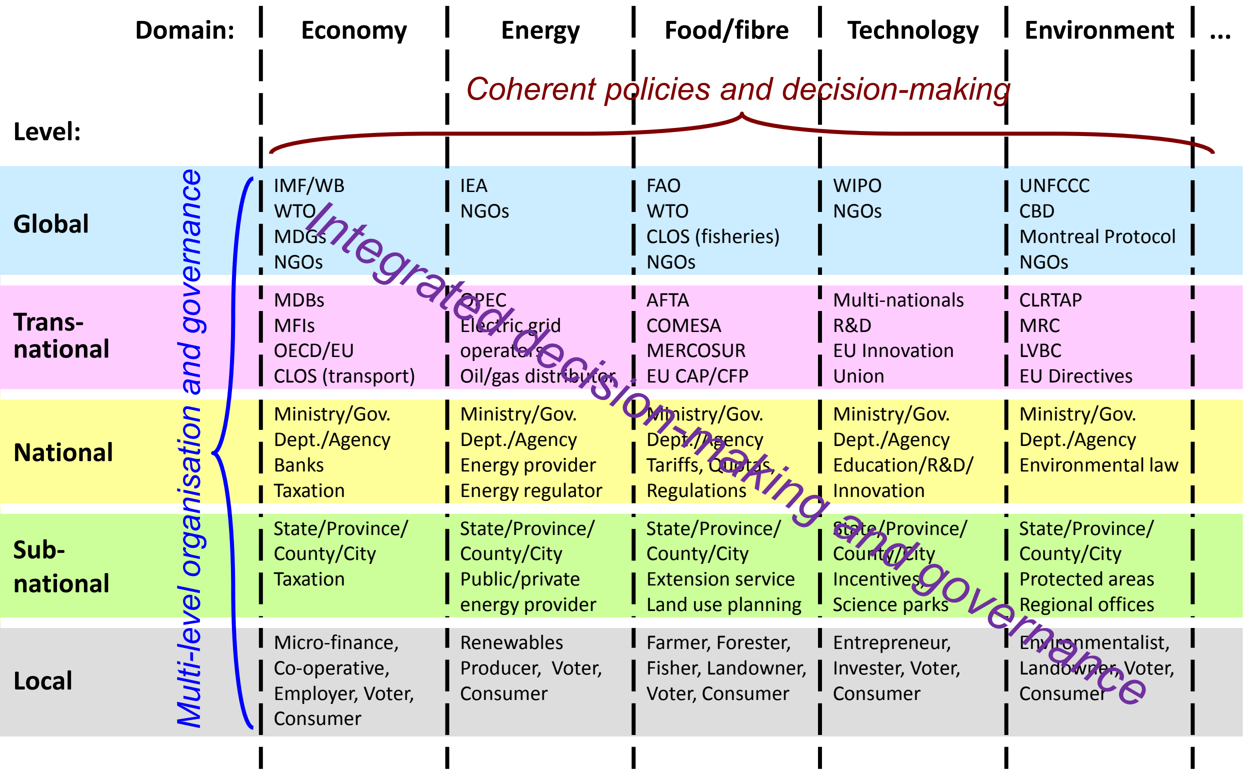
Table 21-1: Dimensions of the institutions and actors involved in climate change decision-making, including example entries referred to in chapters of this volume. Vertical integration can occur within as well as between levels. Decison-making domains are illustrative. Modified and extended from Mickwitz (2009).



Level: / Domain:	Economy	Energy	Food/fibre	Technology	Environment	...
Global	IMF/WB WTO MDGs NGOs	IEA NGOs	FAO WTO CLOS (fisheries) NGOs	WIPO NGOs	UNFCCC CBD Montreal Protocol NGOs	
Trans-national	MDBs MFIs OECD/EU CLOS (transport)	OPEC Electric grid operators Oil/gas distributor	AFTA COMESA MERCOSUR EU CAP/CFP	Multi-nationals R&D EU Innovation Union	CLRTAP MRC LVBC EU Directives	
National	Ministry/Gov. Dept./Agency Banks Taxation	Ministry/Gov. Dept./Agency Energy provider Energy regulator	Ministry/Gov. Dept./Agency Tariffs, Quotas, Regulations	Ministry/Gov. Dept./Agency Education/R&D/ Innovation	Ministry/Gov. Dept./Agency Environmental law	
Sub-national	State/Province/ County/City Taxation	State/Province/ County/City Public/private energy provider	State/Province/ County/City Extension service Land use planning	State/Province/ County/City Incentives Science parks	State/Province/ County/City Protected areas Regional offices	
Local	Micro-finance, Co-operative, Employer, Voter, Consumer	Renewables Producer, Voter, Consumer	Farmer, Forester, Fisher, Landowner, Voter, Consumer	Entrepreneur, Invester, Voter, Consumer	Environmentalist, Landowner, Voter, Consumer	

Acronyms: IMF – International Monetary Fund; WB – World Bank; WTO – World Trade Organization; MDGs – Millennium Development Goals, NGO – Non-governmental Organization; MDBs – Multilateral Development Banks; MFIs Multilateral Financial Institutions; OECD – Organisation for Economic Co-operation and Development; EU – European Union; CLOS – United Nations Convention on the Law of the Sea; IEA – International Energy Agency; OPEC – Organization of the Petroleum Exporting Countries; FAO – Food and Agriculture Organization of the United Nations; AFTA – Association of Southeast Asian Nations (ASEAN) Free Trade Area; COMESA – Common Market for Eastern and Southern Africa; MERCOSUR – Mercado Común del Sur (Southern Common Market); CAP/CFP – Common Agricultural Policy/Common Fisheries Policy; WIPO – World Intellectual Property Organization, UNFCCC – United Nations Framework Convention on Climate Change; CBD – Convention on Biological Diversity; CLRTAP – Convention on Long-range Transboundary Air Pollution (Europe, N. America, C. Asia); MRC – Mekong River Commission For Sustainable Development; Lake Victoria Basin Commission

Table 21-2: Selected examples of regional treatment in previous IPCC Assessment Reports and Special Reports (SR). Major assessments are subdivided by the three Working Group reports, each described by generic titles.

IPCC report [references]	**Year**	**Treatment of regions**
First Assessment Report (FAR) [1, 2, 3]	1990	*Climate*: Climate projections for 2030 in 5 sub-continental regions; Observations averaged for northern/southern hemisphere, by selected regions and by 20° latitude x 60° longitude grid boxes
		Impacts: Agriculture by continent (7 regions); Ecosystem impacts for 4 biomes; water resources for case study regions; Oceans and Coastal Zones treated separately
		Responses: Emissions scenarios by 5 economic groupings; Energy and Industry by 9 regions; Coastal Zone and Wetlands by 20 world regions
Supplements to FAR [4, 5]	1992	*Climate*: IS92 emissions scenarios by 7 world regions
		Impacts: Agriculture by continent (6 regions); Ocean Ecology by 3 latitude zones; Questionnaire to governments on current activities on impacts by 6 WMO regions
SR*: Climate Change 1994* [6]	1994	Evaluation of IS92 emissions scenarios by 4 world regions: OECD, USSR/E. Europe, China/Centrally Planned Asia and Other.
Second Assessment Report (SAR) [7, 8, 9]	1995	*Climate*: Gridded proportional circle maps for observed climate trends (5° latitude/ longitude); climate projections for 7 sub-continental regions
		Impacts, Adaptations, Mitigation: Energy production statistics by 10 world regions; Forests, Wood Production and Management by three zones: Tropical, Temperate, Boreal; separate chapters by physiographic types: Deserts, Mountain Regions, Wetlands, Cryosphere, Oceans, and Coastal Zones and small islands; country case studies, Agriculture by 8 continental-scale regions; Energy supply by 8 world regions
		Economic and Social Dimensions: Social Costs and Response Options by 6 economic regions
SR*: Regional Impacts* [10]	1998	10 continental-scale regions: Africa, Arctic and Antarctic, Australasia, Europe, Latin America, Middle East and Arid Asia, North America, Small Island States, Temperate Asia, Tropical Asia. Subdivisions applied in some regions; Vegetation shifts mapped by 9 biomes; Baseline (1990) Socio-Economic data provided by country and for all regions except polar.
SR*: Land-Use Change and Forestry* [11]	1998	9 Biomes; 15 land-use categories; National and Regional case studies.
SR*: Aviation* [12]	1999	Observed and projected emissions by 22 regional air routes; Inventories by 5 economic regions
SR*: Technology Transfer* [13]	2000	Country case studies; Indicators of technology transfer by 6-7 economic regions
SR*: Emissions Scenarios* [14]	2000	4 SRES world regions defined in common across integrated assessment models; 11 sub-regions; Driving Factors by 6 continental regions
Third Assessment Report (TAR) [15, 16, 17]	2001	*Climate*: gridded observations of Climate trends; 20 example Glaciers; 9 Biomes for Carbon Cycle; Circulation Regimes for model evaluation; 23 "Giorgi" regions for regional climate projections
		Impacts, adaptation and vulnerability: Example projections from 32 "modified-Giorgi" regions; Basins by continent; 5 Coastal types; Urban/Rural Settlements; Insurance by economic regions; 8 continental-scale regions equivalent to 1998 Special report but with single chapter for Asia; Subdivisions used for each region (Africa, Asia and Latin America by climate zones; North America by 6 core regions and 3 border regions)
		Mitigation: Country examples; Developed (Annex I) and Developing (non-Annex I); Various economic regions; Policies, Measures and Instruments by 4 blocs: OECD, Economies in Transition, China and Centrally Planned Asia, and Rest of the World.
SR*: Ozone Layer* [18]	2005	Various economic regions/countries depending on sources and uses of chemicals;
SR*: Carbon Capture and Storage* [19]	2005	CO_2 sources by 9 economic regions; potential storage facilities: by geological formation, by oil/gas wells, by ocean depth,; costs, by 4 economic groupings

Fourth Assessment Report (AR4) [20, 21, 22]	2007	*Climate*: Land-use types for surface forcing of climate; Observations by 19 "Giorgi" regions; Modes of variability for Model Evaluation; Attribution of climate change by 22 "Giorgi-type" regions and by 6 ocean regions; Climate statistics for 30 "Giorgi-type" regions; PDFs of projections for 26 regions; summary graphs for 8 continental regions
		Impacts, adaptation and vulnerability: Studies reporting observed impacts by 7 IPCC regions; comparison of TAR and AR4 climate projections for 32 Giorgi regions; Ecosystems by 11 biomes; Agriculture by latitudinal zone; Examples of Coastal mega-Deltas; Industry and settlement by continetal region; 8 continental regions, as in TAR, but Small Islands not Small Island States; Sub-regional summary maps for each region, using physiographic, biogeographic or geographic definitions; Example vulnerability maps at sub-national scale and globally by country.
		Mitigation: 17 global economic regions for GDP; Energy supply by continent, by economic regions, by 3 UNFCCC groupings; Trends in CO_2 emissions (and projections) , waste and carbon balance by economic regions.
SR*: Renewable Energy Sources and Climate Change Mitigation* [23]	2012	Global maps showing potential resources for renewable energy: land suitability for bioenergy production, global irradiance for solar, geoethermal, hydropower, ocean waves/tidal range, wind); Various economic/continental regions: installed capacity (realised vs. potential), types of technologies, investment cost, cost effectiveness, various scenario-based projections; Country comparisons of deployment and uptake of technologies, share of energy market.
SR*: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* [24]	2012	Trends in observed (tables) and projected (maps and tables) climate extremes (Tmax, Tmin, heat waves, heavy precipitation and dryness) by 26 sub-continental regions covering most land areas of the globe; Attribution studies of return periods of extreme temperatures for 15 "Giorgi-type" regions; Gridded global maps of projected extremes of temperature, precipitation, windspeed, dry spells and soil moisture anomalies; Continental-scale estimates of projected changes in impacts of extremes (floods, cyclones, coastal inundation) as well as frequencies of observed climate extremes and their estimated costs); Distinctions drawn between local, country and international/global actors with respect to risk management and its financing.
Fifth Assessment Report (AR5) *– this assessment*	2014	*Climate*:
		Impacts, adaptation and vulnerability: Nine continental-scale regions, eight as in AR4 plus open oceans.
		Mitigation:

1. IPCC (1990c); 2. IPCC (1990a); 3. IPCC (1990b); 4. IPCC (1992b); 5. IPCC (1992a); 6. IPCC (1994) 7. IPCC (1996c); 8. IPCC (1996b); 9. IPCC (1996a); 10. IPCC (1998b); 11. IPCC (1998a); 12. IPCC (1999); 13. IPCC(2000a), 14. IPCC (2000b); 15. IPCC (2001c); 16. IPCC (2001a); 17. IPCC (2001b); 18. IPCC/TEAP (2005); 19. IPCC (2005); 20. IPCC (2007c); 21. IPCC (2007a); 22. IPCC (2007b); 23. IPCC (2012b); 24. IPCC (2012a)

Table 21-3: Two possible entry points for thinking about vulnerability to climate change (adapted from Füssel 2007).

Context	**Climate change impacts perspective**	**Vulnerability perspective**
Root problem	Climate change	Social vulnerability
Policy context	Climate change mitigation, compensation, technical adaptation	Social adaptation, sustainable development
Illustrative policy question	What are the benefits of climate change mitigation?	How can the vulnerability of societies to climatic hazards be reduced?
Illustrative research question	What are the expected net impacts of climate change in different regions?	Why are some groups more affected by climatic hazards than others?
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to current climate variability
Starting point of analysis	Scenarios of future climate change	Current vulnerability to climatic stimuli
Analytical function	Descriptive, positivist	Explanatory, normative
Main discipline	Natural science	Social science
Meaning of ‘vulnerability’	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors
Vulnerability approach	Integrated, risk-hazard	Political economy
Reference	McCarthy et al (2001)	Adger (1999)

Table 21-4: Dimensions of assessments of impacts and vulnerability and of adaptation drawn upon to serve different target audiences (cf. Table 21-1). Scales refer to the level of aggregation at which study results are presented. Entries are illustrations of different types of study approaches reported and evaluated in this volume, with references given both to the original studies and to the chapters in which they are cited. Aspects of some of the studies in this table are also alluded to in section 21.5.

Approach/audience: Scale:	Impacts/vulnerability	Adaptation	Target audience
Global	Resource availability[1,2,3] Impact costs[4,5,6,7] Vulnerability/risk mapping[8,9,10] Hotspots analysis[11]	Adaptation costs[4,5,7]	- Policy negotiations - Development aid - Disaster planning - Capacity building
Continental/ biome	Observed impacts[12,13,14] Future biophysical impacts[15,16] Impact costs[5,15] Vulnerability/risk mapping[17]	Adaptation costs[5] Modelled adaptation[18]	- Capacity building - International law - Policy negotiations - Regional development
National/ state/province	Observed impacts[19,20,21] Future impacts/risks[22,22,23] Vulnerability assessment[23] Impact costs[24]	Observed adaptation[25] Adaptation assessment[23,26]	- National adaptation plan/strategy - Nat. Communication - Legal requirement - Regulation
Municipality/ basin/patch/ delta/farm	Hazard/risk mapping[27] Pest/disease risk mapping[28] Urban risks/vulnerabilities[29]	Adaptation cost[27] Urban adaptation[29,30]	- Spatial planning - Extension services - Water utilities - Private sector
Site/field/tree/ floodplain/ household	Field experiments[31]	Coping studies[32,33] Economic modelling[34] Agent-based modelling[35]	- Individual actors - Local planners

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Notes for Table 21-4

[1] Global terrestrial water balance, in the Water Model Intercomparison Project (Haddeland *et al.*, 2011), see chapter 3

[2] Global dynamic vegetation model intercomparison (Sitch *et al.*, 2008), see chapter 4

[3] Impacts on agriculture, coasts, water resources, ecosystems and health in the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP – Schiermeier, 2012), see chapter 19

[4] UNFCCC study to estimate the aggregate cost of adaptation (UNFCCC, 2007), which is critiqued by Parry (2009) and Fankhauser (2010).

[5] The Economics of Adaptation to Climate Change study (World Bank, 2010).

[6] Chapter 17 provides a thorough evaluation of global modelling studies (see also chapters 14 and 16)

[7] Impacts on agriculture and costs of adaptation (e.g. Nelson *et al.*, 2009), see chapter 7

[8] Quantifying and Understanding the Earth System (QUEST) Global-scale impacts of climate change (GSI) project (Arnell *et al.*, submitted) [not cited in FOD chapters]

[9] OECD project on Cities and Climate Change (Hanson *et al.*, 2011), see chapters 5, 23, 24 and 26

[10] For critical reviews of global vulnerability studies, see Füssel (2010) and Preston et al.(2011)

[11] A discussion of hotspots can be found in section 21.3.3, with a critique in section 21.5.3

[12] Satellite monitoring of sea ice over polar regions (Comiso and Nishio, 2008), see also Comiso (in prep.) and chapters 18 and 28

[13] Satellite monitoring of vegetation growth (e.g., Piao *et al.*, 2011) and phenology (e.g., Heumann *et al.*, 2007), see chapters 4 and 18

[14] Meta-analysis of range shifts in terrestrial organisms (e.g., Chen *et al.*, 2011), see chapters 4 and 18

[15] Physical and economic impacts of future climate change in Europe (Ciscar *et al.*, 2011), see chapter 23

[16] Impacts on crop yields in West Africa (Roudier *et al.*, 2011) [not cited in FOD chapters]

[17] Climate change integrated methodology for cross-sectoral adaptation and vulnerability in Europe (CLIMSAVE) project (Harrison *et al.*, 2012), see Chapter 23

[18] Modelling agricultural management under climate change in sub-Saharan Africa (Waha *et al.*, 2013) [not cited in FOD chapters]

[19] Satellite monitoring of lake levels in China (Wang *et al.*, 2013) [not cited in FOD chapters]

[20] Satellite monitoring of rice phenology in India (Singh *et al.*, 2006), see chapter 18

[21] UK Climate Change Risk Assessment (CCRA, 2012), see chapter 23

[22] United States Global Change Research Program second (Karl *et al.*, 2009) and third (in review) national climate change impact assessments, see chapter 26

[23] The Global Environment Facility (GEF)-funded Assessments of Impacts and Adaptations to Climate Change (AIACC) program addressed impacts and vulnerability (Leary *et al.*, 2008b) and adaptation (Leary *et al.*, 2008a) in developing countries, see chapter 27

[24] Economics of Climate Change national studies in Kenya and Tanzania (SEI, 2009; GCAP, 2011)[not cited in FOD chapters]

[25] Sowing dates of various crops, Finland (Kaukoranta and Hakala, 2008) [not cited in FOD chapters]

[26] Finnish Climate Change Adaptation Research Programme (ISTO) Synthesis Report (Ruuhela, 2012)

[27] Urban flood risk and adaptation cost, Finland (Perrels *et al.*, 2010) [not cited in FOD chapters]

[28] See Garrett (2013) for a specific example of a risk analysis, or Sutherst (2011) for a review – and see chapter 25.

[29] New York City coastal adaptation (Rosenzweig *et al.*, 2011), see chapters 8 and 26

[30] Bangkok Assessment Report of Climate Change (BMA/GLF/UNEP, 2009), see chapters 8 and 24

[31] Field, chamber and laboratory plant response experiments (e.g., Long *et al.*, 2006; Hyvönen *et al.*, 2007; Wittig *et al.*, 2009; Craufurd *et al.*, 2013), see chapters 4 and 7

[32] Farming response to irrigation water scarcity in China (Liu *et al.*, 2008) and see chapter 13

[33] Farmers' mechanisms for coping with hurricanes in Jamaica (Campbell and Beckford, 2009) and see chapter 29

[34] Modelling micro-insurance of subsistence farmers for drought losses in Ethiopia (Meze-Hausken *et al.*, 2009) [not cited in FOD chapters]

[35] Simulating adaptive behaviour of farming communities in the Philippines (Acosta-Michlik and Espaldon, 2008), see chapter 24

Table 21-5: Reliability of climate information on temperature and precipitation over a range of spatial and temporal scales. Reliability is assigned to one of seven broad categories from Very High (VH) to Medium (M) through to Very Low (VL). Reliability of information on past climate depends on the availability and quality of observations and in general is higher for temperature as it is easier to observe and a temperature observation at a given location is more representative of temperatures in the surrounding areas than a precipitation observation. In the case of future climate change, which relies on using models of the climate system run into the future, reliability depends on the ability of these models to simulate well the processes that lead to these changes. Again, information on temperature is generally more reliable but this is due to there being more confidence in our ability to simulate the past changes in temperature and our understanding of the processes that cause these changes than is the case for precipitation.

There are significant variations in the reliability of past and future climate information at different temporal and spatial scales, in general at finer scales the information tends to be less reliable given the need for either a greater density observations or models maintaining accuracy at high resolutions. Also, there are significant geographical variations, again the root cause being different for information on past climate than on future climate change. For past climate observation availability and quality is again key and in many regions, especially for precipitation, there are issues with either or both. For future climate change, data availability is less of an issue with the advent of large ensembles of climate model projections but quality can be a significant problem in some regions where the models perform poorly and there is little confidence that the processes driving the projected changes are accurately captured.

Scale	**Temporal**	**Annual**		**Seasonal-Monthly**		**Daily**	
Spatial	**Variable** **Era**	**Temp**	**Precip**	**Temp**	**Precip**	**Temp**	**Precip**
Global	Past	VH	H	VH	H	N/A	N/A
	Future change	VH – direction H – amount	H – direction MH – amount	VH – direction H – amount	H – direction MH – amount	N/A	N/A
Regional, Large river basin	Past	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability
	Future change	VH – direction H – amount	H-L depends on capture of processes	VH – direction H – amount	H-L depends on capture of processes	VH – direction MH – amount	H-L depends on capture of processes
National, State	Past	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-L depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability
	Future change	VH – direction H – amount	H-L depends on capture of processes	VH – direction H – amount	H-L depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes
City, County	Past	VH-H depends on observation availability	H-VL depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability	H-MH depends on observation availability	H-VL depends on observation availability
	Future change	H – direction MH – amount	H-VL depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes	H – direction M – amount	M-VL depends on capture of processes
Village, Site/field	Past	VH-H depends on observation availability	H-VL depends on observation availability	VH-H depends on observation availability	H-VL depends on observation availability	H-MH depends on observation availability	H-VL depends on observation availability
	Future change	H – direction MH – amount	H-VL depends on capture of processes	H – direction MH – amount	H-VL depends on capture of processes	H – direction M – amount	M-VL depends on capture of processes

Table 21-6: Placeholder for a table to be derived from the AR5 WG1 Ch14 table (still in development by WG1) evaluating confidence in GCM simulations and projections of temperature and precipitation and linked regional climate phenomena currently being finalised for the final draft of that chapter.

Table 21-7: Leading knowledge gaps and related research needs.

	Knowledge Gap	**Research need**
1	There is no clear understanding of how to integrate the data products from multi-model multi-method research for producing climate change projections. This results in data products of conflicting time and space resolution scales, with differing dependencies and assumptions, and resultant non-equivalency of variables. At present each product is individually plausible and mostly defensible in-so-far as it has physical basis within the assumptions of the method. However, at decision-relevant scales the products collectively indicate a wide range of outcomes with high uncertainty and contradictions and are thus not strongly actionable.	The approaches on how to understand the source of spread and contradiction in the information at scales relevant to users. This raises the strong need to find ways to identify the value signal within the noise of the multi-model multi-method climate projections methods, and build robust messages that are user-relevant and actionable.
2	Limits to predictive information. The community engaged in developing regional climate change projections have forded ahead with increasing sophistication of tools and models, yet at the regional and adaptation decision scales the signal to noise ratio has not advanced commensurately (e.g. Maslin and Austin, 2012). The inherent uncertainty of the emerging projections is poorly articulated (or even absent), and where provided is likely an under-estimate of the true range of uncertainty.	Means to identify the limit of predictive information, and/or articulate the real uncertainty inherent in and information product, are important to inform response to climate change, and understand when climate information is useful at the scales of need. Research is critically needed to distinguish apart the inherent blend of stochastic and deterministic variability and change of the regional climate, which is intrinsically a function of scale, variable, and application.
3	The attributes of regional change through which impacts are manifest, such as the intensity, persistence, distribution, recurrence, and frequency, are poorly understood. The information conveyed to the adaptation community is dominated by aggregates in time and space (e.g. SREX regional averages, or time averages), which hide the important attributes underlying these aggregated changes. In part this is a consequence of (1) and (2) above.	The research need is for greater nuance in the understanding of the data to unpack the regional projections into terms relevant for impacts and adaptation. For example, how is the shape of the distribution of weather events changing (not just the extremes), or information on the stability of critical global teleconnection patterns that contribute to the variability of a region.
4	The historical record for many regions, especially those regions most vulnerable to climate change, is poor to the extent that the historical record is at best an estimate with unknown uncertainty. This severely undermines the development of regional change analysis, limits the evaluation of model skill, and presents a weak baseline against which to assess change signals.	The research need focuses on how to best integrate the multiplicity of historical data, including data rescue, raw observations, processed gridded products (e.g. CRU and GPCP), satellite data, and reanalysis data sets. For any given region data sets present different views of the past, and may even contradict each other. Research such as Zhang et al (2012), which evaluates different reanalysis products, indicates the value that can be attained for advancing understanding of the data veracity at regional scales.
5	Model projections of regional climate change impacts seldom have uncertainty ranges attached to estimates. Even if these are provided, they rarely distinguish the relative contributions of impact model uncertainty and climate projection uncertainty.	There is a need for more rigorous and comprehensive uncertainty analysis of impact models, accounting for both parameter and structural uncertainties. Model inter-comparison exercises offer one means for examining structural uncertainty.
6	Model sensitivity studies and inter-comparison exercises are beginning to reveal fundamental flaws and omissions in some impact models in the representation of key processes that are expected to be important under projected climate changes. For example, high temperature constraints, and CO2 and drought effects on agricultural yields are poorly represented in many crop models.	New field and chamber experiments are required, with controlled atmospheric composition and climate conditions, using modern and potentially adapted cultivars, to improve understanding of key processes operating in crop plants and soils under changed environments. Such experiments are needed across a range of biogeographical and edaphic zones in different regions of the world.
7	New global scenarios are under development, based on climate projections for different representative concentration pathways (RCPs) and socio-economic scenarios based on shared socio-economic pathways (SSPs). However, there is currently little or no guidance on how these projections are to be accessed or applied in IAV studies. Moreover, as yet, quantitative SSPs are available only for large regions (basic SSPs), and regional SSPs that are consistent with the global SSPs have not yet been developed (extended SSPs).	Extended SSPs for major sub-continental regions of the world, including variables that define aspects of adaptive capacity and guidance on how to combine RCP-based regional climate projections with regional SSPs to form plausible regional scenarios for application in IAV analysis.

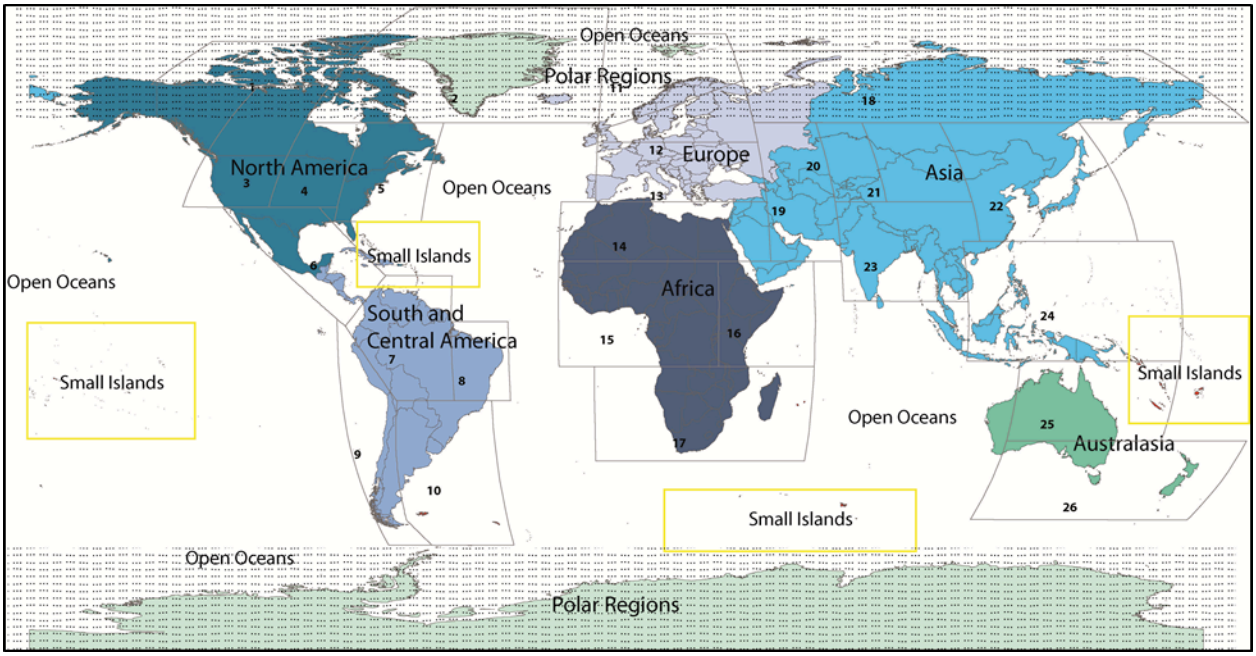


Figure 21-1: Map showing regions described in chapters 22-30 of Part B (colours) with numbered [26] open polygons defining sub-regions over land used to summarise projected changes in climate in this chapter Note that regional specifications are approximate, as aspects of some regions or territories are treated in more than one chapter. Supplementary material contains more details of chapter assignment (Table S21-1) as well as co-ordinates of the polygons (Table S21-2).

Figure 21-2: Entry points for adaptation science, policy, and practice (based on Hinkel et al, submitted).

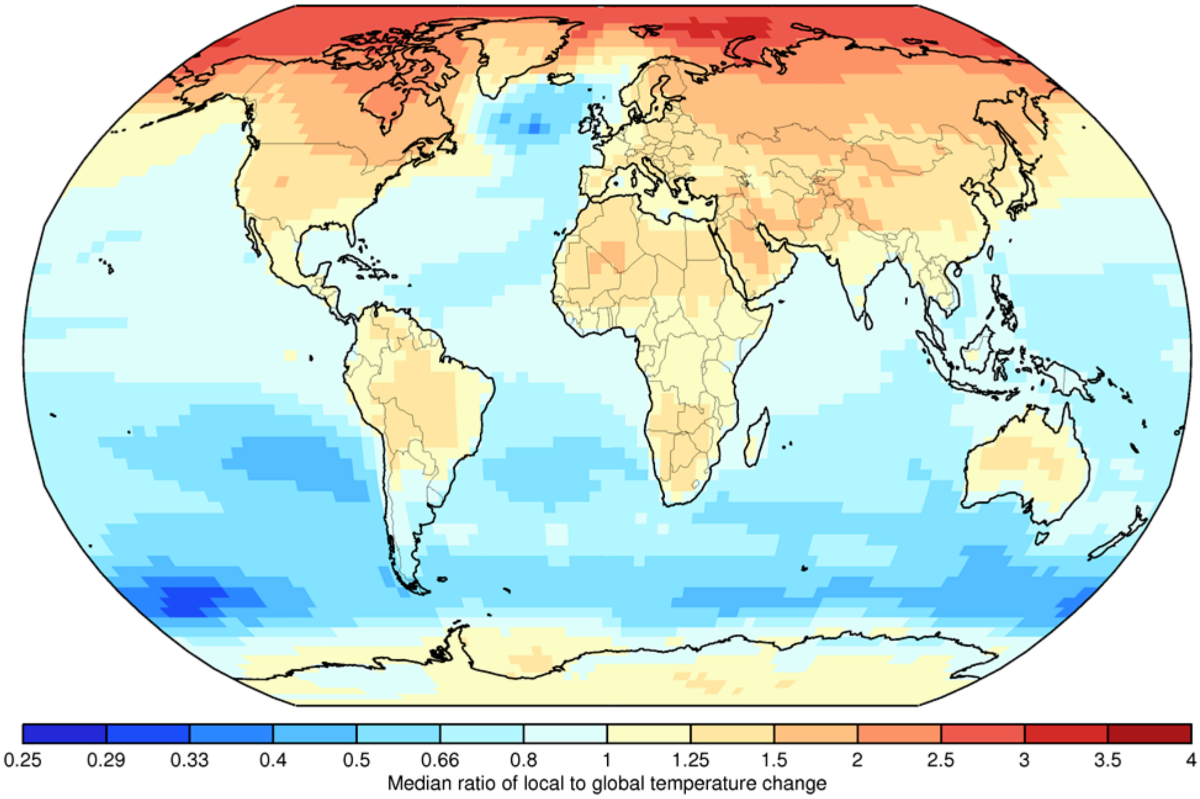


Figure 21-3. CMIP5 ensemble median ratio of local:global average temperature change in the period 2070-2100 relative to 1961-90 under the RCP8.5 emissions/concentrations scenario. The values are displayed on a common 2.5°x3.75° grid onto which each models' data were regridded and they were calculated as follows:

1) For each model calculate the local change between 1961-90 and 2070-2100 at each grid cell and divide by the global average change over the same period;

2) identify the median value across the ensemble at each grid cell.

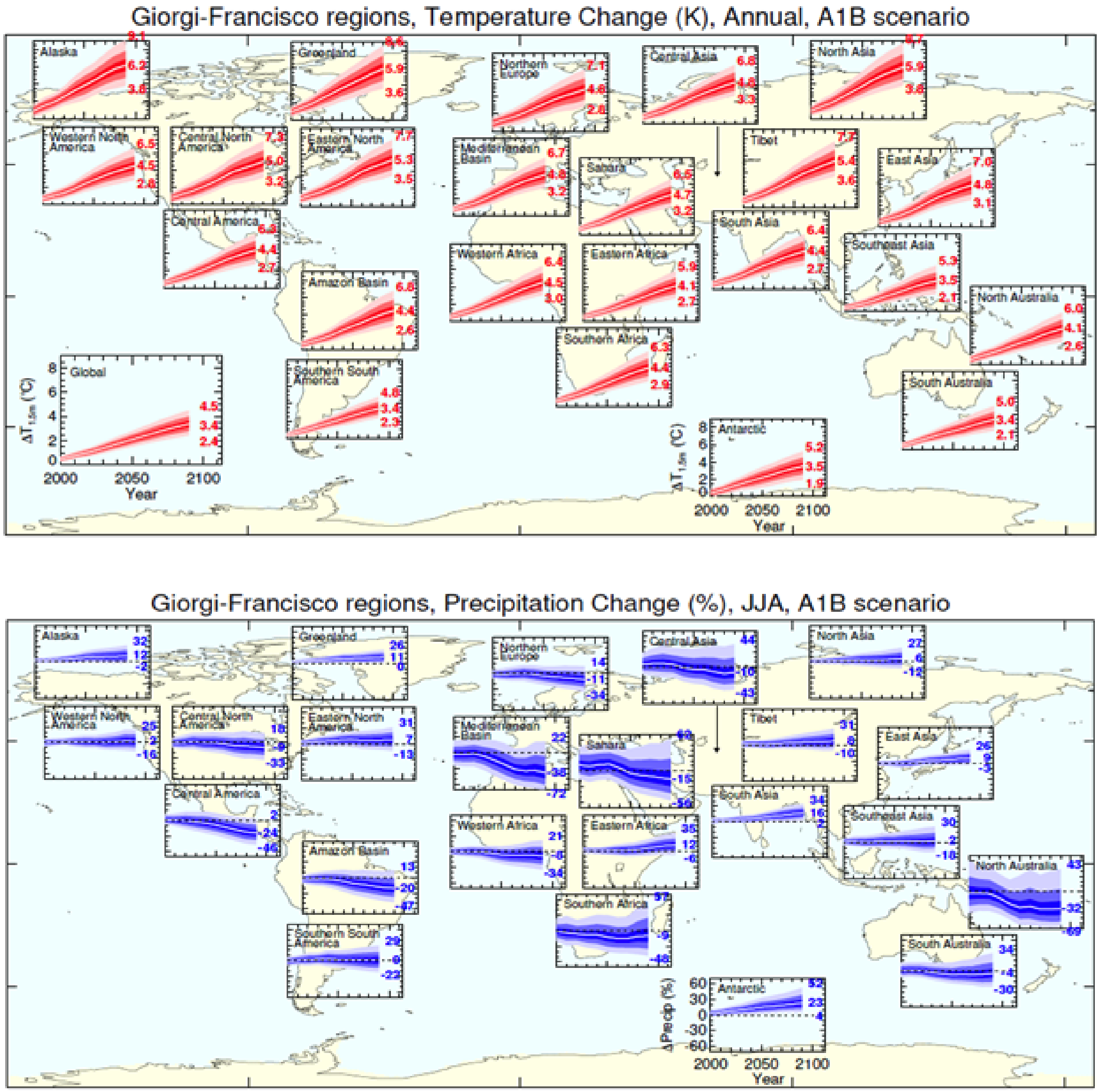


Figure 21-4: Evolution of the 5%, 17%, 33%, 50%, 66%, 83% and 95% percentiles of the distribution functions for annual surface air temperature changes (upper panel) and annual precipitation (lower panel) for the Giorgi-Francisco (2000) regions and the globe with the A1B forcing scenario. Twenty year means relative to the 1961-1990 baseline are plotted in decadal steps using a common y-axis scale. The 5%, 50% and 95% percentile values for the period 2080-2099 are displayed for each region. (From Harris et al. 2012)

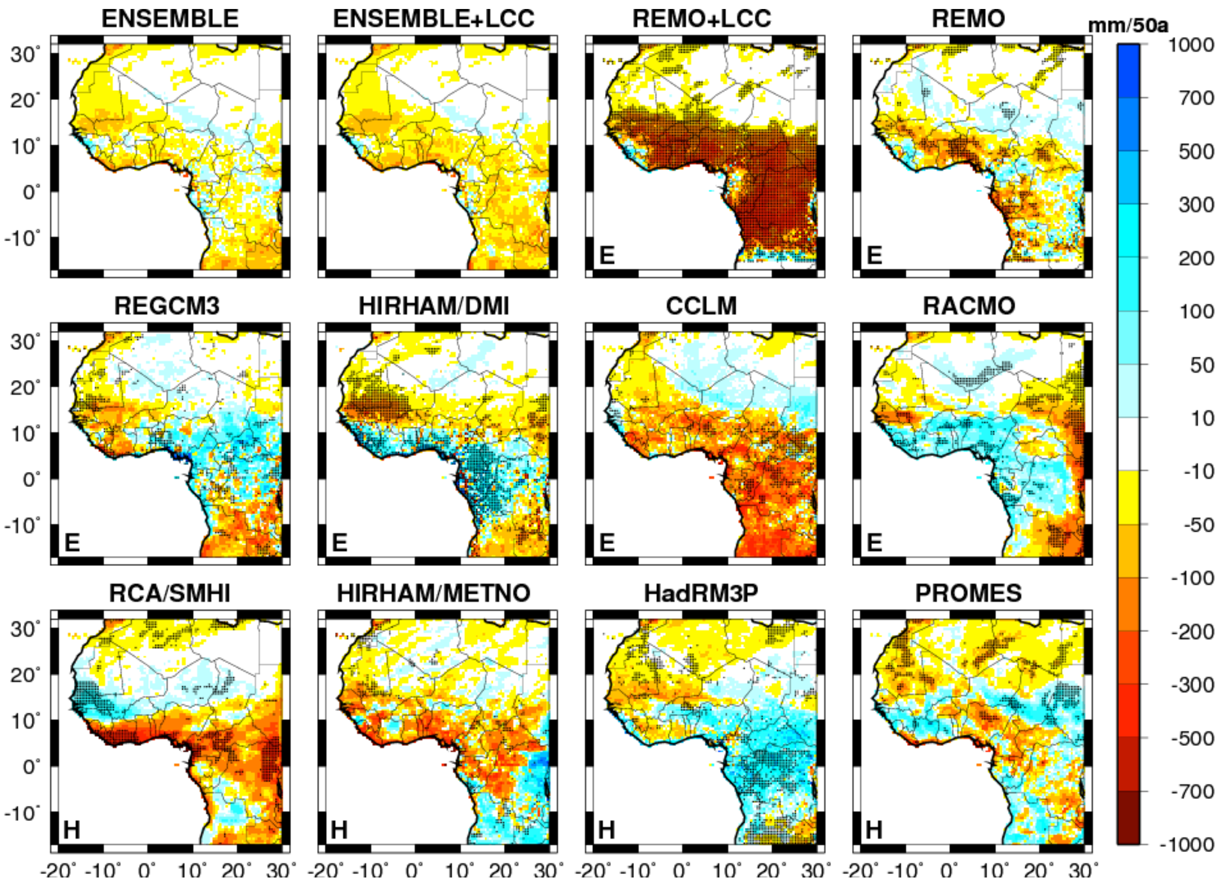


Figure 21-5: Linear changes (i.e. changes obtained by fitting the time series at each grid point with straight lines) of annual precipitation during the 2001-2050 period from 10 individual RCM experiments and the MME mean under the A1B emission scenario. The top middle panels also account for projected land cover changes (see Paeth et al. 2011 for further explanation). Note that the REMO trends in both panels arise from a three-member ensemble whereas all other RCMs are represented by one single simulation. Trends statistically significant at the 5% level are marked by black dots. (From Paeth et al. 2011)

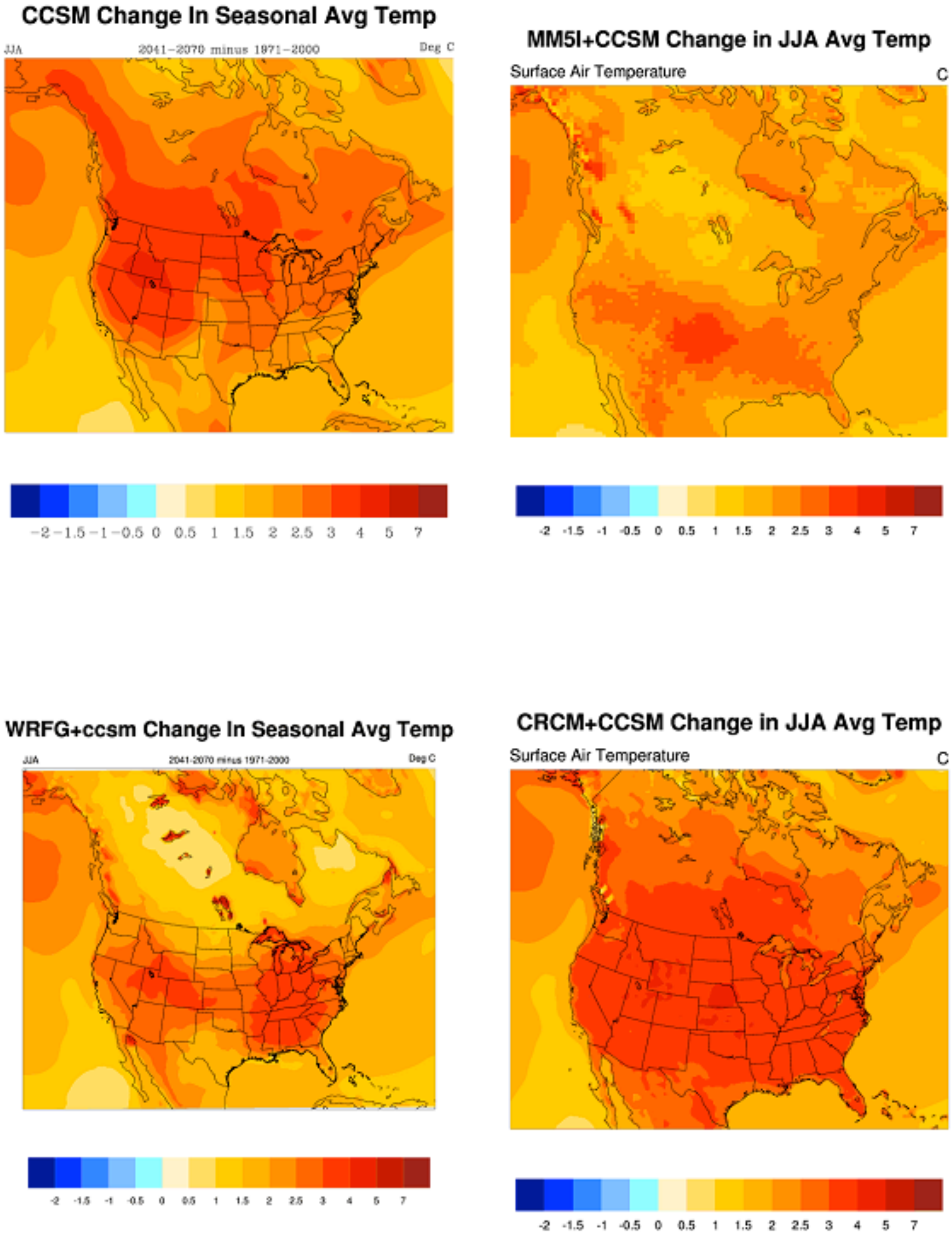


Figure 21-6: Change in summer (JJA) average temperature (2041-2070 minus 1971-2000) from (top left) the NCAR CCSM3, (top right) the MM5 regional climate model driven by the CCSM3; (bottom left) the WRF model, driven by CCSM3, and (bottom right) the Canadian CRCM, driven by CCSM3. Temperature is in °C. Data from the NARCCAP program. (From Mearns et al., 2009, 2013)

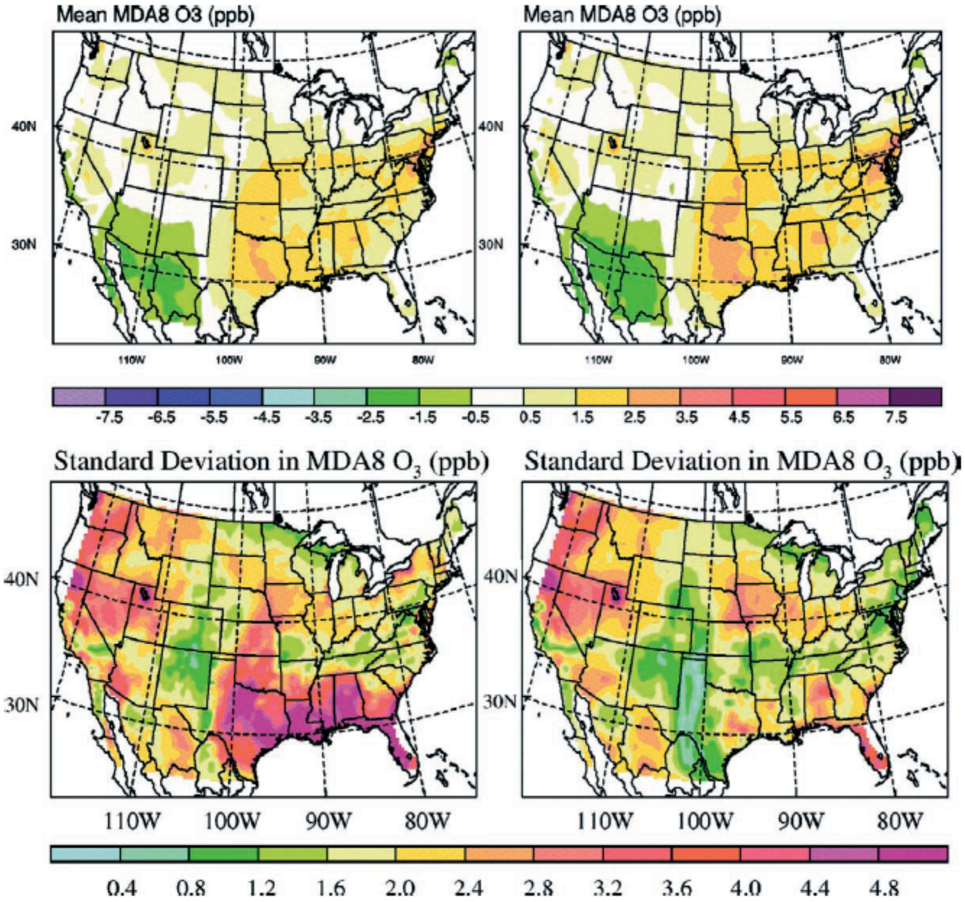


Figure 21-7: Mean (top panels) and standard deviation (bottom panels) in future-minus-present (2081-2100 minus 1981-2000) MDA8 summer ozone concentrations across (left-hand panels) all 7 experiments (5 regional and 2 global) and, for comparison purposes (right-hand panels) not including the WSU experiment (which simulated July only conditions). (From Weaver et al. 2009)

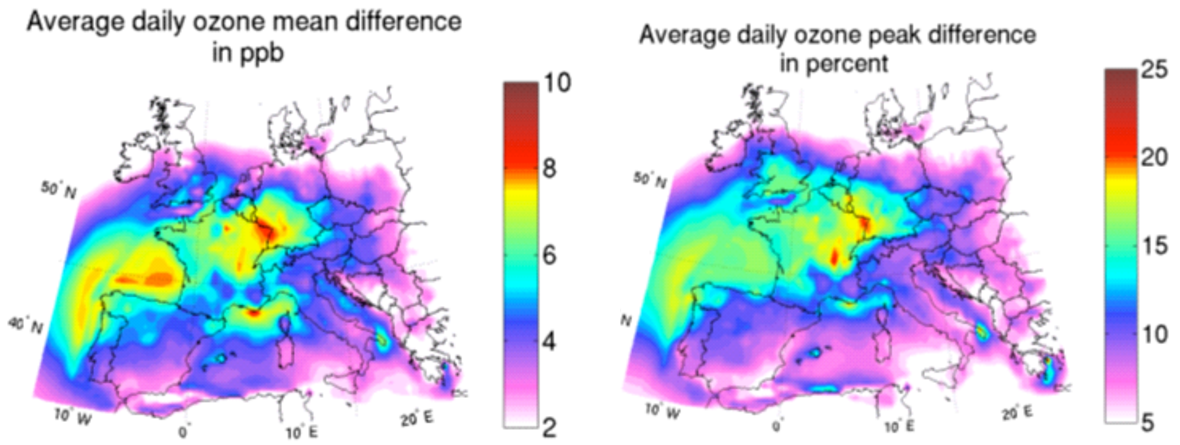


Figure 21-8: Difference in average summer daily ozone mean (left panel) and peak (right panel) concentration over Europe due to climate change, (2071-2100 minus 1961-1990), A2 scenario. (From Meleux et al. 2007)

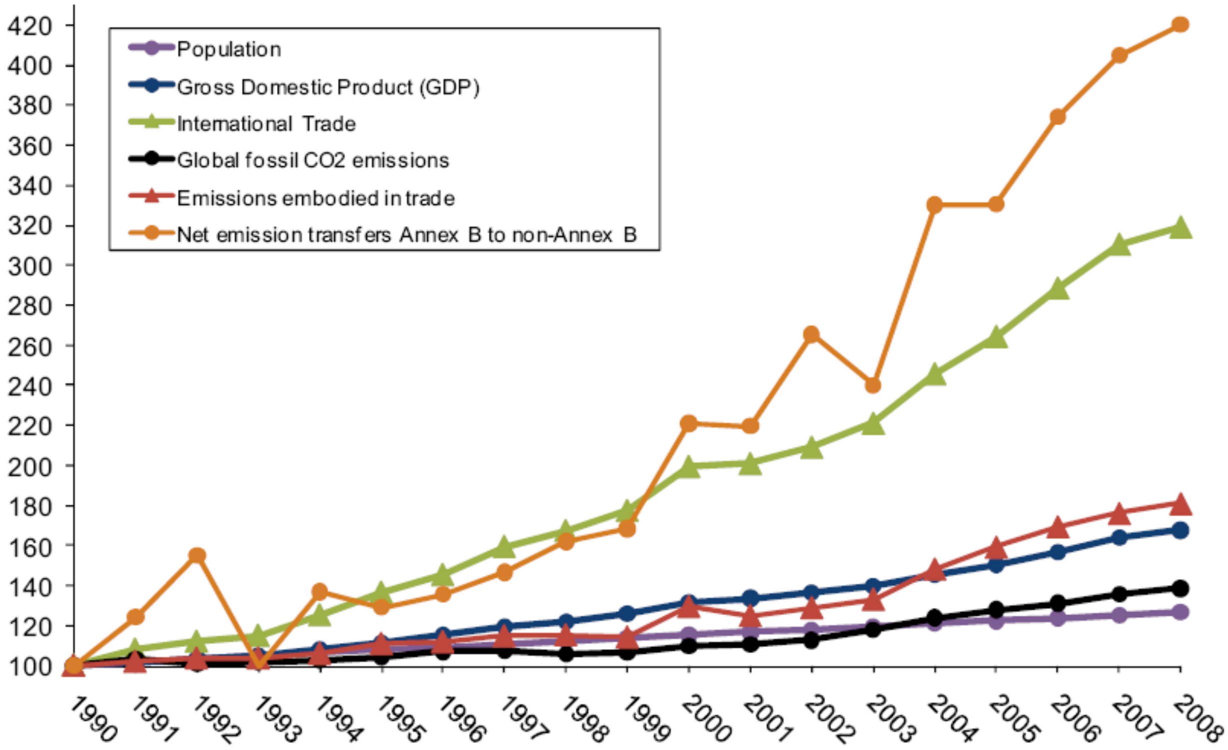


Figure 21-9: Growth rates from 1990-2008 of international trade, its embodied CO_2 emissions and net emissions transfers from Annex B and non-Annex B countries compared to other global macrovariables, all indexed to 1990 (Peters et al., 2011).]

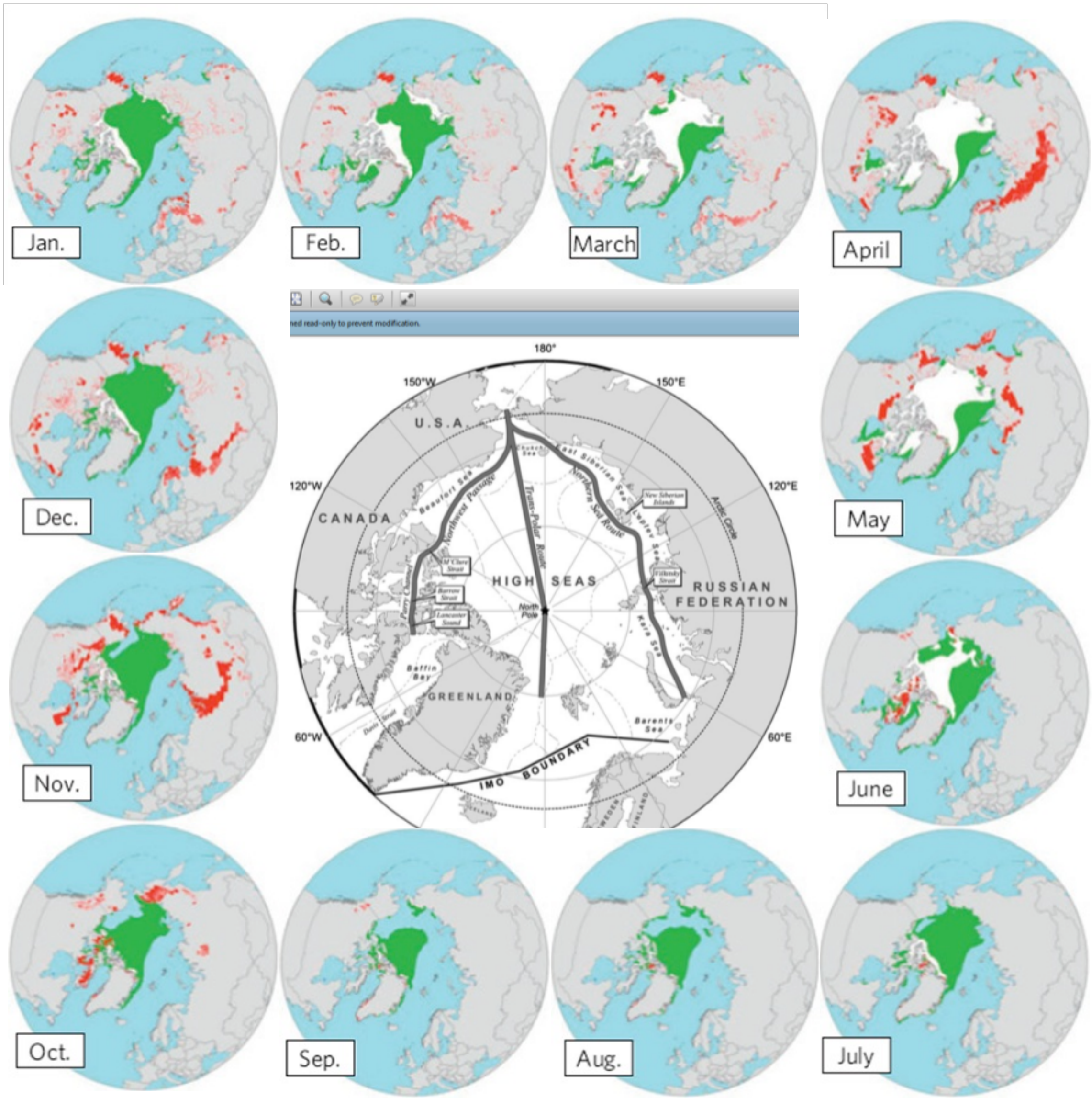


Figure 21-10: (a) Marine exclusive environmental zones (EEZs – dashed lines) of Canada, Greenland/Denmark, Norway, Russia, and the USA, and location of the Northwest Passage, Northern Sea Route, Trans-Polar Route, and international high seas within the IMO Guidelines Boundary for Arctic shipping (thick black border). After Stephenson (2013). (b) Projected change in accessibility of maritime and land-based transportation by mid-century (2045-2059 relative to 2000-2014) using the Arctic Transport Accessibility Model and CCSM3 climate and sea ice estimates assuming an SRES A1B scenario. Green areas denote new maritime access to Polar Class 6 vessels (light icebreaker); white areas remain inaccessible. Red delimits areas of lost winter road potential for ground vehicles exceeding 2 metric tonnes (Stephenson et al., 2011).

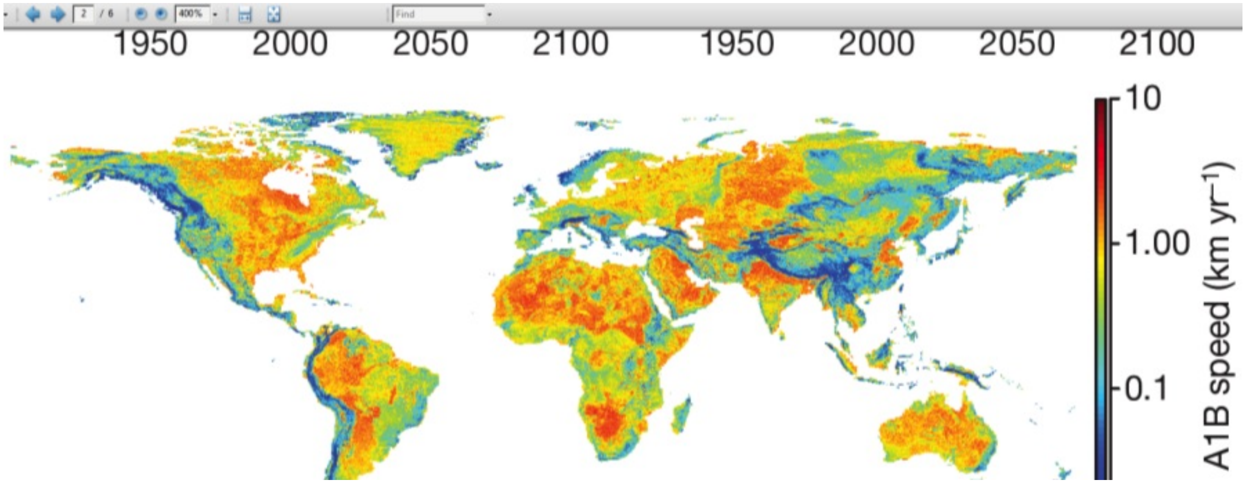


Figure 21-11: The velocity of shifting climatic zones due to climate change based on the average of 16 global climate models for an A1B emissions scenario and temporal gradients computed for 2050-2100. (Loarie et al., 2009).

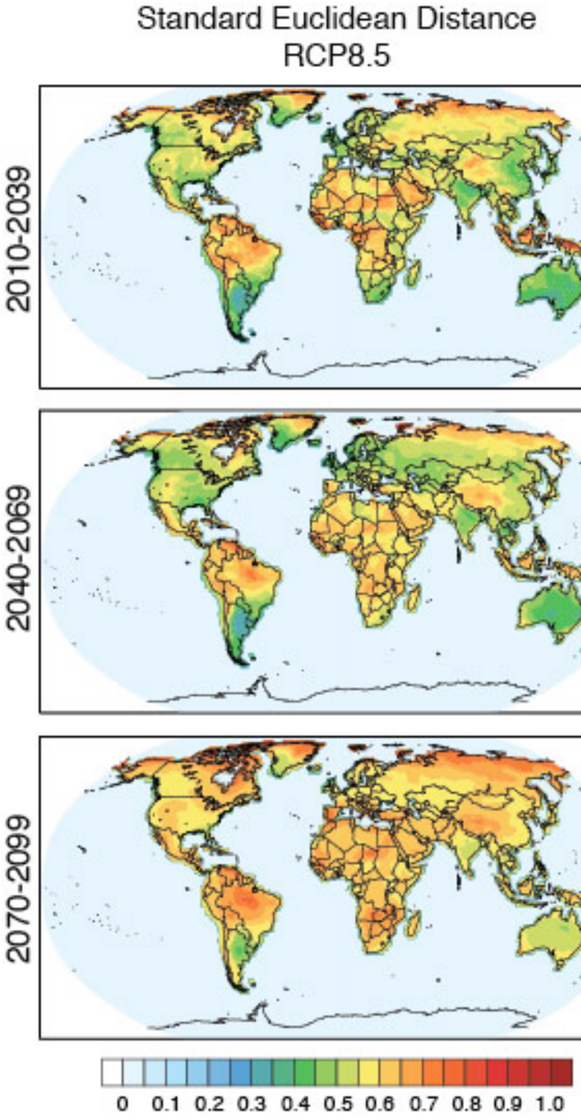
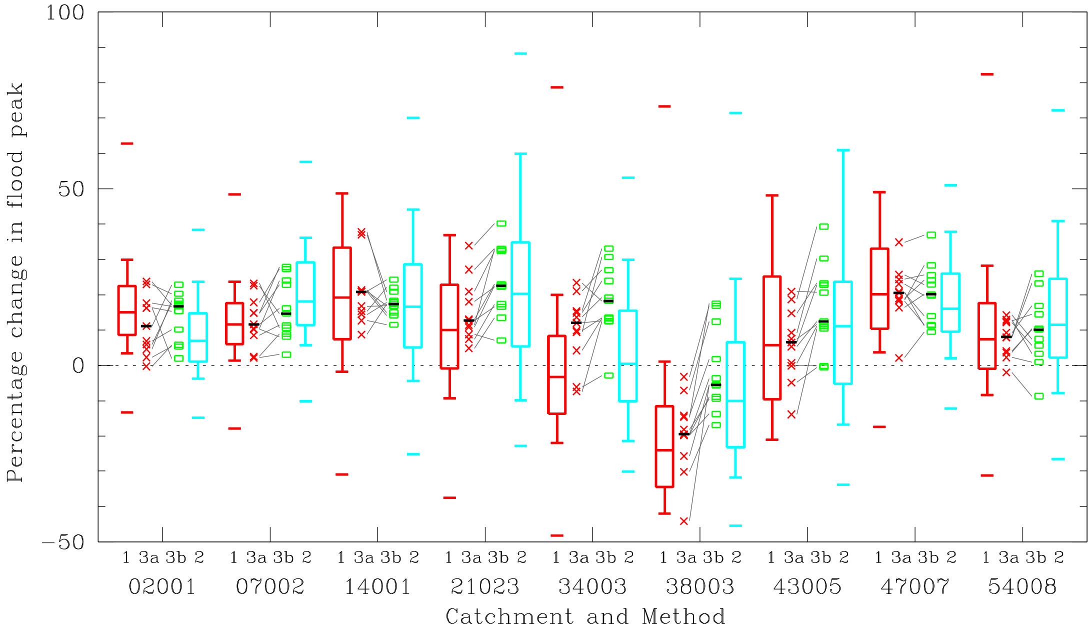


Figure 21-12: The relative aggregate climate change between the 1975-2005 period and the 2010-2039, 2040-2069 and 2070-2099 periods of RCP8.5. The aggregate climate change is calculated using the Standard Euclidean Distance (SED) across the 28-dimensional climate space formed by 7 climate variables in each of 4 seasons. The absolute values of change in each variable are normalized to the maximum global absolute value prior to calculating the SED. The SED values are then normalized to the maximum global SED value. Only land grid points north of 60˚S are used in the normalizations (From Diffenbaugh and Giorgi 2012).

a) 2-year return period



b) 20-year return period

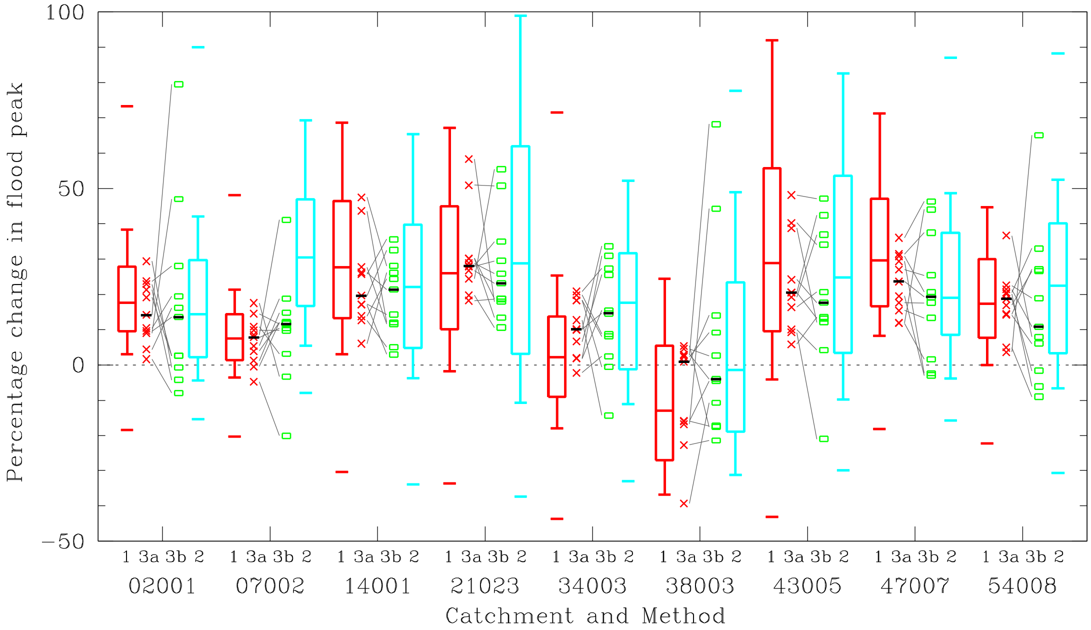


Figure 21-13: The range of percentage change in flood peaks for nine UK catchments at the a) 2-year and b) 20-year return period. Box-and-whisker plots are used to summarise results when using 10,000 UKCP09 Sampled Data (Murphy et al. 2009) change factors (red) and 100 sets of UKCP09 current and future Weather Generator time-series (cyan). Also plotted, are the results when using 11 sets of RCM-derived change factors (red crosses) and when using 11 sets of RCM current and future times-series (green rectangles). The box delineates the 25th-75th percentile range and the whiskers the 10th-90th percentile range, with the median (50th percentile) shown by the line dividing the box. Additional markers outside the whiskers indicate the minima and maxima, if within the plotted range of -50 to +100. The points derived from the RCM results are joined for the corresponding members of the RCM ensemble (grey lines), and the medians for these methods are shown by black horizontal bars.

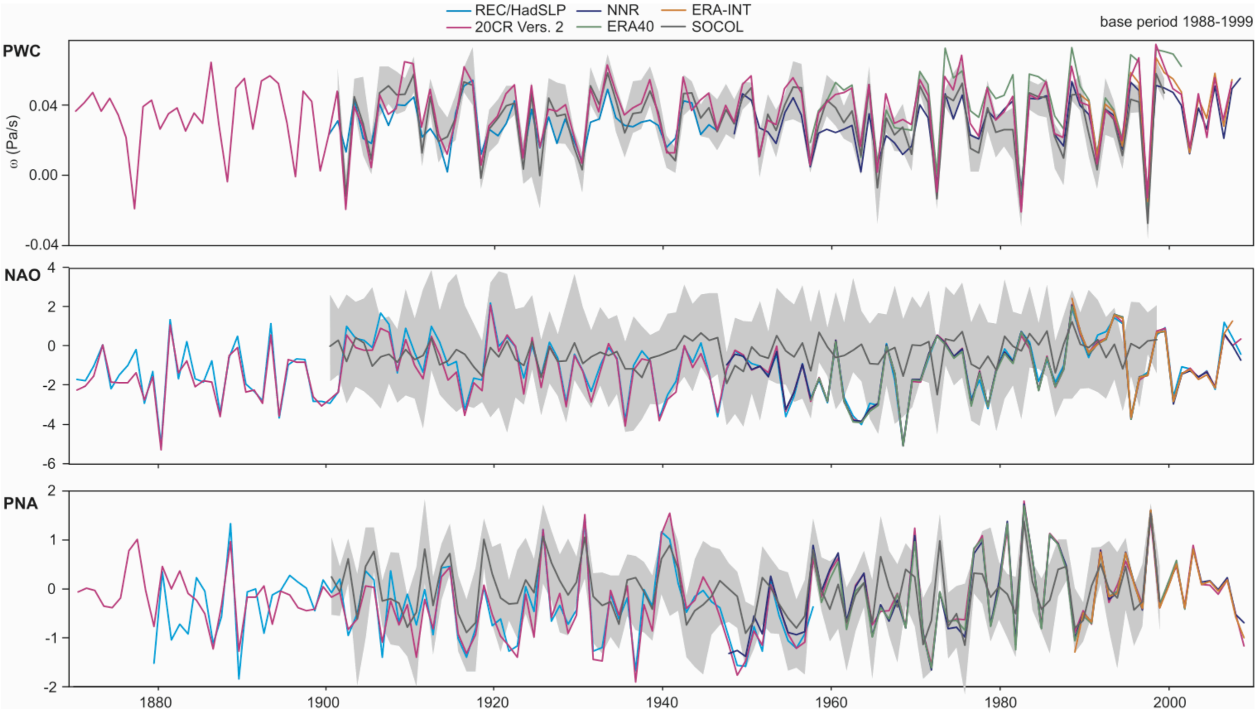


Figure 21-14: Time series of seasonally averaged climate indices representing three modes of large-scale climate variability: (a) the tropical September to January Pacific Walker Circulation (PWC); (b) the December to March North Atlantic Oscillation (NAO); (c) the December to March Pacific North America (PNA) pattern. Indices (as defined in Brönnimann etal. (2009) are calculated (with respect to the overlapping 1989–1999 period) from various observed, reanalysis and model sources: statistical reconstructions of the PWC, the PNA and the NAO, see Brönnimann et al. (2009) for details, (all cyan); 20CR (pink); NCEP–NCAR reanalyses (NNR; dark blue); ERA-40 (green); ERA-Interim (orange). The dark-grey dashed line and grey shading represent the ensemble mean and spread from a climate model ensemble with a lower boundary condition of observed seas-surface temperatures and sea-ice from the HadISST dataset (Rayner et al. 2003), see Brönnimann etal. (2009) for details. The model results provide a measure of the predictability of these modes of variability from sea-surface temperature and sea-ice alone and demonstrate that the reanalyses have significantly higher skill in reproduces these modes of variability.

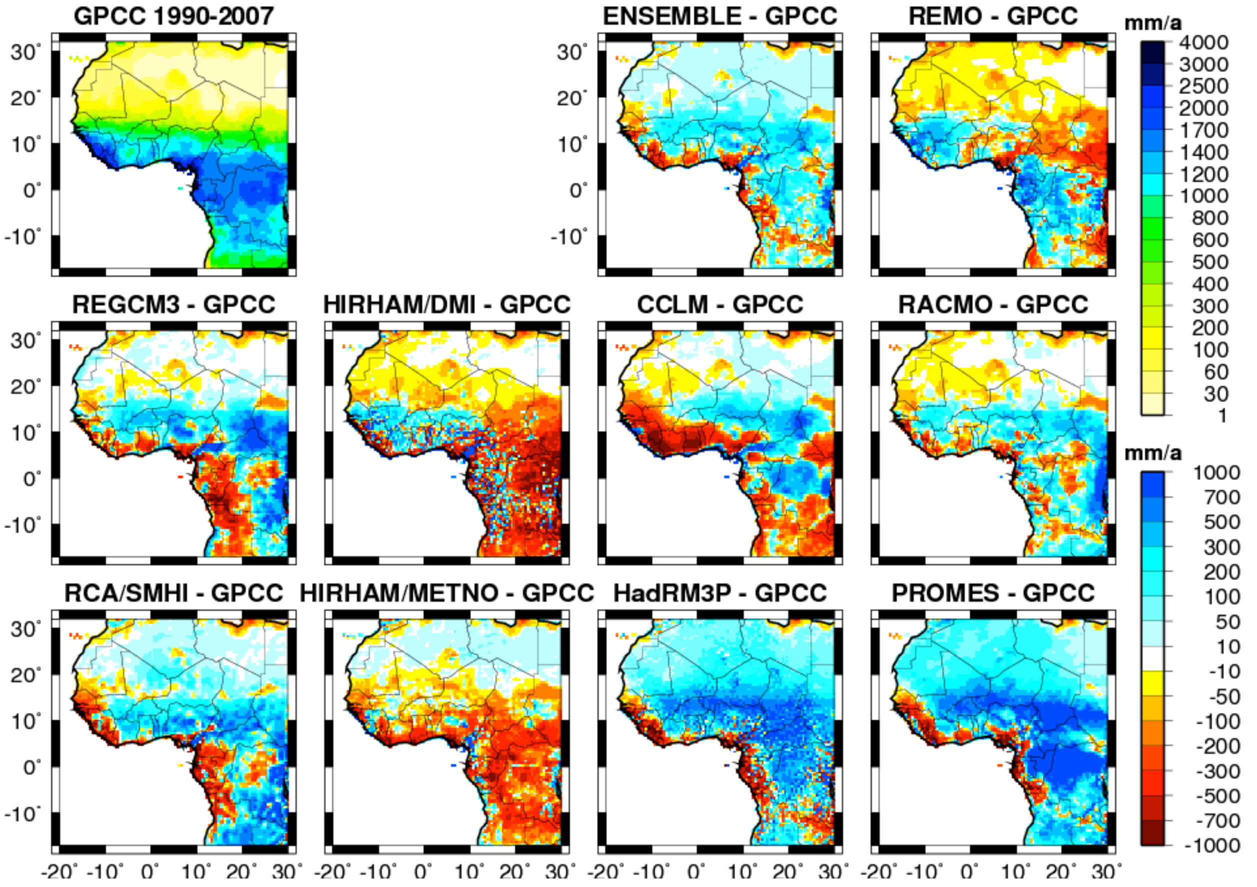
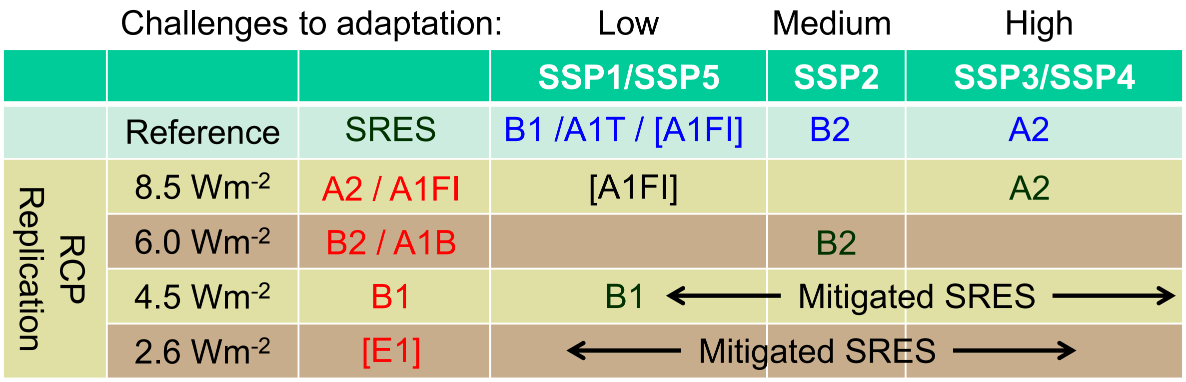
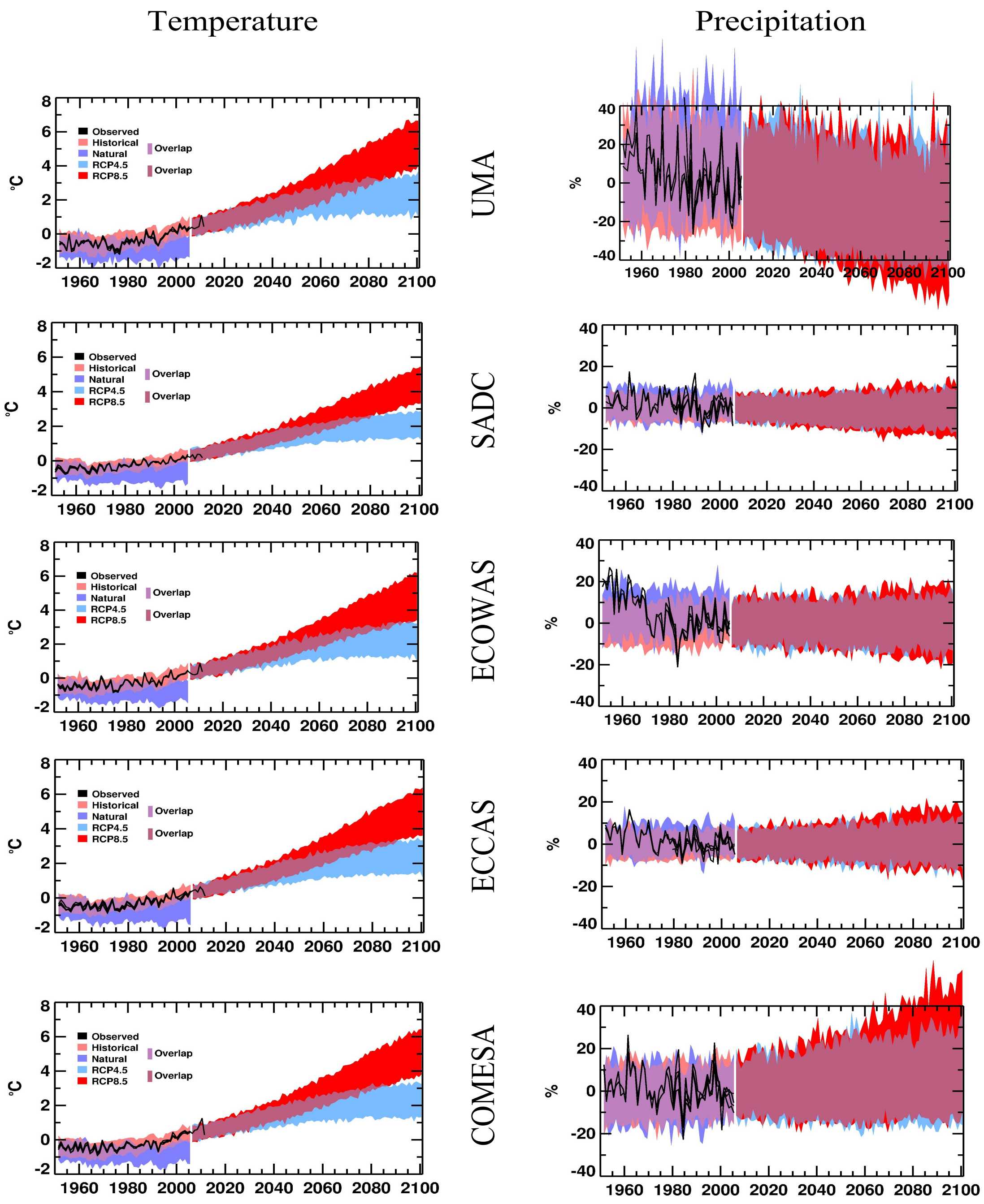


Figure 21-15: Observed 1990-2007 annual precipitation climatology from GPCC (Rudolf et al., 2011), top left, and, in the remaining panels, related systematic errors in 9 individual regional climate model simulations driven by the ERA-Interim reanalyses (Dee et al., 2011) and in the multi-model ensemble mean (Duryan et al., 2010).



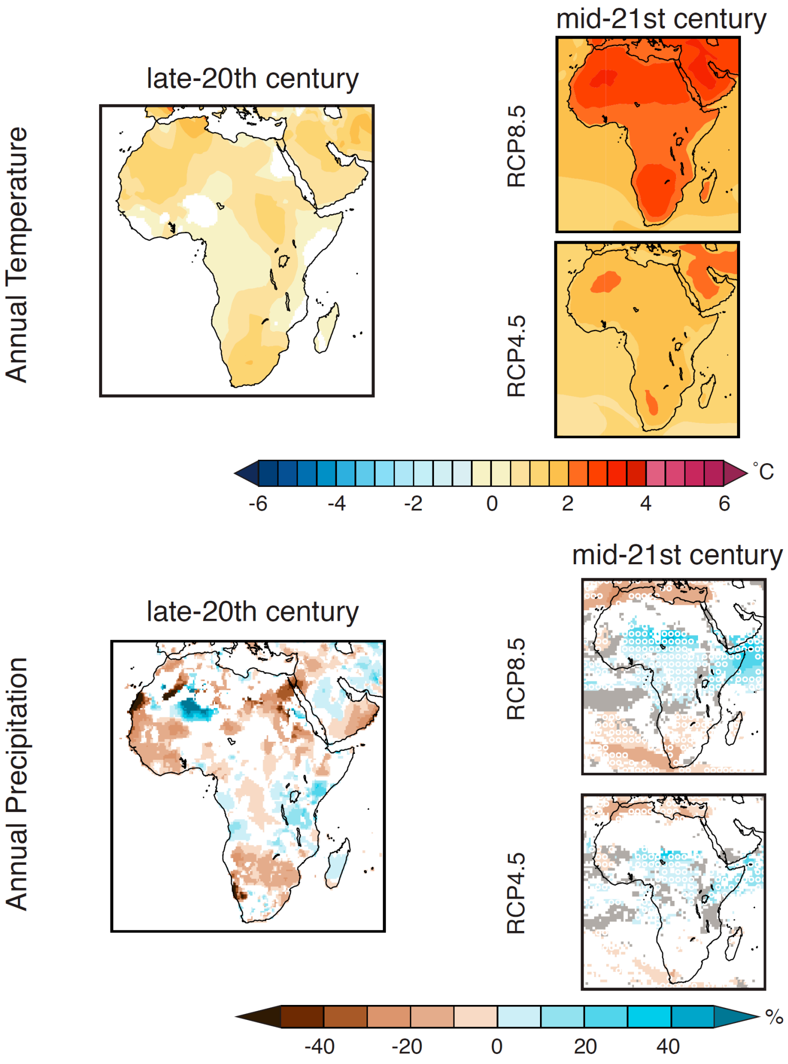
		Challenges to adaptation:	Low	Medium	High
			SSP1/SSP5	SSP2	SSP3/SSP4
	Reference	SRES	B1 /A1T / [A1FI]	B2	A2
RCP Replication	8.5 Wm^{-2}	A2 / A1FI	[A1FI]		A2
	6.0 Wm^{-2}	B2 / A1B		B2	
	4.5 Wm^{-2}	B1	B1 ⟵ Mitigated SRES ⟶		
	2.6 Wm^{-2}	[E1]	⟵ Mitigated SRES ⟶		

Box 21-1 Figure Caption: Approximate mappings of the SRES scenarios onto the new SSP/RCP framework (for details, see text). After Carter et al. (submitted).



Box 21-2 Figure Caption: Observed and simulated variations in past and projected future annual average precipitation and temperature over five African regions, Common Market for Eastern and Southern Africa (COMESA), the Economic Community of Central African States (ECCAS), the Economic Community of West African States (ECOWAS), the Southern African Development Community (SADC) and the Arab Maghreb Union (UMA). Black lines show several estimates from observational measurements. Shading denotes the 5-95 percentile range of climate model simulations, taken from the CMIP5 archive (Taylor et al. 2012), driven with "historical" changes in anthropogenic and natural drivers (68 simulations), historical changes in "natural" drivers only (30) and by two of the RCM emissions/ concentrations scenarios (van Vuuren et al., 2011), "RCP4.5" (68) and "RCP8.5" (68). Data are anomalies from the 1986-2006 average of the individual observational data (for the observational time series) or of the corresponding historical all-forcing simulations. The regions are described in Chapter 22 (section 22.1.2) but the COMESA region labelled here covers COMESA north and includes Rwanda, Uganda, and

Kenya. Precipitation is included for land territories only, while temperature is included for both land and exclusive economic zone territories. The observational datasets used are GISTEMP (Hansen et al. 2010), HadCRUT3 (Brohan et al. 2006), and MLOST (Smith et al. 2008) for temperature, and CMAP (Xie and Arkin 1997), CRU TS 3.10 (Mitchell and Jones 2005), GPCP v2.2 (Adler et al. 2003), and PRECL (Chen et al. 2002) for precipitation. These suffer in some areas from sparse monitoring coverage.



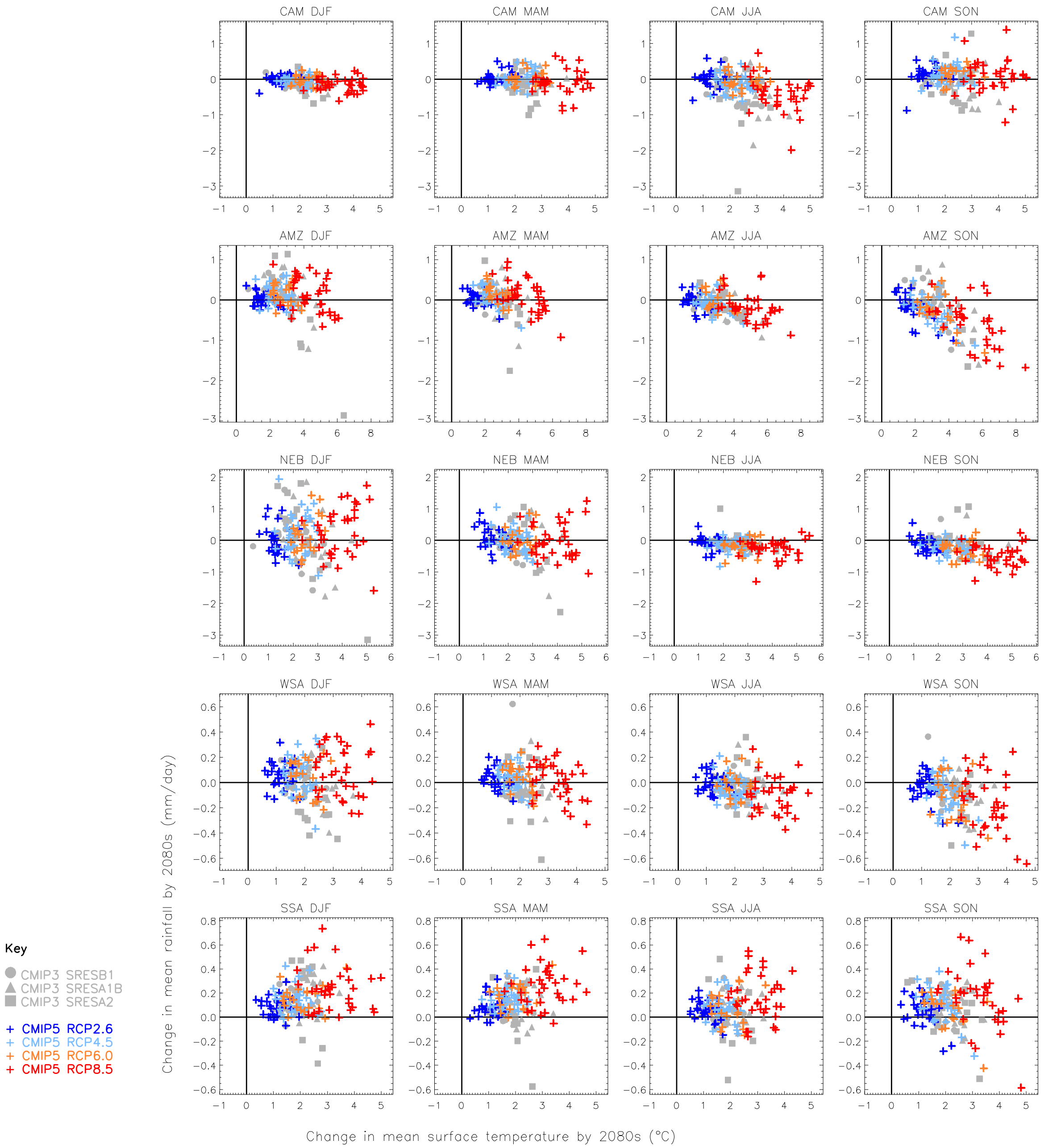
Box 21-3 Figure 1 Caption: Observed and projected changes in annual average temperature and precipitation over Africa. The observations are taken from the CRU TS 3.1 dataset (Harris et al., 2012) and the projections from the CMIP5 multi-model archive (Taylor et al. 2012). Projected changes are shown for the mid-21st century (2046-2065) and the late-21st century (2081-2100) from a baseline period of 1986-2005 under the RCP 4.5 and 8.5 emissions/ concentrations scenarios (van Vuuren et al., 2011). For the observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning in the years 1906 through to 1925. For the CMIP5 projections, four classes of results are displayed:

1) White indicates areas where for >66% of models the change in annual average precipitation is less than twice the baseline standard deviation of the respective model's 20 20-year periods ending in years 1986

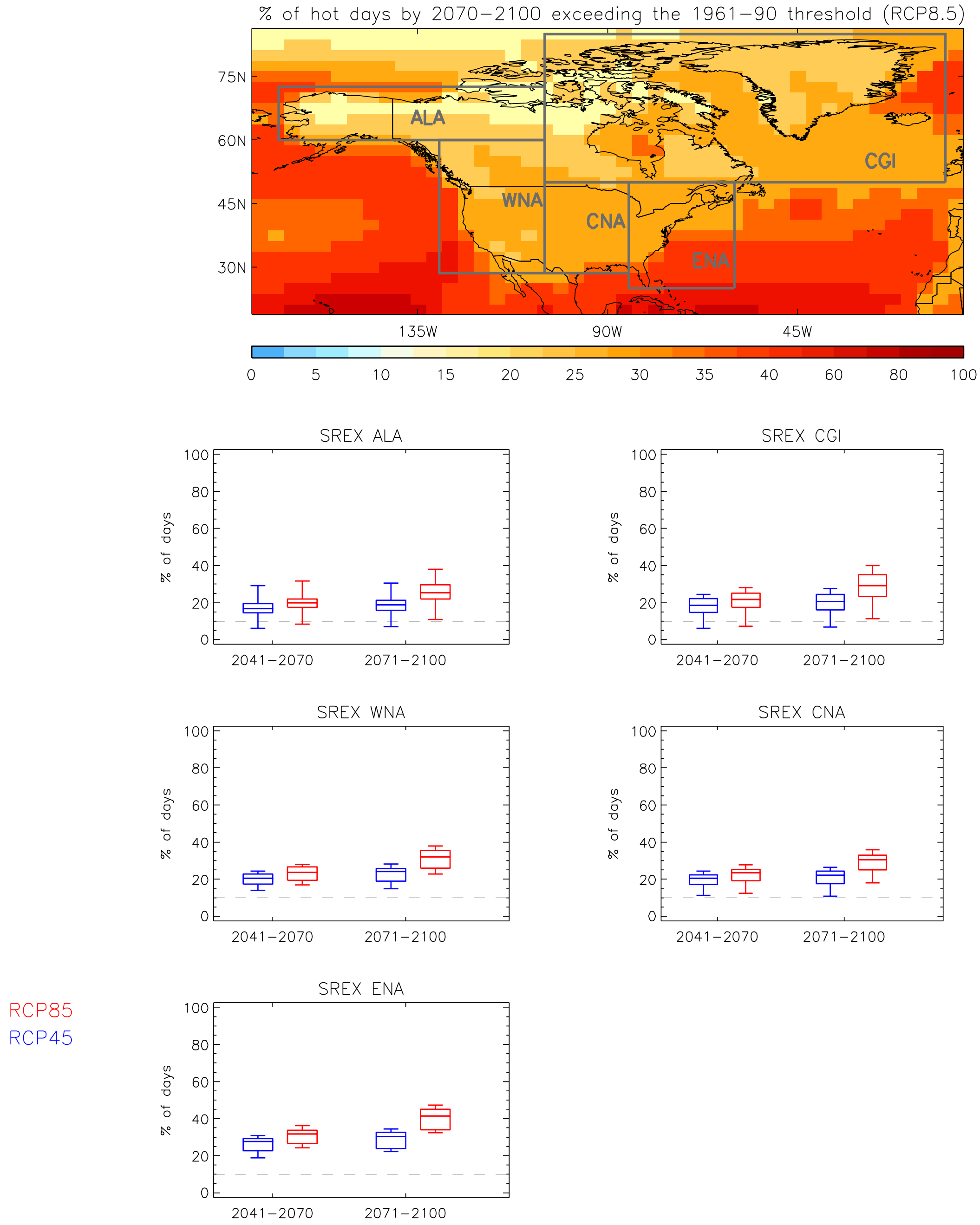
through 2005. Thus in these regions more than 2/3 of models show no significant change (using this measure of significance) in annual average precipitation. However, note that this does not imply no significant change in precipitation averaged over seasonal or shorter time-scales such as months to days.

2) Gray indicates areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation, but <66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation but less than 2/3 agree on whether annual average precipitation will increase or decrease.
3) Colors with circles indicate the change in annual average precipitation averaged over all models in areas where >66% of models exhibit a change greater than twice the respective model baseline standard deviation and >66% of models agree on the sign of change. In these regions more than 2/3 of models show a significant change in annual average precipitation and more than 2/3 agree (but less than 90%) agree on whether annual average precipitation will increase or decrease.
4) Colors without circles indicate the change in annual average precipitation averaged over all models in areas where >90% of models exhibit a change greater than twice the respective model baseline standard deviation and >90% of models agree on whether annual average precipitation will increase or decrease.

For models which have provided multiple realizations for the climate of the recent past and the future, results from each realisation are first averaged to create the baseline-period and future-period mean and standard deviation for each model, from which the multi-model mean and the individual model signal-to-noise ratios are calculated.

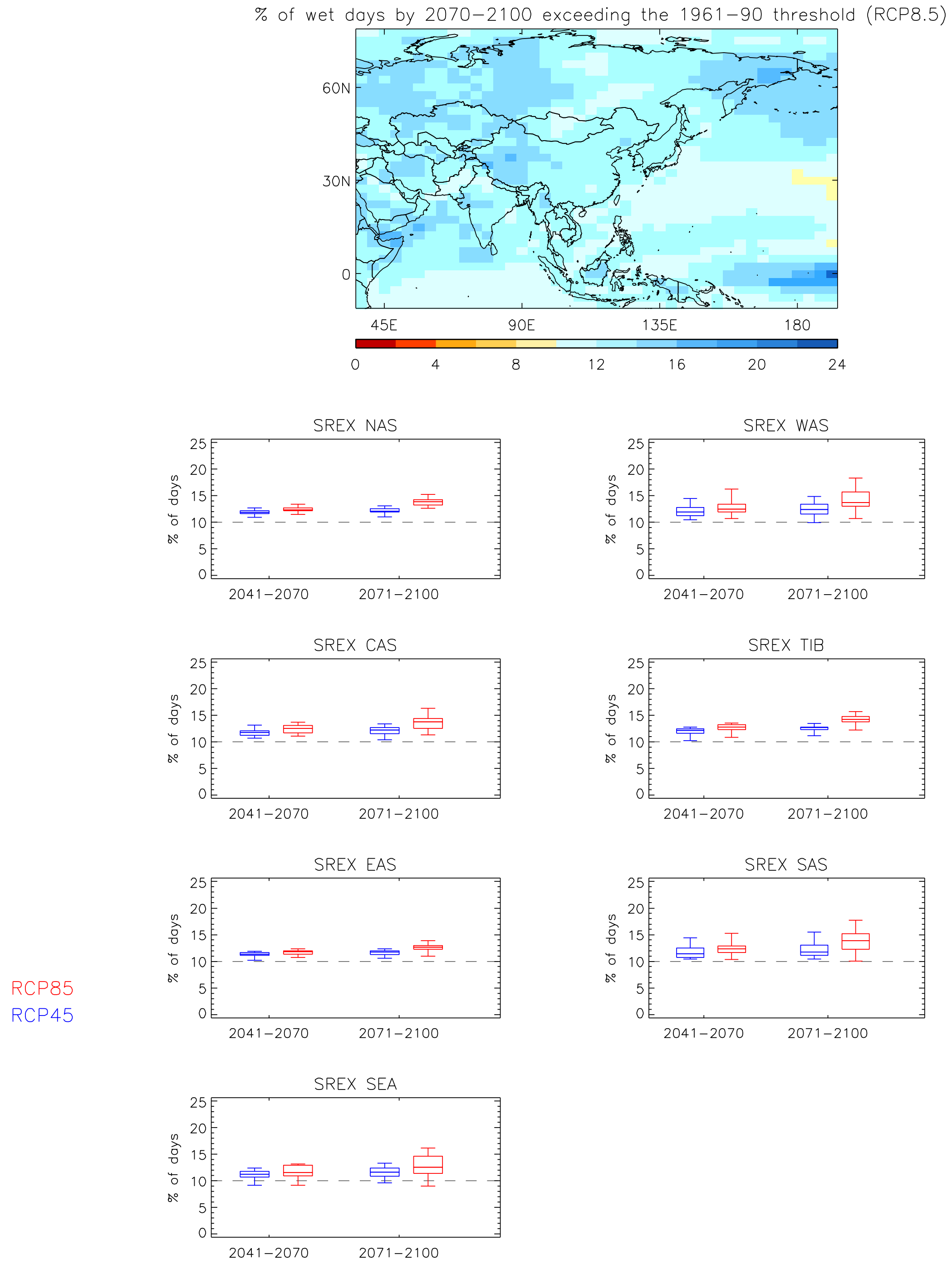


Box 21-3 Figure 2 Caption: Regional average change in seasonal mean temperature and precipitation over five regions covering South and Central America for the period 2070-2100 relative to 1961-90 in GCM projections from the CMIP5 ensemble under four RCP scenarios (van Vuuren et al., 2011) compared with GCM projections from the CMIP3 ensemble under three SRES scenarios (IPCC, 2000). Regional averaged are based on SREX region definitions (see Figure 21-RegAmplFac). Temperature changes are given in ºC and precipitation changes in mm/day with axes scaled relative to the maximum changes projected across the range of models.



[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]

Box 21-3 Figure 3 Caption: The frequency of 'hot days' (defined here as the 90th percentile daily maximum temperature during a baseline period of 1961-1990) projected for the 2071-2100 period by the CMIP5 GCMs for North America. Top: Ensemble median frequency of 'hot days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'hot-day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘Hot days’of 10% is represented on the graphs by the dashed line.



[Figure displayed is a semi-placeholder. Final figure will have box-plots arranged around the map.]

Box 21-3 Figure 4 Caption: The frequency of 'very wet days' (defined here as the 90th percentile of daily precipitation on wet days during a baseline period of 1961-1990 with wet days defined as days with 1mm of precipitation or more) projected for the 2071-2100 period by the CMIP5 GCMs. Top: Ensemble median frequency of 'very wet days' during 2070-2100 under RCP8.5. Bottom: Box-and-whisker plots indicate the range of regionally-averaged 'very wet day' frequency by 2041-2070 and 2071-2100 under RCPs 4.5 and 8.5. Boxes represent inter-quartile range and whiskers indicate full range of projections across the ensemble. The baseline frequency of ‘Very wet days’ of 10% is represented on the graphs by the dashed line.

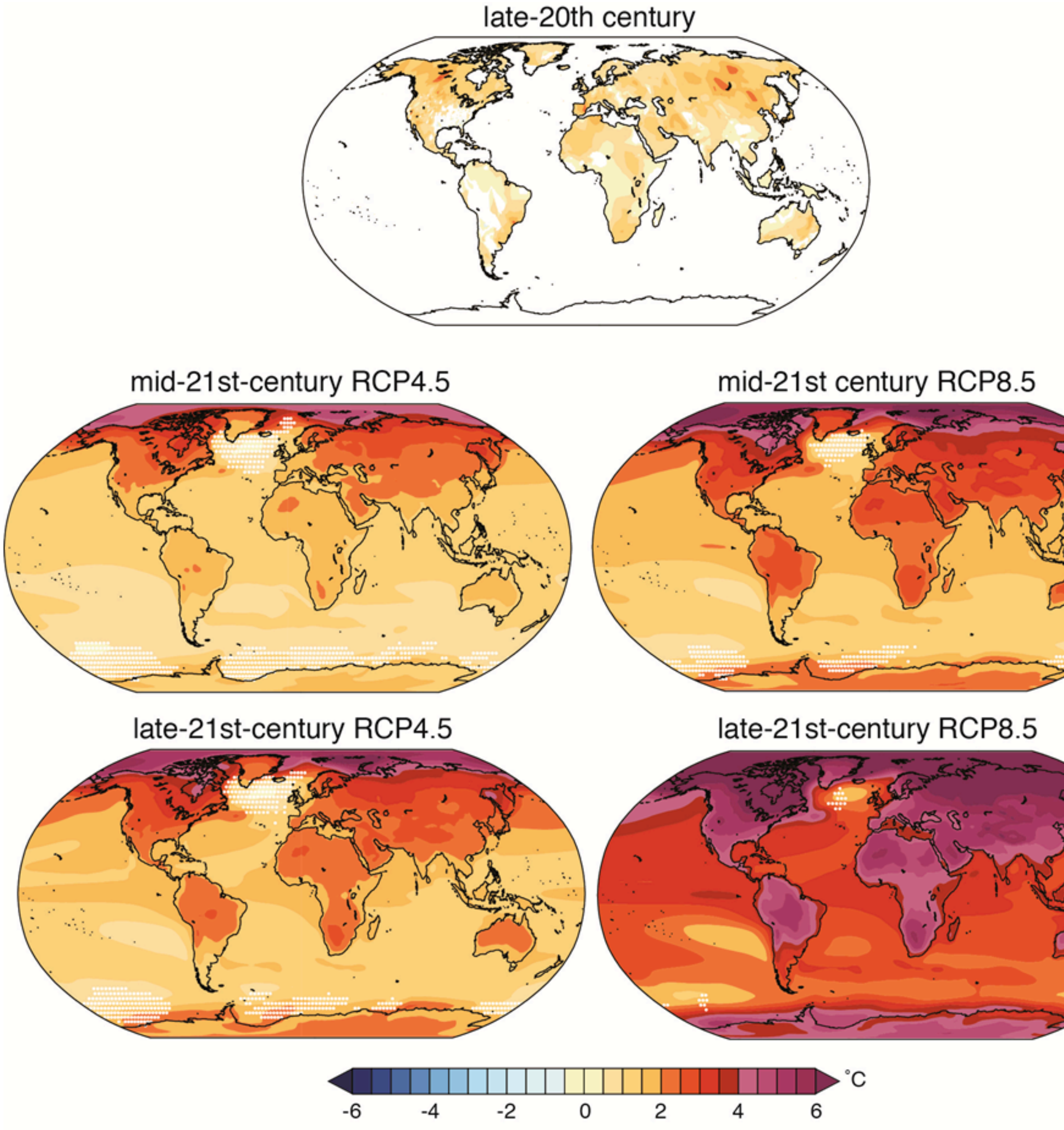


Figure RC-1: Change in annual temperature. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning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

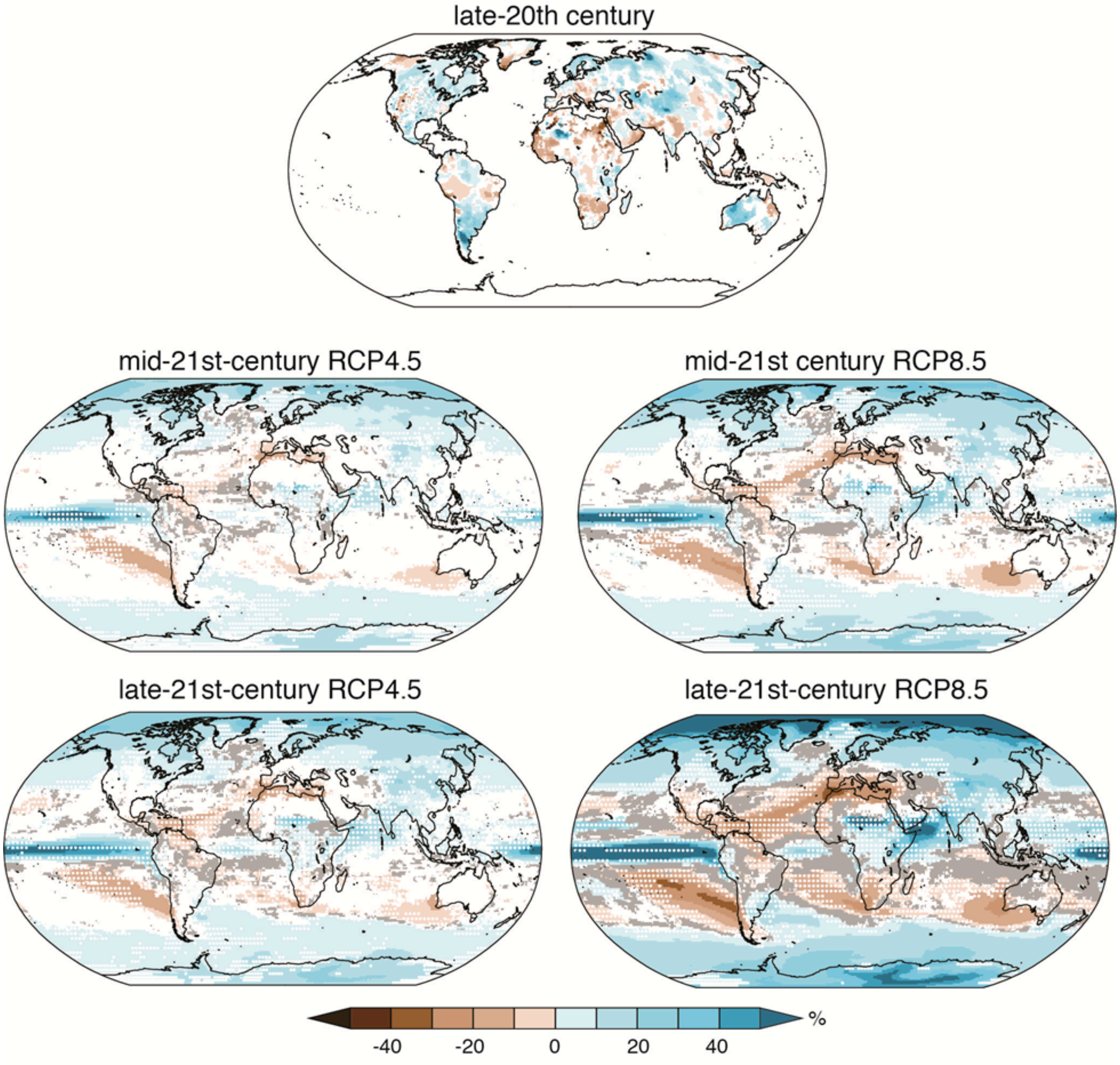


Figure RC-2: Change in annual precipitation. For the CRU observations, differences are shown between the 1986-2005 and 1906-1925 periods, with white indicating areas where the difference between the 1986-2005 and 1906-1925 periods is less than twice the standard deviation of the 20 20-year periods beginning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