4° Turn Down the Heat

Why a 4°C Warmer World Must be Avoided

THE WORLD BANK

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A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics

THE WORLD BANK

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Foreword

It is my hope that this report shocks us into action. Even for those of us already committed to fighting climate change, I hope it causes us to work with much more urgency.

This report spells out what the world would be like if it warmed by 4 degrees Celsius, which is what scientists are nearly unanimously predicting by the end of the century, without serious policy changes.

The 4°C scenarios are devastating: the inundation of coastal cities; increasing risks for food production potentially leading to higher malnutrition rates; many dry regions becoming dryer, wet regions wetter; unprecedented heat waves in many regions, especially in the tropics; substantially exacerbated water scarcity in many regions; increased frequency of high-intensity tropical cyclones; and irreversible loss of biodiversity, including coral reef systems.

And most importantly, a 4°C world is so different from the current one that it comes with high uncertainty and new risks that threaten our ability to anticipate and plan for future adaptation needs.

The lack of action on climate change not only risks putting prosperity out of reach of millions of people in the developing world, it threatens to roll back decades of sustainable development.

It is clear that we already know a great deal about the threat before us. The science is unequivocal that humans are the cause of global warming, and major changes are already being observed: global mean warming is 0.8°C above pre industrial levels; oceans have warmed by 0.09°C since the 1950s and are acidifying; sea levels rose by about 20 cm since pre-industrial times and are now rising at 3.2 cm per decade; an exceptional number of extreme heat waves occurred in the last decade; major food crop growing areas are increasingly affected by drought.

Despite the global community's best intentions to keep global warming below a 2°C increase above pre-industrial climate, higher levels of warming are increasingly likely. Scientists agree that countries' current United Nations Framework Convention on Climate Change emission pledges and commitments would most likely result in 3.5 to 4°C warming. And the longer those pledges remain unmet, the more likely a 4°C world becomes.

Data and evidence drive the work of the World Bank Group. Science reports, including those produced by the Intergovernmental Panel on Climate Change, informed our decision to ramp up work on these issues, leading to, a World Development Report on climate change designed to improve our understanding of the implications of a warming planet; a Strategic Framework on Development and Climate Change, and a report on Inclusive Green Growth. The World Bank is a leading advocate for ambitious action on climate change, not only because it is a moral imperative, but because it makes good economic sense.

But what if we fail to ramp up efforts on mitigation? What are the implications of a 4°C world? We commissioned this report from the Potsdam Institute for Climate Impact Research and Climate Analytics to help us understand the state of the science and the potential impact on development in such a world.

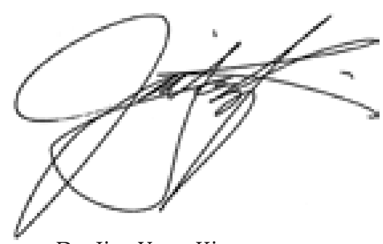
It would be so dramatically different from today's world that it is hard to describe accurately; much relies on complex projections and interpretations.

We are well aware of the uncertainty that surrounds these scenarios and we know that different scholars and studies sometimes disagree on the degree of risk. But the fact that such scenarios cannot be discarded is sufficient to justify strengthening current climate change policies. Finding ways to avoid that scenario is vital for the health and welfare of communities around the world. While every region of the world will be affected, the poor and most vulnerable would be hit hardest.

A 4°C world can, and must, be avoided.

The World Bank Group will continue to be a strong advocate for international and regional agreements and increasing climate financing. We will redouble our efforts to support fast growing national initiatives to mitigate carbon emissions and build adaptive capacity as well as support inclusive green growth and climate smart development. Our work on inclusive green growth has shown that—through more efficiency and smarter use of energy and natural resources—many opportunities exist to drastically reduce the climate impact of development, without slowing down poverty alleviation and economic growth.

This report is a stark reminder that climate change affects everything. The solutions don't lie only in climate finance or climate projects. The solutions lie in effective risk management and ensuring all our work, all our thinking, is designed with the threat of a 4°C degree world in mind. The World Bank Group will step up to the challenge.



Dr. Jim Yong Kim
President, World Bank Group

Executive Summary

Executive Summary

This report provides a snapshot of recent scientific literature and new analyses of likely impacts and risks that would be associated with a 4° Celsius warming within this century. It is a rigorous attempt to outline a range of risks, focusing on developing countries and especially the poor. A 4°C world would be one of unprecedented heat waves, severe drought, and major floods in many regions, with serious impacts on ecosystems and associated services. But with action, a 4°C world can be avoided and we can likely hold warming below 2°C.

Without further commitments and action to reduce greenhouse gas emissions, the world is likely to warm by more than 3°C above the preindustrial climate. Even with the current mitigation commitments and pledges fully implemented, there is roughly a 20 percent likelihood of exceeding 4°C by 2100. If they are not met, a warming of 4°C could occur as early as the 2060s. Such a warming level and associated sea-level rise of 0.5 to 1 meter, or more, by 2100 would not be the end point: a further warming to levels over 6°C, with several meters of sea-level rise, would likely occur over the following centuries.

Thus, while the global community has committed itself to holding warming below 2°C to prevent "dangerous" climate change, and Small Island Developing states (SIDS) and Least Developed Countries (LDCs) have identified global warming of 1.5°C as warming above which there would be serious threats to their own development and, in some cases, survival, the sum total of current policies—in place and pledged—will very likely lead to warming far in excess of these levels. Indeed, present emission trends put the world plausibly on a path toward 4°C warming within the century.

This report is not a comprehensive scientific assessment, as will be forthcoming from the Intergovernmental Panel on Climate Change (IPCC) in 2013–14 in its Fifth Assessment Report. It is focused on developing countries, while recognizing that developed countries are also vulnerable and at serious risk of major damages from climate change. A series of recent extreme events worldwide continue to highlight the vulnerability of not only the developing world but even wealthy industrialized countries.

Uncertainties remain in projecting the extent of both climate change and its impacts. We take a risk-based approach in which risk is defined as *impact multiplied by probability:* an event with low probability can still pose a high risk if it implies serious consequences.

No nation will be immune to the impacts of climate change. However, the distribution of impacts is likely to be inherently unequal and tilted against many of the world's poorest regions, which have the least economic, institutional, scientific, and technical capacity to cope and adapt. For example:

- Even though absolute warming will be largest in high latitudes, the warming that will occur in the tropics is larger when compared to the historical range of temperature and extremes to which human and natural ecosystems have adapted and coped. The projected emergence of unprecedented high-temperature extremes in the tropics will consequently lead to significantly larger impacts on agriculture and ecosystems.
- Sea-level rise is likely to be 15 to 20 percent larger in the tropics than the global mean.
- Increases in tropical cyclone intensity are likely to be felt disproportionately in low-latitude regions.
- Increasing aridity and drought are likely to increase substantially in many developing country regions located in tropical and subtropical areas.

A world in which warming reaches 4°C above preindustrial levels (hereafter referred to as a 4°C world), would be one of unprecedented heat waves, severe drought, and major floods in many regions, with serious impacts on human systems, ecosystems, and associated services.

Warming of 4°C can still be avoided: numerous studies show that there are technically and economically feasible emissions pathways to hold warming likely below 2°C. Thus the level of impacts that developing countries and the rest of the world experience will be a result of government, private sector, and civil society decisions and choices, including, unfortunately, inaction.

Observed Impacts and Changes to the Climate System

The unequivocal effects of greenhouse gas emission–induced change on the climate system, reported by IPCC's Fourth Assessment Report (AR4) in 2007, have continued to intensify, more or less unabated:

- The concentration of the main greenhouse gas, carbon dioxide (CO_2), has continued to increase from its preindustrial concentration of approximately 278 parts per million (ppm) to over 391 ppm in September 2012, with the rate of rise now at 1.8 ppm per year.
- The present CO_2 concentration is higher than paleoclimatic and geologic evidence indicates has occurred at any time in the last 15 million years.
- Emissions of CO_2 are, at present, about 35,000 million metric tons per year (including land-use change) and, absent further policies, are projected to rise to 41,000 million metric tons of CO_2 per year in 2020.
- Global mean temperature has continued to increase and is now about 0.8°C above preindustrial levels.

A global warming of 0.8°C may not seem large, but many climate change impacts have already started to emerge, and the shift from 0.8°C to 2°C warming or beyond will pose even greater challenges. It is also useful to recall that a global mean temperature increase of 4°C approaches the difference between temperatures today and those of the last ice age, when much of central Europe and the northern United States were covered with kilometers of ice and global mean temperatures were about 4.5°C to 7°C lower. And this magnitude of climate change—human induced—is occurring over a century, not millennia.

The global oceans have continued to warm, with about 90 percent of the excess heat energy trapped by the increased greenhouse gas concentrations since 1955 stored in the oceans as heat. The average increase in sea levels around the world over the 20th century has been about 15 to 20 centimeters. Over the last decade the average rate of sea-level rise has increased to about 3.2 cm per decade. Should this rate remain unchanged, this would mean over 30 cm of additional sea-level rise in the 21st century.

The warming of the atmosphere and oceans is leading to an accelerating loss of ice from the Greenland and Antarctic ice sheets, and this melting could add substantially to sea-level rise in the future. Overall, the rate of loss of ice has more than tripled since the 1993–2003 period as reported in the IPCC AR4, reaching 1.3 cm per decade over 2004–08; the 2009 loss rate is equivalent to about 1.7 cm per decade. If ice sheet loss continues at these rates, without acceleration, the increase in global average sea level due to this source would be about 15 cm by the end of the 21st century. A clear illustration of the Greenland ice sheet's increasing vulnerability to warming is the rapid growth in melt area observed since the 1970s. As for Arctic sea ice, it reached a record minimum in September 2012, halving the area of ice covering the Arctic Ocean in summers over the last 30 years.

The effects of global warming are also leading to observed changes in many other climate and environmental aspects of the Earth system. The last decade has seen an exceptional number of extreme heat waves around the world with consequential severe impacts. Human-induced climate change since the 1960s has increased the frequency and intensity of heat waves and thus also likely exacerbated their societal impacts. In some climatic regions, extreme precipitation and drought have increased in intensity and/or frequency with a likely human influence. An example of a recent extreme heat wave is the Russian heat wave of 2010, which had very significant adverse consequences. Preliminary estimates for the 2010 heat wave in Russia put the death toll at 55,000, annual crop failure at about 25 percent, burned areas at more than 1 million hectares, and economic losses at about US$15 billion (1 percent gross domestic product (GDP)).

In the absence of climate change, extreme heat waves in Europe, Russia, and the United States, for example, would be expected to occur only once every several hundred years. Observations indicate a tenfold increase in the surface area of the planet experiencing extreme heat since the 1950s.

The area of the Earth's land surface affected by drought has also likely increased substantially over the last 50 years, somewhat faster than projected by climate models. The 2012 drought in the United States impacted about 80 percent of agricultural land, making it the most severe drought since the 1950s.

Negative effects of higher temperatures have been observed on agricultural production, with recent studies indicating that since the 1980s global maize and wheat production may have been reduced significantly compared to a case without climate change.

Effects of higher temperatures on the economic growth of poor countries have also been observed over recent decades, suggesting a significant risk of further reductions in the economic growth in poor countries in the future due to global warming. An MIT study[1] used historical fluctuations in temperature within countries to identify its effects on aggregate economic outcomes. It reported that higher temperatures substantially reduce economic growth in poor countries and have wide-ranging effects, reducing agricultural output, industrial output, and political stability. These findings inform debates over the climate's role in economic development and suggest the possibility of substantial negative impacts of higher temperatures on poor countries.

Projected Climate Change Impacts in a 4°C World

The effects of 4°C warming will not be evenly distributed around the world, nor would the consequences be simply an extension of those felt at 2°C warming. The largest warming will occur over land and range from 4°C to 10°C. Increases of 6°C or more in average monthly summer temperatures would be expected in large regions of the world, including the Mediterranean, North Africa, the Middle East, and the contiguous United States

Projections for a 4°C world show a dramatic increase in the intensity and frequency of high-temperature extremes. Recent extreme heat waves such as in Russia in 2010 are likely to become the new normal summer in a 4°C world. Tropical South America, central Africa, and all tropical islands in the Pacific are likely to regularly experience heat waves of unprecedented magnitude and duration. In this new high-temperature climate regime, the coolest months are likely to be substantially warmer than the warmest months at the end of the 20th century. In regions such as the Mediterranean, North Africa, the Middle East, and the Tibetan plateau, almost all summer months are likely to be warmer than the most extreme heat waves presently experienced. For example, the warmest July in the Mediterranean region could be 9°C warmer than today's warmest July.

Extreme heat waves in recent years have had severe impacts, causing heat-related deaths, forest fires, and harvest losses. The impacts of the extreme heat waves projected for a 4°C world have not been evaluated, but they could be expected to vastly exceed the consequences experienced to date and potentially exceed the adaptive capacities of many societies and natural systems.

Rising CO_2 Concentration and Ocean Acidification

Apart from a warming of the climate system, one of the most serious consequences of rising carbon dioxide concentration in the atmosphere occurs when it dissolves in the ocean and results in acidification. A substantial increase in ocean acidity has been observed since preindustrial times. A warming of 4°C or more by 2100 would correspond to a CO_2 concentration above 800 ppm and an increase of about 150 percent in acidity of the ocean. The observed and projected rates of change in ocean acidity over the next century appear to be unparalleled in Earth's history. Evidence is already emerging of the adverse consequences of acidification for marine organisms and ecosystems, combined with the effects of warming, overfishing, and habitat destruction.

Coral reefs in particular are acutely sensitive to changes in water temperatures, ocean pH, and intensity and frequency of tropical cyclones. Reefs provide protection against coastal floods, storm surges, and wave damage as well as nursery grounds and habitat for many fish species. Coral reef growth may stop as CO_2 concentration approaches 450 ppm over the coming decades (corresponding to a warming of about 1.4°C in the 2030s). By the time the concentration reaches around 550 ppm (corresponding to a warming of about 2.4°C in the 2060s), it is likely that coral reefs in many areas would start to dissolve. The combination of thermally induced bleaching events, ocean acidification, and sea-level rise threatens large fractions of coral reefs even at 1.5°C global warming. The regional extinction of entire coral reef ecosystems, which could occur well before 4°C is reached, would have profound consequences for their dependent species and for the people who depend on them for food, income, tourism, and shoreline protection.

Rising Sea Levels, Coastal Inundation and Loss

Warming of 4°C will likely lead to a sea-level rise of 0.5 to 1 meter, and possibly more, by 2100, with several meters more to be realized in the coming centuries. Limiting warming to 2°C would likely reduce sea-level rise by about 20 cm by 2100 compared to a 4°C world. However, even if global warming is limited to 2°C, global mean sea level could continue to rise, with some estimates ranging between 1.5 and 4 meters above present-day levels by the year 2300. Sea-level rise would likely be limited to below 2 meters only if warming were kept to well below 1.5°C.

Sea-level rise will vary regionally: for a number of geophysically determined reasons, it is projected to be up to 20 percent higher in the tropics and below average at higher latitudes. In particular, the melting of the ice sheets will reduce the gravitational pull on the ocean toward the ice sheets and, as a consequence, ocean water will tend to gravitate toward the Equator. Changes in wind and ocean currents due to global warming and other factors will also affect regional sea-level rise, as will patterns of ocean heat uptake and warming.

[1] Dell, Melissa, Benjamin F. Jones, and Benjamin A. Olken. 2012. "Temperature Shocks and Economic Growth: Evidence from the Last Half Century." *American Economic Journal: Macroeconomics*, 4(3): 66–95.

Sea-level rise impacts are projected to be asymmetrical even within regions and countries. Of the impacts projected for 31 developing countries, only 10 cities account for two-thirds of the total exposure to extreme floods. Highly vulnerable cities are to be found in Mozambique, Madagascar, Mexico, Venezuela, India, Bangladesh, Indonesia, the Philippines, and Vietnam.

For small island states and river delta regions, rising sea levels are likely to have far ranging adverse consequences, especially when combined with the projected increased intensity of tropical cyclones in many tropical regions, other extreme weather events, and climate change–induced effects on oceanic ecosystems (for example, loss of protective reefs due to temperature increases and ocean acidification).

Risks to Human Support Systems: Food, Water, Ecosystems, and Human Health

Although impact projections for a 4°C world are still preliminary and it is often difficult to make comparisons across individual assessments, this report identifies a number of extremely severe risks for vital human support systems. With extremes of temperature, heat waves, rainfall, and drought are projected to increase with warming; risks will be much higher in a 4°C world compared to a 2°C world.

In a world rapidly warming toward 4°C, the most adverse impacts on water availability are likely to occur in association with growing water demand as the world population increases. Some estimates indicate that a 4°C warming would significantly exacerbate existing water scarcity in many regions, particularly northern and eastern Africa, the Middle East, and South Asia, while additional countries in Africa would be newly confronted with water scarcity on a national scale due to population growth.

- Drier conditions are projected for southern Europe, Africa (except some areas in the northeast), large parts of North America and South America, and southern Australia, among others.
- Wetter conditions are projected in particular for the northern high latitudes—that is, northern North America, northern Europe, and Siberia—and in some monsoon regions. Some regions may experience reduced water stress compared to a case without climate change.
- Subseasonal and subregional changes to the hydrological cycle are associated with severe risks, such as flooding and drought, which may increase significantly even if annual averages change little.

With extremes of rainfall and drought projected to increase with warming, these risks are expected to be much higher in a 4°C world as compared to the 2°C world. In a 2°C world:

- River basins dominated by a monsoon regime, such as the Ganges and Nile, are particularly vulnerable to changes in the seasonality of runoff, which may have large and adverse effects on water availability.
- Mean annual runoff is projected to decrease by 20 to 40 percent in the Danube, Mississippi, Amazon, and Murray Darling river basins, but increase by roughly 20 percent in both the Nile and the Ganges basins.

All these changes approximately double in magnitude in a 4°C world.

The risk for disruptions to ecosystems as a result of ecosystem shifts, wildfires, ecosystem transformation, and forest dieback would be significantly higher for 4°C warming as compared to reduced amounts. Increasing vulnerability to heat and drought stress will likely lead to increased mortality and species extinction.

Ecosystems will be affected by more frequent extreme weather events, such as forest loss due to droughts and wildfire exacerbated by land use and agricultural expansion. In Amazonia, forest fires could as much as double by 2050 with warming of approximately 1.5°C to 2°C above preindustrial levels. Changes would be expected to be even more severe in a 4°C world.

In fact, in a 4°C world climate change seems likely to become the dominant driver of ecosystem shifts, surpassing habitat destruction as the greatest threat to biodiversity. Recent research suggests that large-scale loss of biodiversity is likely to occur in a 4°C world, with climate change and high CO_2 concentration driving a transition of the Earth´s ecosystems into a state unknown in human experience. Ecosystem damage would be expected to dramatically reduce the provision of ecosystem services on which society depends (for example, fisheries and protection of coastline—afforded by coral reefs and mangroves).

Maintaining adequate food and agricultural output in the face of increasing population and rising levels of income will be a challenge irrespective of human-induced climate change. The IPCC AR4 projected that global food production would increase for local average temperature rise in the range of 1°C to 3°C, but may decrease beyond these temperatures.

New results published since 2007, however, are much less optimistic. These results suggest instead a rapidly rising risk of crop yield reductions as the world warms. Large negative effects have been observed at high and extreme temperatures in several regions including India, Africa, the United States, and Australia. For example, significant nonlinear effects have been observed in the United States for local daily temperatures increasing to 29°C for corn and 30°C for soybeans. These new results and observations indicate a significant risk of high-temperature thresholds being crossed that could substantially undermine food security globally in a 4°C world.

Compounding these risks is the adverse effect of projected sea-level rise on agriculture in important low-lying delta areas, such as in Bangladesh, Egypt, Vietnam, and parts of the African coast. Sea-level rise would likely impact many mid-latitude coastal areas and increase seawater penetration into coastal aquifers used for irrigation of coastal plains. Further risks are posed by the likelihood of increased drought in mid-latitude regions and increased flooding at higher latitudes.

The projected increase in intensity of extreme events in the future would likely have adverse implications for efforts to reduce poverty, particularly in developing countries. Recent projections suggest that the poor are especially sensitive to increases in drought intensity in a 4°C world, especially across Africa, South Asia, and other regions.

Large-scale extreme events, such as major floods that interfere with food production, could also induce nutritional deficits and the increased incidence of epidemic diseases. Flooding can introduce contaminants and diseases into healthy water supplies and increase the incidence of diarrheal and respiratory illnesses. The effects of climate change on agricultural production may exacerbate under-nutrition and malnutrition in many regions—already major contributors to child mortality in developing countries. Whilst economic growth is projected to significantly reduce childhood stunting, climate change is projected to reverse these gains in a number of regions: substantial increases in stunting due to malnutrition are projected to occur with warming of 2°C to 2.5°C, especially in Sub-Saharan Africa and South Asia, and this is likely to get worse at 4°C. Despite significant efforts to improve health services (for example, improved medical care, vaccination development, surveillance programs), significant additional impacts on poverty levels and human health are expected. Changes in temperature, precipitation rates, and humidity influence vector-borne diseases (for example, malaria and dengue fever) as well as hantaviruses, leishmaniasis, Lyme disease, and schistosomiasis.

Further health impacts of climate change could include injuries and deaths due to extreme weather events. Heat-amplified levels of smog could exacerbate respiratory disorders and heart and blood vessel diseases, while in some regions climate change–induced increases in concentrations of aeroallergens (pollens, spores) could amplify rates of allergic respiratory disorders.

Risks of Disruptions and Displacements in a 4°C World

Climate change will not occur in a vacuum. Economic growth and population increases over the 21st century will likely add to human welfare and increase adaptive capacity in many, if not most, regions. At the same time, however, there will also be increasing stresses and demands on a planetary ecosystem already approaching critical limits and boundaries. The resilience of many natural and managed ecosystems is likely to be undermined by these pressures and the projected consequences of climate change.

The projected impacts on water availability, ecosystems, agriculture, and human health could lead to large-scale displacement of populations and have adverse consequences for human security and economic and trade systems. The full scope of damages in a 4°C world has not been assessed to date.

Large-scale and disruptive changes in the Earth system are generally not included in modeling exercises, and rarely in impact assessments. As global warming approaches and exceeds 2°C, the risk of crossing thresholds of nonlinear tipping elements in the Earth system, with abrupt climate change impacts and unprecedented high-temperature climate regimes, increases. Examples include the disintegration of the West Antarctic ice sheet leading to more rapid sea-level rise than projected in this analysis or large-scale Amazon dieback drastically affecting ecosystems, rivers, agriculture, energy production, and livelihoods in an almost continental scale region and potentially adding substantially to 21st-century global warming.

There might also be nonlinear responses within particular economic sectors to high levels of global warming. For example, nonlinear temperature effects on crops are likely to be extremely relevant as the world warms to 2°C and above. However, most of our current crop models do not yet fully account for this effect, or for the potential increased ranges of variability (for example, extreme temperatures, new invading pests and diseases, abrupt shifts in critical climate factors that have large impacts on yields and/or quality of grains).

Projections of damage costs for climate change impacts typically assess the costs of local damages, including infrastructure, and do not provide an adequate consideration of cascade effects (for example, value-added chains and supply networks) at national and regional scales. However, in an increasingly globalized world that experiences further specialization in production systems, and thus higher dependency on infrastructure to deliver produced goods, damages to infrastructure systems can lead to substantial indirect impacts. Seaports are an example of an initial point where a breakdown or substantial disruption in infrastructure facilities could trigger impacts that reach far beyond the particular location of the loss.

The cumulative and interacting effects of such wide-ranging impacts, many of which are likely to be felt well before 4°C warming, are not well understood. For instance, there has not been a study published in the scientific literature on the full ecological, human, and economic consequences of a collapse of coral reef ecosystems, much less when combined with the likely concomitant loss of marine production due to rising ocean temperatures and increasing acidification, and the large-scale impacts on human settlements and infrastructure in low-lying fringe coastal zones that would result from sea-level rise of a meter or more this century and beyond.

As the scale and number of impacts grow with increasing global mean temperature, interactions between them might increasingly occur, compounding overall impact. For example, a large shock to agricultural production due to extreme temperatures across many regions, along with substantial pressure on water resources and changes in the hydrological cycle, would likely impact both human health and livelihoods. This could, in turn, cascade into effects on economic development by reducing a population´s work capacity, which would then hinder growth in GDP.

With pressures increasing as warming progresses toward 4°C and combining with nonclimate–related social, economic, and population stresses, the risk of crossing critical social system thresholds will grow. At such thresholds existing institutions that would have supported adaptation actions would likely become much less effective or even collapse. One example is a risk that sea-level rise in atoll countries exceeds the capabilities of controlled, adaptive migration, resulting in the need for complete abandonment of an island or region. Similarly, stresses on human health, such as heat waves, malnutrition, and decreasing quality of drinking water due to seawater intrusion, have the potential to overburden health-care systems to a point where adaptation is no longer possible, and dislocation is forced.

Thus, given that uncertainty remains about the full nature and scale of impacts, there is also no certainty that adaptation to a 4°C world is possible. A 4°C world is likely to be one in which communities, cities and countries would experience severe disruptions, damage, and dislocation, with many of these risks spread unequally. It is likely that the poor will suffer most and the global community could become more fractured, and unequal than today. The projected 4°C warming simply must not be allowed to occur—the heat must be turned down. Only early, cooperative, international actions can make that happen.

Abbreviations

°C	degrees Celsius
AIS	Antarctic Ice Sheet
AOGCM	Atmosphere-Ocean General Circulation Model
AOSIS	Alliance of Small Island States
AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
BAU	Business as Usual
$CaCO_3$	Calcium Carbonate
cm	Centimeter
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DIVA	Dynamic Interactive Vulnerability Assessment
DJF	December January February
GCM	General Circulation Model
GDP	Gross Domestic Product
GIS	Greenland Ice Sheet
$GtCO_2e$	Gigatonnes—billion metric tons—of Carbon Dioxide Equivalent
IAM	Integrated Assessment Model
IBAU	"IMAGE (Model) Business As Usual" Scenario (Hinkel et al. 2011)
ISI-MIP	Inter-Sectoral Model Inter-comparison Project
IPCC	Intergovernmental Panel on Climate Change
JJA	June July August
LDC	Least Developed Country
MGIC	Mountain Glaciers and Ice Caps
NH	Northern Hemisphere
NOAA	National Oceanic and Atmospheric Administration (United States)
OECD	Organisation for Economic Cooperation and Development
PG	Population Growth
PGD	Population Growth Distribution
ppm	Parts per Million
RBAU	"Rahmstorf Business As Usual" Scenario (Hinkel et al. 2011)
RCP	Representative Concentration Pathway
SH	Southern Hemisphere
SLR	Sea-Level Rise
SRES	IPCC Special Report on Emissions Scenarios
SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
SSA	Sub-Saharan Africa
UNFCCC	United National Framework Convention on Climate Change
WBG	World Bank Group
WBGT	Wet-Bulb Global Temperature
WDR	World Development Report
WHO	World Health Organization

Chapter 1

Introduction

Since the 2009 Climate Convention Conference in Copenhagen, the internationally agreed climate goal has been to hold global mean warming below a 2°C increase above the preindustrial climate. At the same time that the Copenhagen Conference adopted this goal, it also agreed that this limit would be reviewed in the 2013–15 period, referencing in particular the 1.5°C increase limit that the Alliance of Small Island States (AOSIS) and the least developed countries (LDCs) put forward.

While the global community has committed itself to holding warming below 2°C to prevent "dangerous" climate change, the sum total of current policies—in place and pledged—will very likely lead to warming far in excess of this level. Indeed, present emission trends put the world plausibly on a path toward 4°C warming within this century.

Levels greater than 4°C warming could be possible within this century should climate sensitivity be higher, or the carbon cycle and other climate system feedbacks more positive, than anticipated. Current scientific evidence suggests that even with the current commitments and pledges fully implemented, there is roughly a 20 percent likelihood of exceeding 4°C by 2100, and a 10 percent chance of 4°C being exceeded as early as the 2070s.

Warming would not stop there. Because of the slow response of the climate system, the greenhouse gas emissions and concentrations that would lead to warming of 4°C by 2100 would actually commit the world to much higher warming, exceeding 6°C or more, in the long term, with several meters of sea-level rise ultimately associated with this warming (Rogelj et al. 2012; IEA 2012; Schaeffer & van Vuuren 2012).

Improvements in knowledge have reinforced the findings of the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), especially with respect to an increasing risk of rapid, abrupt, and irreversible change with high levels of warming. These risks include, but are not limited, to the following:

- Meter-scale sea-level rise by 2100 caused by the rapid loss of ice from Greenland and the West Antarctic Ice Sheet
- Increasing aridity, drought, and extreme temperatures in many regions, including Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia
- Rapid ocean acidification with wide-ranging, adverse implications for marine species and entire ecosystems
- Increasing threat to large-scale ecosystems, such as coral reefs and a large part of the Amazon rain forest

Various climatic extremes can be expected to change in intensity or frequency, including heat waves, intense rainfall events and related floods, and tropical cyclone intensity.

There is an increasing risk of substantial impacts with consequences on a global scale, for example, concerning food production. A new generation of studies is indicating adverse impacts of observed warming on crop production regionally and globally (for example, Lobell et al. 2011). When factored into analyses of expected food availability under global warming scenarios, these results indicate a greater sensitivity to warming than previously estimated, pointing to larger risks for global and regional food production than in earlier assessments. Such potential factors have yet to be fully accounted for in global risk assessments, and if realized in practice, would have substantial consequences for many sectors and systems, including human health, human security, and development prospects in already vulnerable regions. There is also a growing literature on the potential for cascades of impacts or hotspots of impacts, where impacts projected for different sectors converge spatially. The increasing fragility of natural and managed ecosystems and their services is in turn expected to diminish the resilience of global socioeconomic systems, leaving them more vulnerable to nonclimatic stressors and shocks, such as emerging pandemics, trade disruptions, or financial market shocks (for example, Barnosky et al. 2012; Rockström et al. 2009).

This context has generated a discussion in the scientific community over the implications of 4°C, or greater, global warming for human societies and natural ecosystems (New et al. 2011). The IPCC AR4 in 2007 provided an overview of the impacts and vulnerabilities projected up to, and including, this level of global mean warming. The results of this analysis confirm that global mean warming of 4°C would result in far-reaching and profound changes to the climate system, including oceans, atmosphere, and cryosphere, as well as natural ecosystems—and pose major challenges to human systems. The impacts of these changes are likely to be severe and to undermine sustainable development prospects in many regions. Nevertheless, it is also clear that the assessments to date of the likely consequences of 4°C global mean warming are limited, may not capture some of the major risks and may not accurately account for society's capacity to adapt. There have been few systematic attempts to understand and quantify the differences of climate change impacts for various levels of global warming across sectors.

This report provides a snapshot of recent scientific literature and new analyses of likely impacts and risks that would be associated with a 4°C warming within this century. It is a rigorous attempt to outline a range of risks, focusing on developing countries, especially the poor.

This report is not a comprehensive scientific assessment, as will be forthcoming from the Intergovernmental Panel on Climate Change (IPCC) in 2013/14 in its Fifth Assessment Report (AR5). It is focused on developing countries while recognizing that developed countries are also vulnerable and at serious risk of major damages from climate change.

Chapter 2 summarizes some of the observed changes to the Earth's climate system and their impacts on human society that are already being observed. Chapter 3 provides some background on the climate scenarios referred to in this report and discusses the likelihood of a 4°C warming. It also examines projections for the coming century on the process of ocean acidification, changes in precipitation that may lead to droughts or floods, and changes in the incidence of extreme tropical cyclones. Chapters 4 and 5 provide an analysis of projected sea-level rise and increases in heat extremes, respectively. Chapter 6 discusses the implications of projected climate changes and other factors for society, specifically in the sectors of agriculture, water resources, ecosystems, and human health. Chapter 7 provides an outlook on the potential risks of nonlinear impacts and identifies where scientists' understanding of a 4°C world is still very limited.

Uncertainties remain in both climate change and impact projections. This report takes a risk-based approach where risk is defined as impact times probability: an event with low probability can still pose a high risk if it implies serious consequences.

While not explicitly addressing the issue of adaptation, the report provides a basis for further investigation into the potential and limits of adaptive capacity in the developing world. Developed countries are also vulnerable and at serious risk of major damages from climate change. However, as this report reflects, the distribution of impacts is likely to be inherently unequal and tilted against many of the world's poorest regions, which have the least economic, institutional, scientific, and technical capacity to cope and adapt proactively. The low adaptive capacity of these regions in conjunction with the disproportionate burden of impacts places them among the most vulnerable parts of the world.

The World Development Report 2010 (World Bank Group 2010a) reinforced the findings of the IPCC AR4: the impacts of climate change will undermine development efforts, which calls into question whether the Millennium Development Goals can be achieved in a warming world. This report is, thus, intended to provide development practitioners with a brief sketch of the challenges a warming of 4°C above preindustrial levels (hereafter, referred to as a 4°C world) would pose, as a prelude to further and deeper examination. It should be noted that this does not imply a scenario in which global mean temperature is stabilized by the end of the century.

Given the uncertainty of adaptive capacity in the face of unprecedented climate change impacts, the report simultaneously serves as a call for further mitigation action as the best insurance against an uncertain future.

Chapter 2

Observed Climate Changes and Impacts

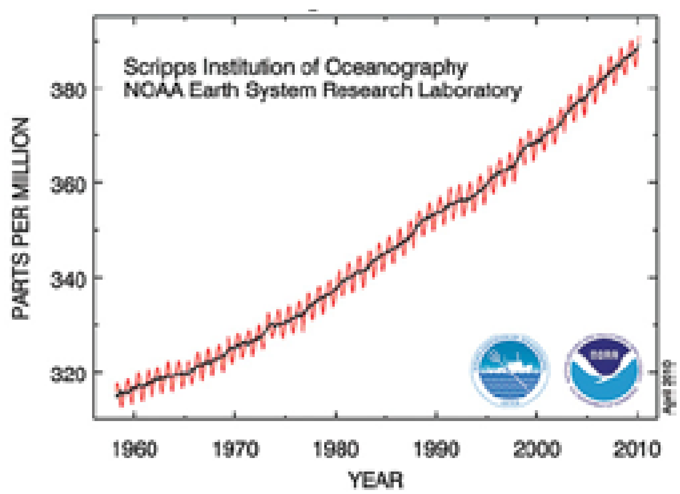
There is a growing and well-documented body of evidence regarding observed changes in the climate system and impacts that can be attributed to human-induced climate change. What follows is a snapshot of some of the most important observations. For a full overview, the reader is referred to recent comprehensive reports, such as *State of the Climate 2011*, published by the American Metrological Society in cooperation with National Oceanic and Atmospheric Administration (NOAA) (Blunden et al. 2012).

The Rise of CO_2 Concentrations and Emissions

In order to investigate the hypothesis that atmospheric CO_2 concentration influences the Earth's climate, as proposed by John Tyndall (Tyndall 1861), Charles D. Keeling made systematic measurements of atmospheric CO_2 emissions in 1958 at the Mauna Loa Observatory, Hawaii (Keeling et al. 1976; Pales & Keeling 1965). Located on the slope of a volcano 3,400 m above sea level and remote from external sources and sinks of carbon dioxide, the site was identified as suitable for long-term measurements (Pales and Keeling 1965), which continue to the present day. Results show an increase from 316 ppm (parts per million) in March 1958 to 391 ppm in September 2012. Figure 1 shows the measured carbon dioxide data (red curve) and the annual average CO_2 concentrations in the period 1958–2012. The seasonal oscillation shown on the red curve reflects the growth of plants in the Northern Hemisphere, which store more CO_2 during the boreal spring and summer than is respired, effectively taking up carbon from the atmosphere (Pales and Keeling 1965). Based on ice-core measurements,[2] pre-industrial CO_2 concentrations have been shown to have been in the range of 260 to 280 ppm (Indermühle 1999). Geological and paleo-climatic evidence makes clear that the present atmospheric CO_2 concentrations are higher than at any time in the last 15 million years (Tripati, Roberts, and Eagle 2009).

Since 1959, approximately 350 billion metric tons of carbon (or GtC)[3] have been emitted through human activity, of which 55

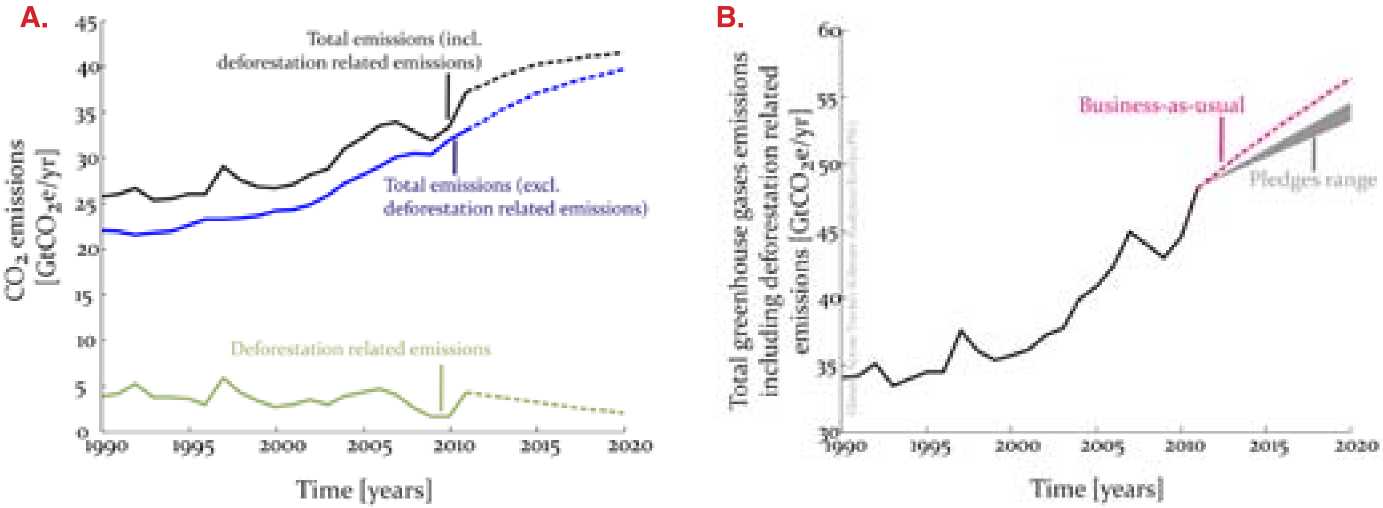
Figure 1: Atmospheric CO_2 concentrations at Mauna Loa Observatory.



[2] The report adopts 1750 for defining CO_2 concentrations. For global mean temperature pre-industrial is defined as from mid-19th century.

[3] Different conventions are used are used in the science and policy communities. When discussing CO_2 emissions it is very common to refer to CO_2 emissions by the weight of carbon—3.67 metric tons of CO_2 contains 1 metric ton of carbon, whereas when CO_2 equivalent emissions are discussed, the CO_2 (not carbon) equivalent is almost universally used. In this case 350 billion metric tons of carbon is equivalent to 1285 billion metric tons of CO_2.

Figure 2: Global CO_2 (a) and total greenhouse gases (b) historic (solid lines) and projected (dashed lines) emissions. CO_2 data source: PRIMAP4BIS[a] baseline and greenhouse gases data source: Climate Action Tracker[b]. Global pathways include emissions from international transport. Pledges ranges in (b) consist of the current best estimates of pledges put forward by countries and range from minimum ambition, unconditional pledges, and lenient rules to maximum ambition, conditional pledges, and more strict rules.



[a] https://sites.google.com/a/primap.org/www/the-primap-model/documentation/baselines
[b] http://climateactiontracker.org/

percent has been taken up by the oceans and land, with the rest remaining in the atmosphere (Ballantyne et al. 2012). Figure 2a shows that CO_2 emissions are rising. Absent further policy, global CO_2 emissions (including emissions related to deforestation) will reach 41 billion metric tons of CO_2 per year in 2020. Total greenhouse gases will rise to 56 $GtCO_2e$[4] in 2020, if no further climate action is taken between now and 2020 (in a "business-as-usual" scenario). If current pledges are fully implemented, global total greenhouse gases emissions in 2020 are likely to be between 53 and 55 billion metric tons CO_2e per year (Figure 2b).

Rising Global Mean Temperature

The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) found that the rise in global mean temperature and warming of the climate system were "unequivocal." Furthermore, "most of the observed increase in global average temperature since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations" (Solomon, Miller et al. 2007). Recent work reinforces this conclusion. Global mean warming is now approximately 0.8°C above preindustrial levels.[5]

The emergence of a robust warming signal over the last three decades is very clear, as has been shown in a number of studies. For example, Foster and Rahmstorf (2011) show the clear signal that emerges after removal of known factors that affect short-term temperature variations. These factors include solar variability and volcanic aerosol effects, along with the El Niño/Southern oscillation events (Figure 3). A suite of studies, as reported by the IPCC, confirms that the observed warming cannot be explained by natural factors alone and thus can largely be attributed to anthropogenic influence (for example, Santer et al 1995; Stott et al. 2000). In fact, the IPCC (2007) states that during the last 50 years "the sum of solar and volcanic forcings would likely have produced cooling, not warming", a result which is confirmed by more recent work (Wigley and Santer 2012).

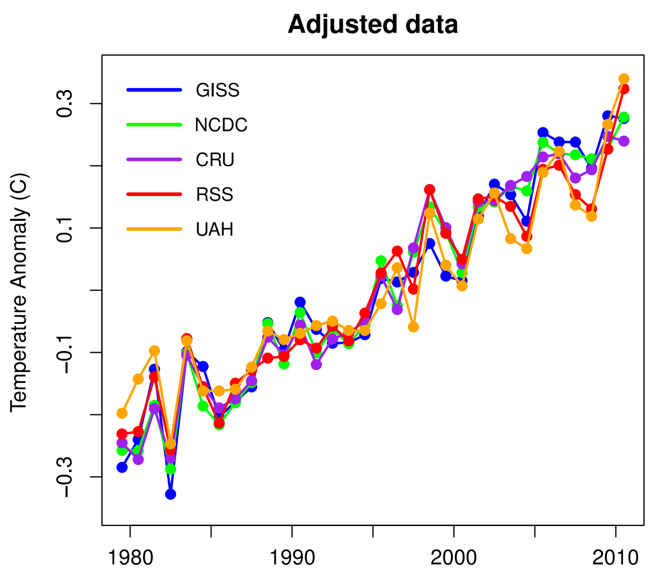
Increasing Ocean Heat Storage

While the warming of the surface temperature of the Earth is perhaps one of the most noticeable changes, approximately 93 percent of the additional heat absorbed by the Earth system resulting from an increase in greenhouse gas concentration since 1955 is stored

[4] Total greenhouse gas emissions (CO_2e) are calculated by multiplying emissions of each greenhouse gas by its Global Warming Potential (GWPs), a measure that compares the integrated warming effect of greenhouses to a common base (carbon dioxide) on a specified time horizon. This report applies 100-year GWPs from IPCC's Second Assessment Report, to be consistent with countries reporting national communications to the UNFCCC.

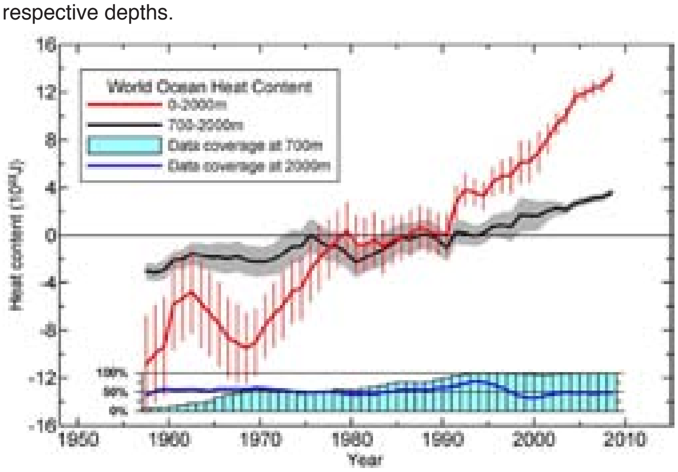
[5] See HadCRUT3v: http://www.cru.uea.ac.uk/cru/data/temperature/ and (Jones et al. 2012).

Figure 3: Temperature data from different sources (GISS: NASA Goddard Institute for Space Studies GISS; NCDC: NOAA National Climate Data Center; CRU: Hadley Center/ Climate Research Unit UK; RSS: data from Remote Sensing Systems; UAH: University of Alabama at Huntsville) corrected for short-term temperature variability. When the data are adjusted to remove the estimated impact of known factors on short-term temperature variations (El Nino/Southern Oscillation, volcanic aerosols and solar variability), the global warming signal becomes evident.



Source: Foster and Rahmstorf 2012.

Figure 4: The increase in total ocean heat content from the surface to 2000 m, based on running five-year analyses. Reference period is 1955–2006. The black line shows the increasing heat content at depth (700 to 2000 m), illustrating a significant and rising trend, while most of the heat remains in the top 700 m of the ocean. Vertical bars and shaded area represent +/–2 standard deviations about the five-year estimate for respective depths.



Source: Levitus et al. 2012.

in the ocean. Recent work by Levitus and colleagues (Levitus et al. 2012) extends the finding of the IPCC AR4. The observed warming of the world's oceans "can only be explained by the increase in atmospheric greenhouse gases." The strong trend of increasing ocean heat content continues (Figure 4). Between 1995 and 2010 the world's oceans as a whole have warmed on average by 0.09°C.

In concert with changes in marine chemistry, warming waters are expected to adversely affect fisheries, particularly in tropical regions as stocks migrate away from tropical countries towards cooler waters (Sumaila 2010). Furthermore, warming surface waters can enhance stratification, potentially limiting nutrient availability to primary producers. Another particularly severe consequence of increasing ocean warming could be the expansion of ocean hypoxic zones,[6] ultimately interfering with global ocean production and damaging marine ecosystems. Reductions in the oxygenation zones of the ocean are already occurring, and in some ocean basins have been observed to reduce the habitat for tropical pelagic fishes, such as tuna (Stramma et al. 2011).

Rising Sea Levels

Sea levels are rising as a result of anthropogenic climate warming. This rise in sea levels is caused by thermal expansion of the oceans and by the addition of water to the oceans as a result of the melting and discharge of ice from mountain glaciers and ice caps and from the much larger Greenland and Antarctic ice sheets. A significant fraction of the world population is settled along coastlines, often in large cities with extensive infrastructure, making sea-level rise potentially one of the most severe long-term

6 The ocean hypoxic zone is a layer in the ocean with very low oxygen concentration (also called OMZ – Oxygen Minimum Zone), due to stratification of vertical layers (limited vertical mixing) and high activity of microbes, which consume oxygen in processing organic material deposited from oxygen-rich shallower ocean layers with high biological activity. An hypoxic zone that expands upwards to shallower ocean layers, as observed, poses problems for zooplankton that hides in this zone for predators during daytime, while also compressing the oxygen-rich surface zone above, thereby stressing bottom-dwelling organisms, as well as pelagic (open-sea) species. Recent observations and modeling suggest the hypoxic zones globally expand upward (Stramma et al 2008; Rabalais 2010) with increased ocean-surface temperatures, precipitation and/or river runoff, which enhances stratification, as well as changes in ocean circulation that limit transport from colder, oxygen-rich waters into tropical areas and finally the direct outgassing of oxygen, as warmer waters contain less dissolved oxygen. "Hypoxic events" are created by wind changes that drive surface waters off shore, which are replaced by deeper waters from the hypoxic zones entering the continental shelves, or by the rich nutrient content of such waters stimulating local plankton blooms that consume oxygen when abruptly dying and decomposing. The hypoxic zones have also expanded near the continents due to increased fertilizer deposition by precipitation and direct influx of fertilizers transported by continental runoff, increasing the microbe activity creating the hypoxic zones. Whereas climate change might enhance precipitation and runoff, other human activities might enhance, or suppress fertilizer use, as well as runoff.

impacts of climate change, depending upon the rate and ultimate magnitude of the rise.

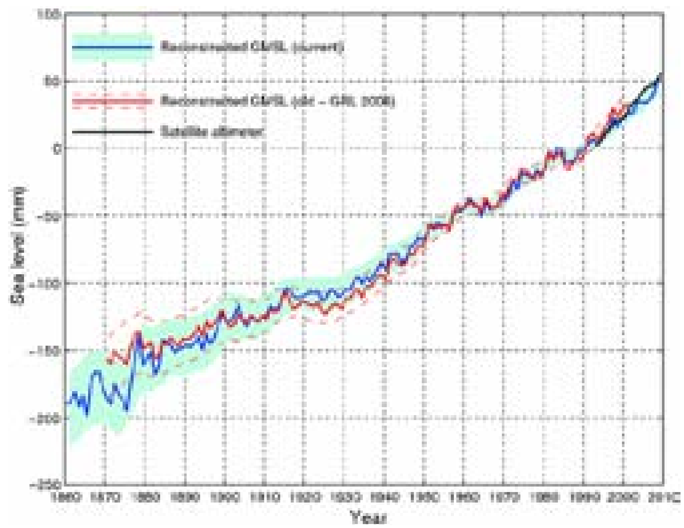
Substantial progress has been made since the IPCC AR4 in the quantitative understanding of sea-level rise, especially closure of the sea-level rise budget. Updated estimates and reconstructions of sea-level rise, based on tidal gauges and more recently, satellite observations, confirm the findings of the AR4 (Figure 5) and indicate a sea-level rise of more than 20 cm since preindustrial times[7] to 2009 (Church and White 2011). The rate of sea-level rise was close to 1.7 mm/year (equivalent to 1.7 cm/decade) during the 20th century, accelerating to about 3.2 mm/year (equivalent to 3.2 cm/decade) on average since the beginning of the 1990s (Meyssignac and Cazenave 2012).

In the IPCC AR4, there were still large uncertainties regarding the share of the various contributing factors to sea-level rise, with the sum of individually estimated components accounting for less than the total observed sea-level rise. Agreement on the quantitative contribution has improved and extended to the 1972–2008 period using updated observational estimates (Church et al. 2011) (Figure 6): over that period, the largest contributions have come from thermal expansion (0.8 mm/year or 0.8 cm/decade), mountain glaciers, and ice caps (0.7 mm/year or 0.7 cm/decade), followed by the ice sheets (0.4 mm/year or 0.4 cm/decade). The study by Church et al. (2011) concludes that the human influence on the hydrological cycle through dam building (negative contribution as water is retained on land) and groundwater mining (positive contribution because of a transfer from land to ocean) contributed negatively (–0.1 mm/year or –0.1 cm/decade), to sea-level change over this period. The acceleration of sea-level rise over the last two decades is mostly explained by an increasing land-ice contribution from 1.1 cm/decade over 1972–2008 period to 1.7 cm/decade over 1993–2008 (Church et al. 2011), in particular because of the melting of the Greenland and Antarctic ice sheets, as discussed in the next section. The rate of land ice contribution to sea level rise has increased by about a factor of three since the 1972–1992 period.

There are significant regional differences in the rates of observed sea-level rise because of a range of factors, including differential heating of the ocean, ocean dynamics (winds and currents), and the sources and geographical location of ice melt, as well as subsidence or uplifting of continental margins. Figure 7 shows reconstructed sea level, indicating that many tropical ocean regions have experienced faster than global average increases in sea-level rise. The regional patterns of sea-level rise will vary according to the different causes contributing to it. This is an issue that is explored in the regional projections of sea-level rise later in this report (see Chapter 4).

Longer-term sea-level rise reconstructions help to locate the contemporary rapid rise within the context of the last few thousand years. The record used by Kemp et al. (2011), for example, shows a clear break in the historical record for North Carolina, starting in the late 19th century (Figure 8). This picture is replicated in other locations globally.

Figure 5: Global mean sea level (GMSL) reconstructed from tide-gauge data (blue, red) and measured from satellite altimetry (black). The blue and red dashed envelopes indicate the uncertainty, which grows as one goes back in time, because of the decreasing number of tide gauges. Blue is the current reconstruction to be compared with one from 2006. Source: Church and White 2011. Note the scale is in mm of sea-level-rise—divide by 10 to convert to cm.



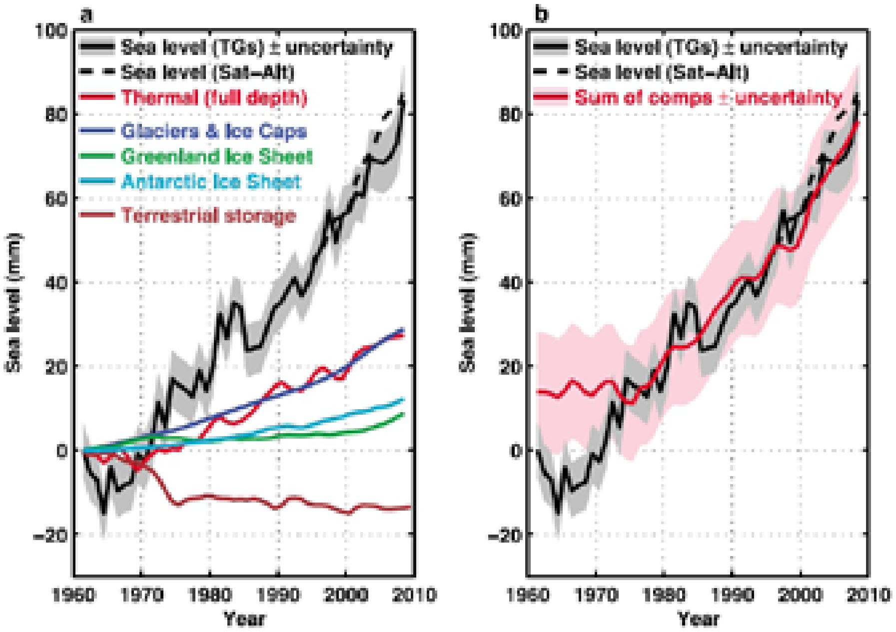
Source: Church and White (2011).

Increasing Loss of Ice from Greenland and Antarctica

Both the Greenland and Antarctic ice sheets have been losing mass since at least the early 1990s. The IPCC AR4 (Chapter 5.5.6 in working group 1) reported 0.41 ±0.4 mm/year as the rate of sea-level rise from the ice sheets for the period 1993–2003, while a more recent estimate by Church et al. in 2011 gives 1.3 ±0.4 mm/year for the period 2004–08. The rate of mass loss from the ice sheets has thus risen over the last two decades as estimated from a combination of satellite gravity measurements, satellite sensors, and mass balance methods (Velicogna 2009; Rignot et al. 2011). At present, the losses of ice are shared roughly equally between Greenland and Antarctica. In their recent review of observations (Figure 9),

[7] While the reference period used for climate projections in this report is the preindustrial period (circa 1850s), we reference sea-level rise changes with respect to contemporary base years (for example, 1980–1999 or 2000), because the attribution of past sea-level rise to different potential causal factors is difficult.

Figure 6: Left panel (a): The contributions of land ice (mountain glaciers and ice caps and Greenland and Antarctic ice sheets), thermosteric sea-level rise, and terrestrial storage (the net effects of groundwater extraction and dam building), as well as observations from tide gauges (since 1961) and satellite observations (since 1993). Right panel (b): the sum of the individual contributions approximates the observed sea-level rise since the 1970s. The gaps in the earlier period could be caused by errors in observations.

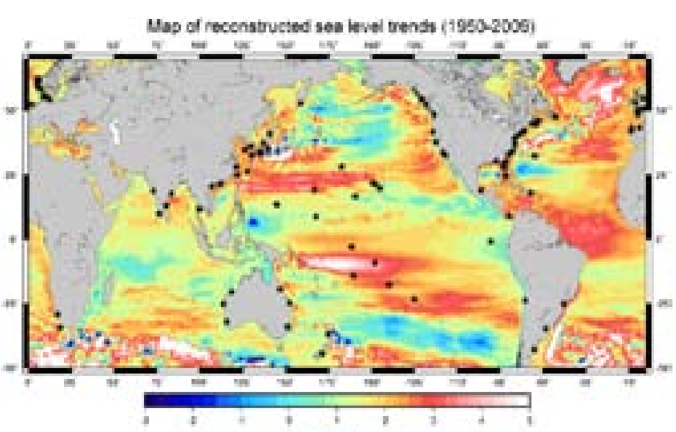


Source: Church et al., 2011.

Rignot and colleagues (Rignot et al. 2011) point out that if the present acceleration continues, the ice sheets alone could contribute up to 56 cm to sea-level rise by 2100. If the present-day loss rate continues, but without further acceleration, there would be a 13 cm contribution by 2100 from these ice sheets. Note that these numbers are simple extrapolations in time of currently observed trends and, therefore, cannot provide limiting estimates for projections about what could happen by 2100.

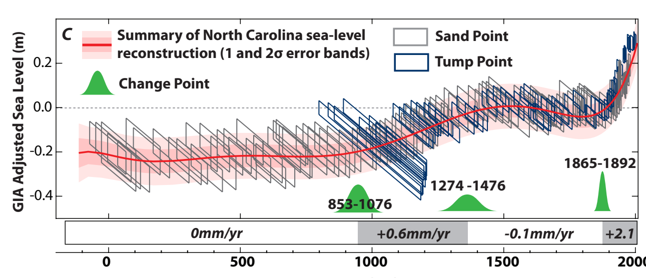
Observations from the pre-satellite era, complemented by regional climate modeling, indicate that the Greenland ice sheet moderately contributed to sea-level rise in the 1960s until early

Figure 7: Reconstruction of regional sea-level rise rates for the period 1952–2009, during which the average sea-level rise rate was 1.8 mm per year (equivalent to 1.8 cm/decade). Black stars denote the 91 tide gauges used in the global sea-level reconstruction.



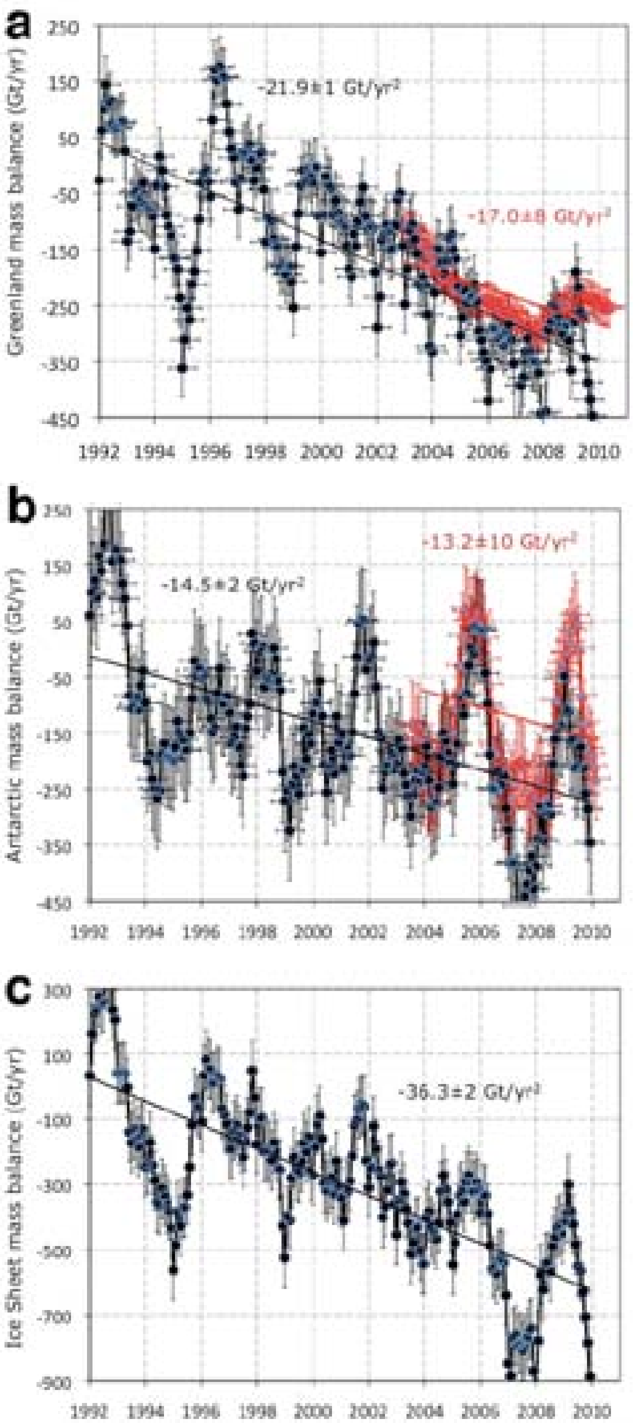
Source: Becker et al. 2012.

Figure 8: The North Carolina sea-level record reconstructed for the past 2,000 years. The period after the late 19th century shows the clear effect of human induced sea-level rise.



Source: Kemp et al. 2011.

Figure 9: Total ice sheet mass balance, dM/dt, between 1992 and 2010 for (a) Greenland, (b) Antarctica, and c) the sum of Greenland and Antarctica, in Gt/year from the Mass Budget Method (MBM) (solid black circle) and GRACE time-variable gravity (solid red triangle), with associated error bars.



Source: E. Rignot, Velicogna, Broeke, Monaghan, and Lenaerts 2011.

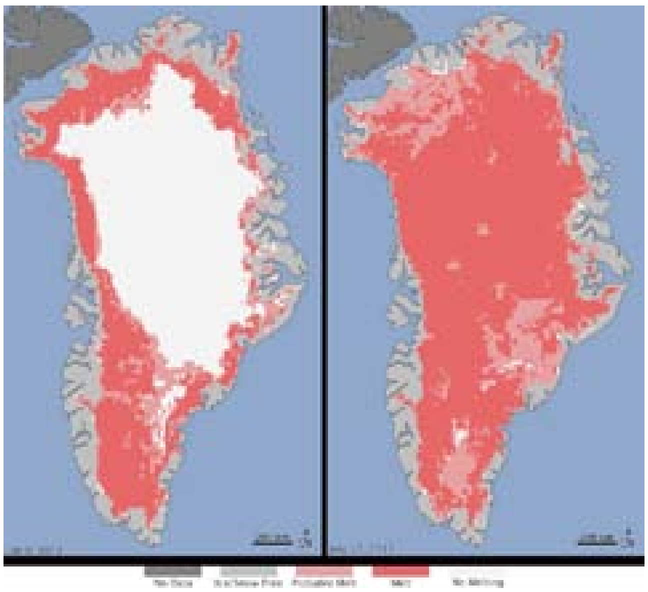
1970s, but was in balance until the early 1990s, when it started losing mass again, more vigorously (Rignot, Box, Burgess, and Hanna 2008). Earlier observations from aerial photography in southeast Greenland indicate widespread glacier retreat in the 1930s, when air temperatures increased at a rate similar to present (Bjørk et al. 2012). At that time, many land-terminating glaciers retreated more rapidly than in the 2000s, whereas marine terminating glaciers, which drain more of the inland ice, experienced a more rapid retreat in the recent period in southeast Greenland. Bjørk and colleagues note that this observation may have implications for estimating the future sea-level rise contribution of Greenland.

Recent observations indicate that mass loss from the Greenland ice sheet is presently equally shared between increased surface melting and increased dynamic ice discharge into the ocean (Van den Broeke et al. 2009). While it is clear that surface melting will continue to increase under global warming, there has been more debate regarding the fate of dynamic ice discharge, for which physical understanding is still limited. Many marine-terminating glaciers have accelerated (near doubling of the flow speed) and retreated since the late 1990s (Moon, Joughin, Smith, and Howat 2012; Rignot and Kanagaratnam 2006). A consensus has emerged that these retreats are triggered at the terminus of the glaciers, for example when a floating ice tongue breaks up (Nick, Vieli, Howat, and Joughin 2009). Observations of intrusion of relatively warm ocean water into Greenland fjords (Murray et al. 2010; Straneo et al. 2010) support this view. Another potential explanation of the recent speed-up, namely basal melt-water lubrication,[8] seems not to be a central mechanism, in light of recent observations (Sundal et al. 2011) and theory (Schoof 2010).

Increased surface melting mainly occurs at the margin of the ice sheet, where low elevation permits relatively warm air temperatures. While the melt area on Greenland has been increasing since the 1970s (Mernild, Mote, and Liston 2011), recent work also shows a period of enhanced melting occurred from the early 1920s to the early 1960s. The present melt area is similar in magnitude as in this earlier period. There are indications that the greatest melt extent in the past 225 years has occurred in the last decade (Frauenfeld, Knappenberger, and Michaels 2011). The extreme surface melt in early July 2012, when an estimated 97 percent of the ice sheet surface had thawed by July 12 (Figure 10), rather than the typical pattern of thawing around the ice sheet's margin, represents an uncommon but not unprecedented event. Ice cores from the central part of the ice sheet show that similar thawing has occurred historically, with the last event being dated to 1889 and previous ones several centuries earlier (Nghiem et al. 2012).

8 When temperatures rise above zero for sustained periods, melt water from surface melt ponds intermittently flows down to the base of the ice sheet through crevasses and can lubricate the contact between ice and bedrock, leading to enhanced sliding and dynamic discharge.

Figure 10: Greenland surface melt measurements from three satellites on July 8 (left panel) and July 12 (right panel), 2012.



Source: NASA 2012.

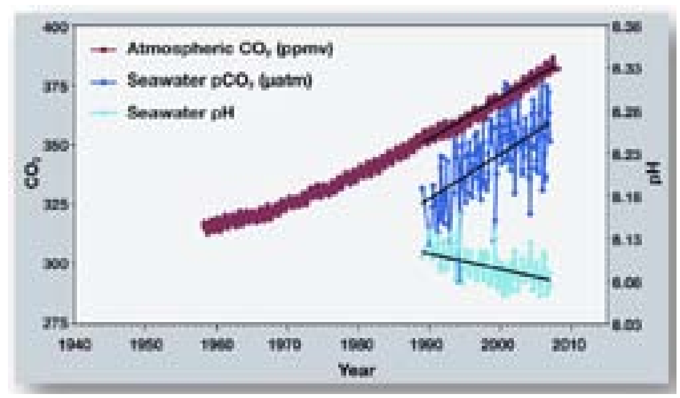
The Greenland ice sheet's increasing vulnerability to warming is apparent in the trends and events reported here—the rapid growth in melt area observed since the 1970s and the record surface melt in early July 2012.

Ocean Acidification

The oceans play a major role as one of the Earth´s large CO_2 sinks. As atmospheric CO_2 rises, the oceans absorb additional CO_2 in an attempt to restore the balance between uptake and release at the oceans' surface. They have taken up approximately 25 percent of anthropogenic CO_2 emissions in the period 2000–06 (Canadell et al. 2007). This directly impacts ocean biogeochemistry as CO_2 reacts with water to eventually form a weak acid, resulting in what has been termed "ocean acidification." Indeed, such changes have been observed in waters across the globe. For the period 1750–1994, a decrease in surface pH[9] of 0.1 pH has been calculated (Figure 11), which corresponds to a 30 percent increase in the concentration of the hydrogen ion (H^+) in seawater (Raven 2005). Observed increases in ocean acidity are more pronounced at higher latitudes than in the tropics or subtropics (Bindoff et al. 2007).

Acidification of the world's oceans because of increasing atmospheric CO_2 concentration is, thus, one of the most tangible consequences of CO_2 emissions and rising CO_2 concentration. Ocean acidification is occurring and will continue to occur, in

Figure 11: Observed changes in ocean acidity (pH) compared to concentration of carbon dioxide dissolved in seawater (p CO_2) alongside the atmospheric CO_2 record from 1956. A decrease in pH indicates an increase in acidity.



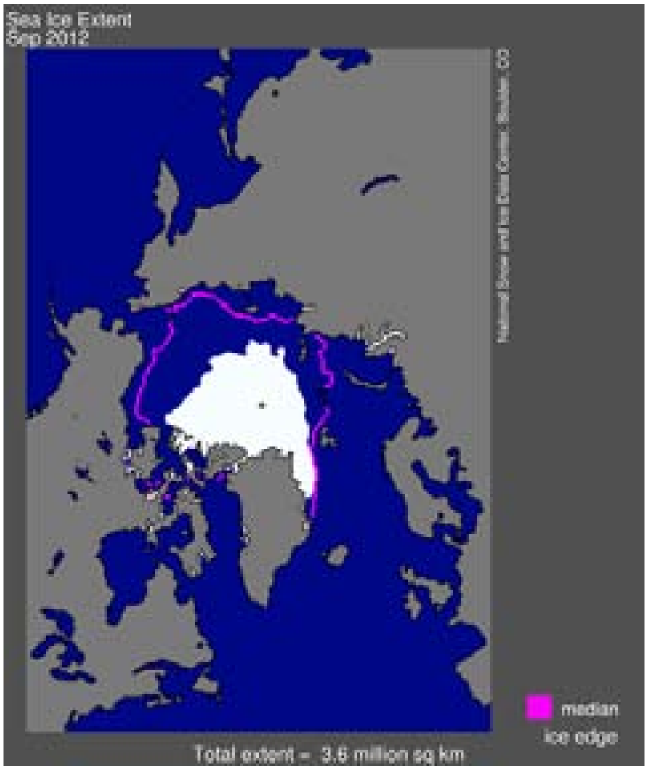
Source: NOAA 2012, PMEL Carbon Program.

the context of warming and a decrease in dissolved oxygen in the world's oceans. In the geological past, such observed changes in pH have often been associated with large-scale extinction events (Honisch et al. 2012). These changes in pH are projected to increase in the future. The rate of changes in overall ocean biogeochemistry currently observed and projected appears to be unparalleled in Earth history (Caldeira and Wickett 2003; Honisch et al. 2012).

Critically, the reaction of CO_2 with seawater reduces the availability of carbonate ions that are used by various marine biota for skeleton and shell formation in the form of calcium carbonate ($CaCO_3$). Surface waters are typically supersaturated with aragonite (a mineral form of $CaCO_3$), favoring the formation of shells and skeletons. If saturation levels are below a value of 1.0, the water is corrosive to pure aragonite and unprotected aragonite shells (Feely, Sabine, Hernandez-Ayon, Ianson, and Hales 2008). Because of anthropogenic CO_2 emissions, the levels at which waters become undersaturated with respect to aragonite have become shallower when compared to preindustrial levels. Aragonite saturation depths have been calculated to be 100 to 200 m shallower in the Arabian Sea and Bay of Bengal, while in the Pacific they are between 30 and 80 m shallower south of 38°S and between 30 and 100 m north of 3°N (Feely et al. 2004). In upwelling areas, which are often biologically highly productive, undersaturation levels have been observed to be shallow enough for corrosive waters to be upwelled intermittently to the surface.

9 Measure of acidity. Decreasing pH indicates increasing acidity and is on a logarithmic scale; hence a small change in pH represents quite a large physical change.

Figure 12: Geographical overview of the record reduction in September's sea ice extent compared to the median distribution for the period 1979–2000.



Source: NASA 2012.

Without the higher atmospheric CO_2 concentration caused by human activities, this would very likely not be the case (Fabry, Seibel, Feely, and Orr 2008).

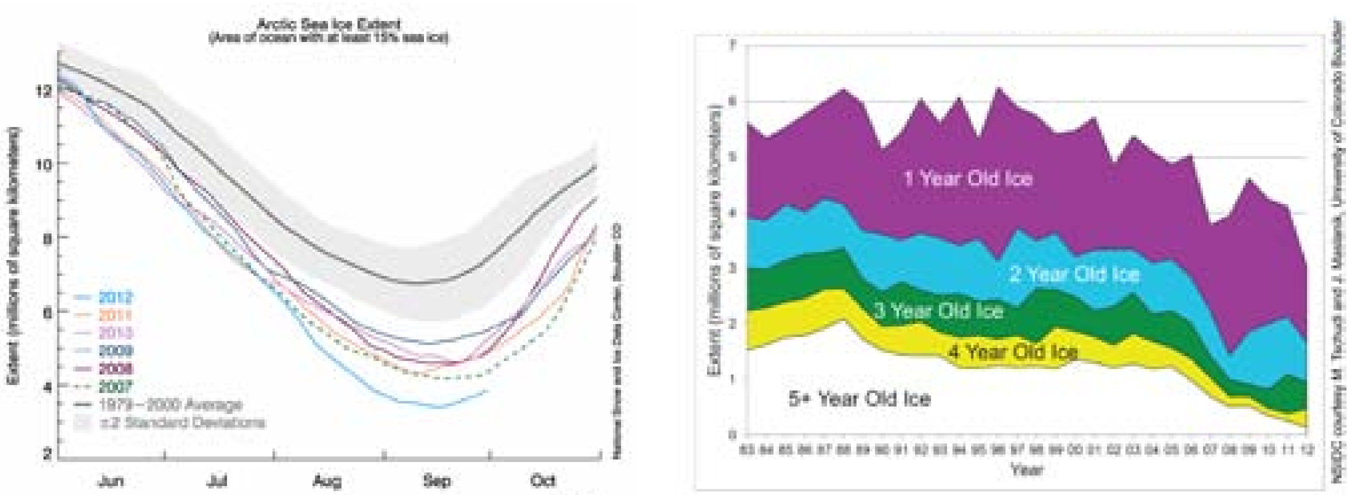
Loss of Arctic Sea Ice

Arctic sea ice reached a record minimum in September 2012 (Figure 12). This represents a record since at least the beginning of reliable satellite measurements in 1973, while other assessments estimate that it is a minimum for about at least the last 1,500 years (Kinnard et al. 2011). The linear trend of September sea ice extent since the beginning of the satellite record indicates a loss of 13 percent per decade, the 2012 record being equivalent to an approximate halving of the ice covered area of the Arctic Ocean within the last three decades.

Apart from the ice covered area, ice thickness is a relevant indicator for the loss of Arctic sea ice. The area of thicker ice (that is, older than two years) is decreasing, making the entire ice cover more vulnerable to such weather events as the 2012 August storm, which broke the large area into smaller pieces that melted relatively rapidly (Figure 13).

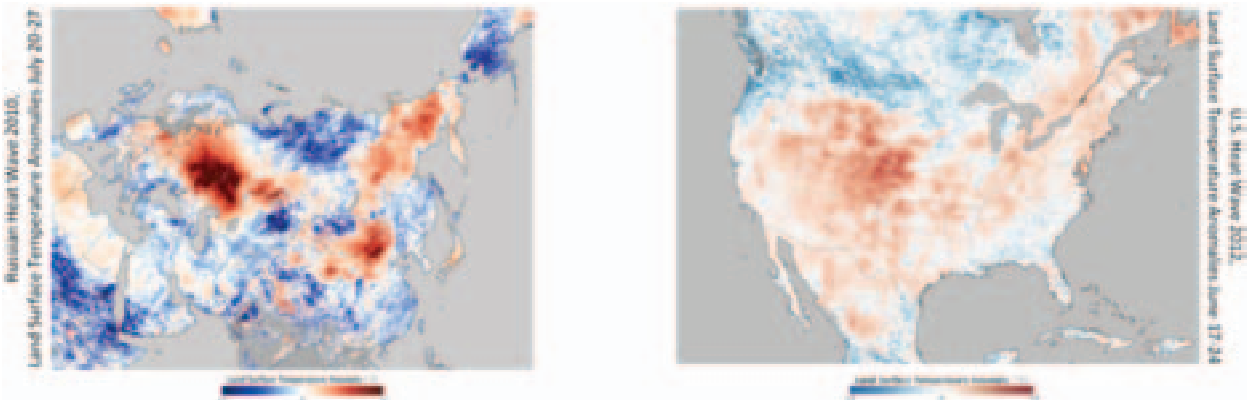
Recent scientific studies consistently confirm that the observed degree of extreme Arctic sea ice loss can only be explained by anthropogenic climate change. While a variety of factors have influenced Arctic sea ice during Earth's history (for example, changes in summer insolation because of variations in the Earth's orbital parameters or natural variability of wind patterns), these factors can be excluded as causes for the

Figure 13: Left panel: Arctic sea ice extent for 2007–12, with the 1979–2000 average in dark grey; light grey shading represents two standard deviations. Right panel: Changes in multiyear ice from 1983 to 2012.



Source: NASA 2012. Credits (right panel): NSIDC (2012) and M. Tschudi and J. Maslanik, University of Colorado Boulder.

Figure 14: Russia 2010 and United States 2012 heat wave temperature anomalies as measured by satellites.



Source: NASA Earth Observatory 2012.

recently observed trend (Min, Zhang, Zwiers, and Agnew 2008; Notz and Marotzke 2012).

Apart from severe consequences for the Arctic ecosystem and human populations associated with them, among the potential impacts of the loss of Arctic sea ice are changes in the dominating air pressure systems. Since the heat exchange between ocean and atmosphere increases as the ice disappears, large-scale wind patterns can change and extreme winters in Europe may become more frequent (Francis and Vavrus 2012; Jaiser, Dethloff, Handorf, Rinke, and Cohen 2012; Petoukhov and Semenov 2010).

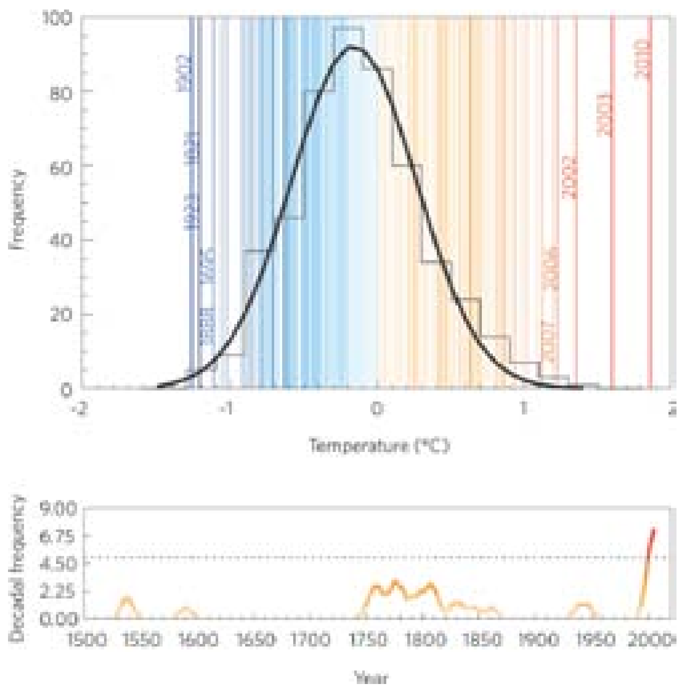
Heat Waves and Extreme Temperatures

The past decade has seen an exceptional number of extreme heat waves around the world that each caused severe societal impacts (Coumou and Rahmstorf 2012). Examples of such events include the European heat wave of 2003 (Stott et al. 2004), the Greek heat wave of 2007 (Founda and Giannaopoulos 2009), the Australian heat wave of 2009 (Karoly 2009), the Russian heat wave of 2010 (Barriopedro et al. 2011), the Texas heat wave of 2011 (NOAA 2011; Rupp et al. 2012), and the U.S. heat wave of 2012 (NOAA 2012, 2012b) (Figure 14).

These heat waves often caused many heat-related deaths, forest fires, and harvest losses (for example, Coumou and Rahmstorf 2012). These events were highly unusual with monthly and seasonal temperatures typically more than 3 standard deviations (sigma) warmer than the local mean temperature—so-called 3-sigma events. Without climate change, such 3-sigma events would be expected to occur only once in several hundreds of years (Hansen et al. 2012).

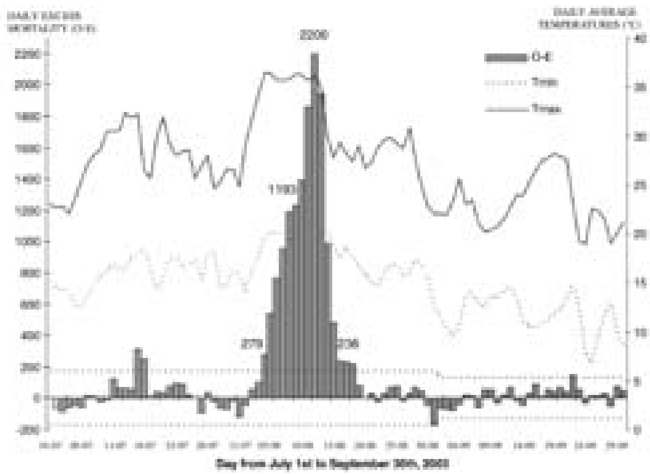
The five hottest summers in Europe since 1500 all occurred after 2002, with 2003 and 2010 being exceptional outliers (Figure 15) (Barriopedro et al. 2011). The death toll of the 2003 heat wave is estimated at 70,000 (Field et al. 2012), with daily excess mortality reaching up to 2,200 in France (Fouillet et al. 2006) (Figure 16). The heatwave in Russia in 2010 resulted in an estimated death toll of 55,000, of which 11,000 deaths were in Moscow alone, and more than 1 million hectares of burned land (Barriopedro et al. 2011). In 2012, the United States, experienced a devastating heat wave

Figure 15: Distribution (top panel) and timeline (bottom) of European summer temperatures since 1500.



Source: Barriopedro et al. 2011.

Figure 16: Excess deaths observed during the 2003 heat wave in France. O= observed; E= expected.

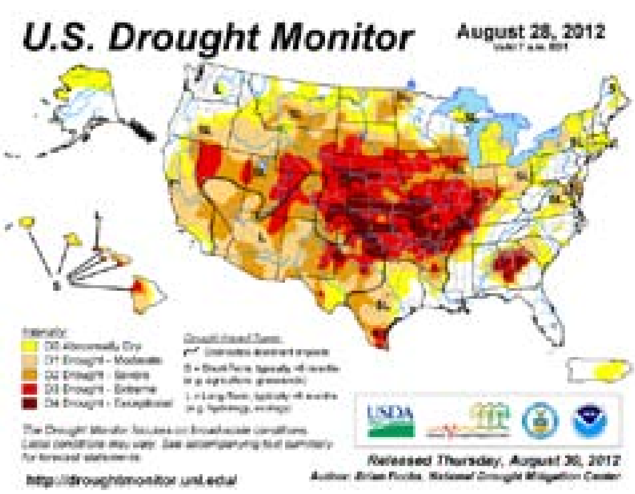


Source: Fouillet et al. 2006.

and drought period (NOAA 2012, 2012b). On August 28, about 63 percent of the contiguous United States was affected by drought conditions (Figure 17) and the January to August period was the warmest ever recorded. That same period also saw numerous wildfires, setting a new record for total burned area—exceeding 7.72 million acres (NOAA 2012b).

Recent studies have shown that extreme summer temperatures can now largely be attributed to climatic warming since the 1960s

Figure 17: Drought conditions experienced on August 28 in the contiguous United States.



Source: "U.S. Drought Monitor" 2012.

(Duffy and Tebaldi 2012; Jones, Lister, and Li 2008; Hansen et al. 2012; Stott et al. 2011). In the 1960s, summertime extremes of more than three standard deviations warmer than the mean of the climate were practically absent, affecting less than 1 percent of the Earth's surface. The area increased to 4–5 percent by 2006–08, and by 2009–11 occurred on 6–13 percent of the land surface. Now such extremely hot outliers typically cover about 10 percent of the land area (Figure 18) (Hansen et al. 2012).

The above analysis implies that extremely hot summer months and seasons would almost certainly not have occurred in the absence of global warming (Coumou, Robinson, and Rahmstorf, in review; Hansen et al. 2012). Other studies have explicitly attributed individual heat waves, notably those in Europe in 2003 (Stott, Stone, and Allen 2004), Russia in 2010 (Otto et al. 2012), and Texas in 2011 (Rupp et al. 2012) to the human influence on the climate.

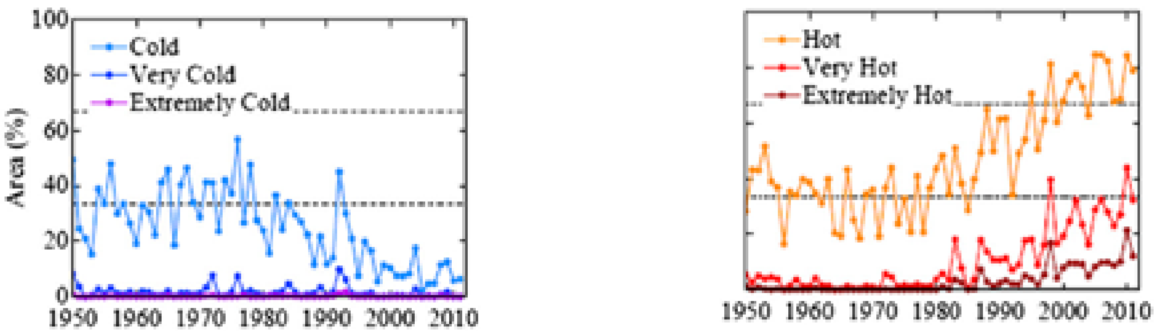
Drought and Aridity Trends

On a global scale, warming of the lower atmosphere strengthens the hydrologic cycle, mainly because warmer air can hold more water vapor (Coumou and Rahmstorf 2012; Trenberth 2010). This strengthening causes dry regions to become drier and wet regions to become wetter, something which is also predicted by climate models (Trenberth 2010). Increased atmospheric water vapor loading can also amplify extreme precipitation, which has been detected and attributed to anthropogenic forcing over Northern Hemisphere land areas (Min, Zhang, Zwiers, and Hegerl 2011).

Observations covering the last 50 years show that the intensification of the water cycle indeed affected precipitation patterns over oceans, roughly at twice the rate predicted by the models (Durack et al. 2012). Over land, however, patterns of change are generally more complex because of aerosol forcing (Sun, Roderick, and Farquhar 2012) and regional phenomenon including soil, moisture feedbacks (C.Taylor, deJeu, Guichard, Harris and Dorigo, 2012). Anthropogenic aerosol forcing likely played a key role in observed precipitation changes over the period 1940–2009 (Sun et al. 2012). One example is the likelihood that aerosol forcing has been linked to Sahel droughts (Booth, Dunstone, Halloran, Andrews, and Bellouin 2012), as well as a downward precipitation trend in Mediterranean winters (Hoerling et al. 2012). Finally, changes in large-scale atmospheric circulation, such as a poleward migration of the mid-latitudinal storm tracks, can also strongly affect precipitation patterns.

Warming leads to more evaporation and evapotranspiration, which enhances surface drying and, thereby, the intensity and duration of droughts (Trenberth 2010). Aridity (that is, the degree to which a region lacks effective, life-promoting moisture) has increased since the 1970s by about 1.74 percent per decade, but natural cycles have played a role as well (Dai 2010, 2011).

Figure 18: Northern Hemisphere land area covered (left panel) by cold (< –0.43σ), very cold (< –2σ), extremely cold (< –3σ) and (right panel) by hot (> 0.43σ), very hot (> 2σ) and extremely hot (> 3σ) summer temperatures.



Source: Hansen et al. 2012.

Dai (2012) reports that warming induced drying has increased the areas under drought by about 8 percent since the 1970s. This study, however, includes some caveats relating to the use of the drought severity index and the particular evapotranspiration parameterization that was used, and thus should be considered as preliminary.

One affected region is the Mediterranean, which experienced 10 of the 12 driest winters since 1902 in just the last 20 years (Hoerling et al. 2012). Anthropogenic greenhouse gas and aerosol forcing are key causal factors with respect to the downward winter precipitation trend in the Mediterranean (Hoerling et al. 2012). In addition, other subtropical regions, where climate models project winter drying when the climate warms, have seen severe droughts in recent years (MacDonald 2010; Ummenhofer et al. 2009), but specific attribution studies are still lacking. East Africa has experienced a trend towards increased drought frequencies since the 1970s, linked to warmer sea surface temperatures in the Indian-Pacific warm pool (Funk 2012), which are at least partly attributable to greenhouse gas forcing (Gleckler et al. 2012). Furthermore, a preliminary study of the Texas drought event in 2011 concluded that the event was roughly 20 times more likely now than in the 1960s (Rupp, Mote, Massey, Rye, and Allen 2012). Despite these advances, attribution of drought extremes remains highly challenging because of limited observational data and the limited ability of models to capture meso-scale precipitation dynamics (Sun et al. 2012), as well as the influence of aerosols.

Agricultural Impacts

Since the 1960s, sown areas for all major crops have increasingly experienced drought, with drought affected areas for maize more than doubling from 8.5 percent to 18.6 percent (Li, Ye, Wang, and Yan 2009). Lobell et al. 2011 find that since the 1980s, global crop production has been negatively affected by climate trends, with maize and wheat production declining by 3.8 percent and 5.5 percent, respectively, compared to a model simulation without climate trends. The drought conditions associated with the Russian heat wave in 2010 caused grain harvest losses of 25 percent, leading the Russian government to ban wheat exports, and about $15 billion (about 1 percent gross domestic product) of total economic loss (Barriopedro et al. 2011).

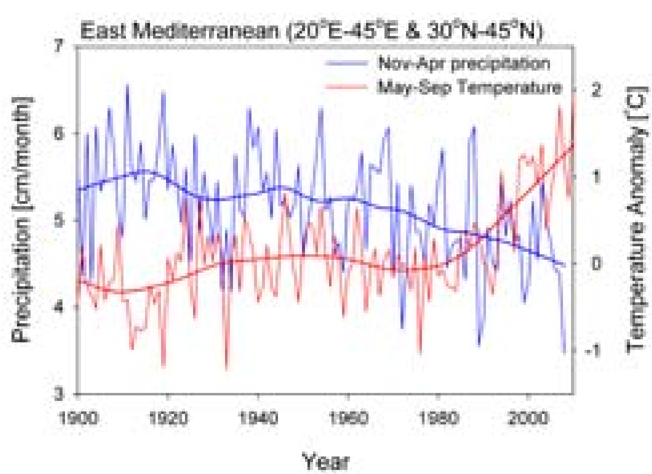
The high sensitivity of crops to extreme temperatures can cause severe losses to agricultural yields, as has been observed in the following regions and countries:

- Africa: Based on a large number of maize trials (covering varieties that are already used or intended to be used by African farmers) and associated daily weather data in Africa, Lobell et al. (2011) have found a particularly high sensitivity of yields to temperatures exceeding 30°C within the growing season. Overall, they found that each "growing degree day" spent at a temperature above 30°C decreases yields by 1 percent under optimal (drought-free) rainfed conditions. A test experiment where daily temperatures were artificially increased by 1°C showed that—based on the statistical model the researchers fitted to the data—65 percent of the currently maize growing areas in Africa would be affected by yield losses under optimal rainfed conditions. The trial conditions the researchers analyzed were usually not as nutrient limited as many agricultural areas in Africa. Therefore, the situation is not directly comparable to "real world" conditions, but the study underlines the nonlinear relationship between warming and yields.

- United States: In the United State, significant nonlinear effects are observed above local temperatures of 29°C for maize, 30°C for soybeans, and 32°C for cotton (Schlenker and Roberts 2009).
- Australia: Large negative effects of a "surprising" dimension have been found in Australia for regional warming variations of +2°C, which Asseng, Foster, and Turner argue have general applicability and could indicate a risk that "could substantially undermine future global food security" (Asseng, Foster, and Turner 2011).
- India: Lobell et al. 2012 analyzed satellite measurements of wheat growth in northern India to estimate the effect of extreme heat above 34°C. Comparison with commonly used process-based crop models led them to conclude that crop models probably underestimate yield losses for warming of 2°C or more by as much as 50 percent for some sowing dates, where warming of 2°C more refers to an artificial increase of daily temperatures of 2°C. This effect might be significantly stronger under higher temperature increases.

High impact regions are expected to be those where trends in temperature and precipitation go in opposite directions. One such "hotspot" region is the eastern Mediterranean where wintertime precipitation, which contributes most to the annual budget, has been declining (Figure 19), largely because of increasing anthropogenic greenhouse gas and aerosol forcing (Hoerling et al. 2012). At the same time, summertime temperatures have been increasing steadily since the 1970s (Figure 19), further drying the soils because of more evaporation.

Figure 19: Observed wintertime precipitation (blue), which contributes most to the annual budget, and summertime temperature (red), which is most important with respect to evaporative drying, with their long-term trend for the eastern Mediterranean region.



These climatic trends accumulated to produce four consecutive dry years following 2006 in Syria, with the 2007–08 drought being particularly devastating (De Schutter 2011; Trigo et al. 2010). As the vast majority of crops in this country are nonirrigated (Trigo et al. 2010), the region is highly vulnerable to meteorological drought. In combination with water mismanagement, the 2008 drought rapidly led to water stress with more than 40 percent of the cultivated land affected, strongly reducing wheat and barley production (Trigo et al. 2010). The repeated droughts resulted in significant losses for the population, affecting in total 1.3 million people (800,000 of whom were severely affected), and contributing to the migration of tens of thousands of families (De Schutter 2011). Clearly, these impacts are also strongly influenced by nonclimatic factors, such as governance and demography, which can alter the exposure and level of vulnerability of societies. Accurate knowledge of the vulnerability of societies to meteorological events is often poorly quantified, which hampers quantitative attribution of impacts (Bouwer 2012). Nevertheless, qualitatively one can state that the largely human-induced shift toward a climate with more frequent droughts in the eastern Mediterranean (Hoerling et al. 2012) is already causing societal impacts in this climatic "hotspot."

Extreme Events in the Period 2000–12

Recent work has begun to link global warming to recent record-breaking extreme events with some degree of confidence. Heat waves, droughts, and floods have posed challenges to affected societies in the past. Table 1 below shows a number of unusual weather events for which there is now substantial scientific evidence linking them to global warming with medium to high levels of confidence. Note that while floods are not included in this table, they have had devastating effects on human systems and are expected to increase in frequency and size with rising global temperatures.

Possible Mechanism for Extreme Event Synchronization

The Russian heat wave and Pakistan flood in 2010 can serve as an example of synchronicity between extreme events. During these events, the Northern Hemisphere jet stream exhibited a strongly meandering pattern, which remained blocked for several weeks. Such events cause persistent and, therefore, potentially extreme weather conditions to prevail over unusually longtime spans. These patterns are more likely to form when the latitudinal temperature gradient is small, resulting in a weak circumpolar vortex. This is just what occurred in 2003 as a result of anomalously high near-Arctic sea-surface temperatures (Coumou and Rahmstorf 2012). Ongoing melting of Arctic sea ice over recent decades has been linked to observed changes in the mid-latitudinal jet stream with possible implications for the occurrence of extreme events, such as heat waves, floods, and droughts, in different regions (Francis and Vavrus 2012).

Recent analysis of planetary-scale waves indicates that with increasing global warming, extreme events could occur in a globally synchronized way more often (Petoukhov, Rahmstorf, Petri, and Schellnhuber, in review). This could significantly exacerbate associated risks globally, as extreme events occurring simultaneously in different regions of the world are likely to put unprecedented stresses on human systems. For instance, with three large areas of the world adversely affected by drought at the same time, there is a growing risk that agricultural production globally may not be able to compensate as it has in the past for regional droughts (Dai 2012). While more research is needed here, it appears that extreme events occurring in different sectors would at some point exert pressure on finite resources for relief and damage compensation.

Welfare Impacts

A recent analysis (Dell and Jones 2009) of historical data for the period 1950 to 2003 shows that climate change has adversely affected economic growth in poor countries in recent decades. Large negative effects of higher temperatures on the economic growth of poor countries have been shown, with a 1°C rise in regional temperature in a given year reducing economic growth in that year by about 1.3 percent. The effects on economic growth are not limited to reductions in output of individual sectors affected by high temperatures but are felt throughout the economies of poor countries. The effects were found to persist over 15-year time horizons. While not conclusive, this study is arguably suggestive of a risk of reduced economic growth rates in poor countries in the future, with a likelihood of effects persisting over the medium term.

Table 1: Selection of record-breaking meteorological events since 2000, their societal impacts and qualitative confidence level that the meteorological event can be attributed to climate change. Adapted from Ref.[1]

Region (Year)	Meteorological Record-breaking Event	Confidence in attribution to climate change	Impact, costs
England and Wales (2000)	Wettest autumn on record since 1766. Several short-term rainfall records[2]	Medium based on[3–5]	~£1.3 billion[3]
Europe (2003)	hottest summer in at least 500 years[6]	High based on[7,8]	Death toll exceeding 70,000[9]
England and Wales (2007)	May to July wettest since records began in 1766[10]	Medium based on[3,4]	Major flooding causing ~£3 billion damage
Southern Europe (2007)	Hottest summer on record in Greece since 1891[11]	Medium based on[8,12–14]	Devastating wildfires
Eastern Mediter-ranean, Middle-East (2008)	Driest winter since 1902 (see Fig. 20)	High based on[15]	Substantial damage to cereal production[16]
Victoria (Aus) (2009)	Heat wave, many station temperature records (32–154 years of data)[17]	Medium based on[8,14]	Worst bushfires on record, 173 deaths, 3,500 houses destroyed[17]
Western Russia (2010)	Hottest summer since 1500[18]	Medium based on[8,13,14,19]	500 wildfires around Moscow, crop failure of ~25%, death toll ~55,000, ~US$15B economic losses[18]
Pakistan (2010)	Rainfall records[20]	Low to Medium based on[21,22]	Worst flooding in its history, nearly 3000 deaths, affected 20M people[23].
Colombia (2010)	Heaviest rains since records started in 1969[26]	Low to Medium based on[21]	47 deaths, 80 missing[26]
Western Amazon (2010)	Drought, record low water level in Rio Negro[27]	Low[27]	Area with significantly increased tree mortality spanning3.2 million km[27]
Western Europe (2011)	Hottest and driest spring on record in France since 1880[28]	Medium based on[8,14,29]	French grain harvest down by 12%
4 US states (TX, OK, NM, LA) (2011)	Record-breaking summer heat and drought since 1880[30,31]	High based on[13,14,31,32]	Wildfires burning 3 million acres (preliminary impact of $6 to $8 billion)[33]
Continental U.S. (2012)	July warmest month on record since 1895[34] and severe drought conditions	Medium based on[13,14,32]	Abrupt global food price increase due to crop losses[35]

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Table 1: Selection of record-breaking meteorological events since 2000, their societal impacts and qualitative confidence level that the meteorological event can be attributed to climate change. Adapted from Ref.[1] (*continued*)

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Chapter 3

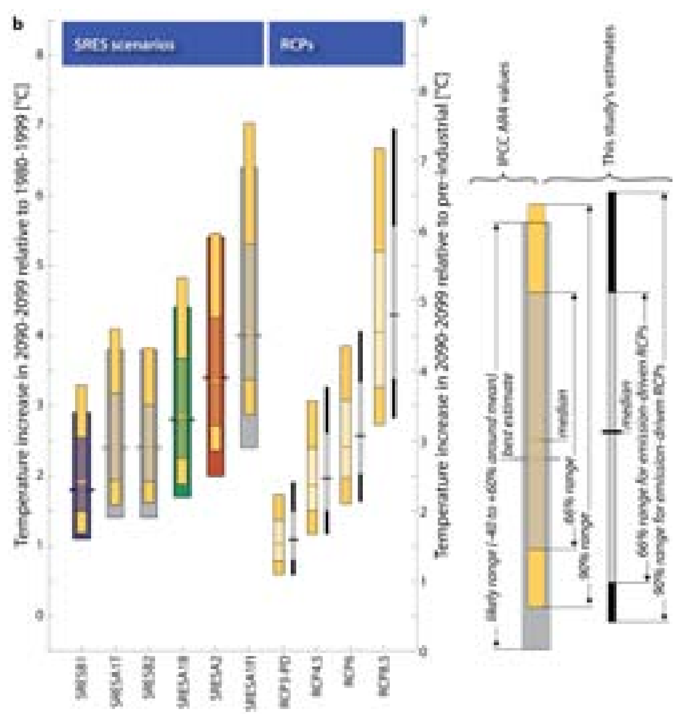
21st Century Projections

This section provides an overview of 21st century climate projections, comparing the effects of strong mitigation actions that limit warming to 1.5 and 2°C above preindustrial levels with a distinctly different world in which low mitigation efforts result in warming approaching 4°C by 2100. The section looks at how likely a 4°C world is and compares the global mean consequence of a range of mitigation scenarios, which show that 4°C warming is not inevitable and that warming can still be limited to 2°C or lower with sustained policy action. It then explores some of the consequences of a 4°C world.

The nonmitigation IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000), assessed in the IPCC AR4, gave a warming range for 2100 of 1.6–6.9°C above preindustrial temperatures. In these projections, about half the uncertainty range is due to the uncertainties in the climate system response to greenhouse gas emissions. Assuming a "best guess" climate response, the warming response was projected at 2.3–4.5°C by 2100, the remaining uncertainty being due to different assumptions about how the world population, economy, and technology will develop during the 21st century. No central, or most likely, estimate was provided of future emissions for the SRES scenarios, as it was not possible to choose one emissions pathway over another as more likely (Nakicenovic and Swart 2000). The range from the SRES scenarios, nevertheless, indicates that there are many nonmitigation scenarios that could lead to warming in excess of 4°C. The evolution of policies and emissions since the SRES was completed points to a warming of above 3°C being much more likely than those levels below, even after including mitigation pledges and targets adopted since 2009.

While the SRES generation of scenarios did not include mitigation of greenhouse gas emissions to limit global warming, a range of new scenarios was developed for the IPCC AR5, three of which are derived from mitigation scenarios. These so-called Representative Concentration Pathways (RCPs) (Moss et al. 2010) are compared with the SRES scenarios in Figure 20. Three of the RCPs are derived from mitigation scenarios produced by Integrated Assessment Models (IAMs) that are constructed to simulate the international energy-economic system and allow for a wide variety of energy

Figure 20: Probabilistic temperature estimates for old (SRES) and new (RCP) IPCC scenarios. Depending on which global emissions path is followed, the 4°C temperature threshold could be exceeded before the end of the century.



Source: Rogelj, Meinshausen, et al. 2012.

Box 1: What are Emissions Scenarios?

The climate system is highly sensitive to concentrations of greenhouse gases in the atmosphere. These concentrations are a result of emissions of different greenhouse gases from various anthropogenic or natural sources (for example, combustion of fossil fuels, deforestation, and agriculture). To better understand the impacts of climate change in the future, it is crucial to estimate the amount of greenhouse gases in the atmosphere in the years to come.

Based on a series of assumptions on driving forces (such as economic development, technology enhancement rate, and population growth, among others), emissions scenarios describe future release into the atmosphere of greenhouse gases and other pollutants. Because of the high level of uncertainty in these driving forces, emissions scenarios usually provide a range of possibilities of how the future might unfold. They assist in climate change analysis, including climate modeling and the assessment of impacts, adaptation, and mitigation.

The following emissions scenarios have been used to project future climate change and develop mitigation strategies. The Special Report on Emissions Scenarios (SRES), published by the IPCC in 2000, has provided the climate projections for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). They do not include mitigation assumptions. Since then, a new set of four scenarios (the representative concentration pathways or RCPs) has been designed, which includes mitigation pathways. The Fifth Assessment Report (AR5) will be based on these.

SRES Scenarios

The SRES study includes consideration of 40 different scenarios, each making different assumptions about the driving forces determining future greenhouse gas emissions. These emissions scenarios are organized into families:

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks at mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies.
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions for economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than that of A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Representative Concentration Pathways

Representative Concentration Pathways (RCPs) are based on carefully selected scenarios from work on integrated assessment modeling, climate modeling, and modeling and analysis of impacts. Nearly a decade of new economic data, information about emerging technologies, and observations of environmental factors, such as land use and land cover change, are reflected in this work. Rather than starting with detailed socioeconomic storylines to generate emissions scenarios, the RCPs are consistent sets of projections of only the components of radiative forcing (the change in the balance between incoming and outgoing radiation to the atmosphere caused primarily by changes in atmospheric composition) that are meant to serve as input for climate modeling. These radiative forcing trajectories are not associated with unique socio-economic or emissions scenarios, and instead can result from different combinations of economic, technological, demographic, policy, and institutional futures. Four RCPs were selected, defined, and named according to their total radiative forcing in 2100:

- RCP 8.5: Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100
- RCP 6: Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100
- RCP 4.5: Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100
- RCP 3PD: Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline

These RCPS will be complemented by so-called "shared socio-economic pathways" (SSPs), comprising a narrative and trajectories for key factors of socioeconomic development.

technologies to satisfy demand (Masui et al. 2011; Thomson et al. 2011; Vuuren et al. 2011; Rao and Riahi 2006).

The purpose of the RCP exercise was to derive a wide range of plausible pathways through 2100 (and beyond) to be used to drive the climate and climate impact models, the results of which would be summarized in the IPCC.

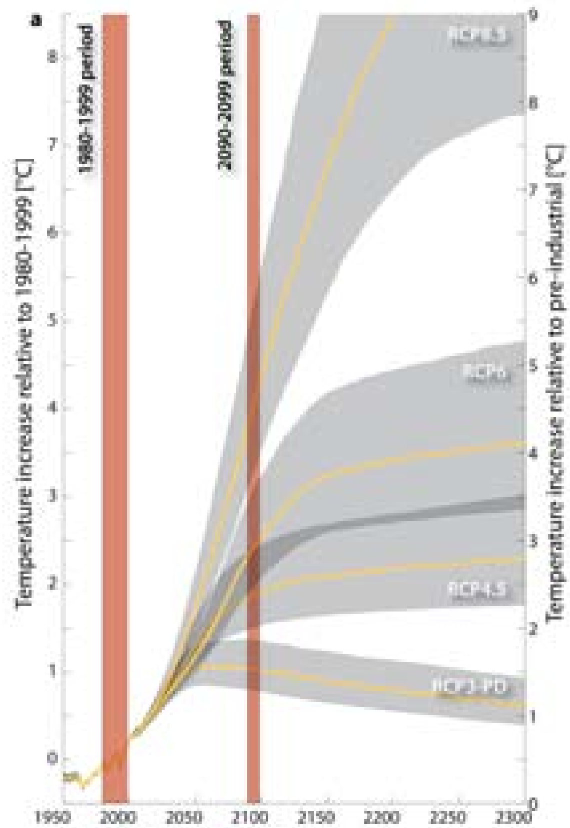
The highest RCP scenario, RCP8.5 (Riahi, Rao, et al. 2011), is the only nonmitigation pathway within this AR5 scenario group and is comparable to the highest AR4 SRES scenario (SRES A1FI). It projects warming by 2100 of close to 5°C. However, RCP6, one of the RCP mitigation scenarios that assumes only a limited degree of climate policy intervention, already projects warming exceeding 4°C by 2100 with a probability of more than 15 percent. As illustrated in Figure 20, the range of changes in temperature for the RCP scenarios is wider than for the AR4 SRES scenarios. The main reason for this is that the RCPs span a greater range of plausible emissions scenarios, including both scenarios assuming no mitigation efforts (RCP8.5) and scenarios that assume relatively ambitious mitigation efforts (RCP3PD). This wide variety of the RCP pathway range is further illustrated in Figure 21. The median estimate of warming in 2100 under the nonmitigation RCP8.5 pathway is close to 5°C and still steeply rising, while under the much lower RCP3PD pathway temperatures have already peak and slowly transition to a downward trajectory before the end of this century.

How Likely is a 4°C World?

The emission pledges made at the climate conventions in Copenhagen and Cancun, if fully met, place the world on a trajectory for a global mean warming of well over 3°C. Even if these pledges are fully implemented there is still about a 20 percent chance of exceeding 4°C in 2100.[10] If these pledges are not met then there is a much higher likelihood—more than 40 percent—of warming exceeding 4°C by 2100, and a 10 percent possibility of this occurring already by the 2070s, assuming emissions follow the medium business-as-usual reference pathway. On a higher fossil fuel intensive business-as-usual pathway, such as the IPCC SRESA1FI, warming exceeds 4°C earlier in the 21st century. It is important to note, however, that such a level of warming can still be avoided. There are technically and economically feasible emission pathways that could still limit warming to 2°C or below in the 21st century.

To illustrate a possible pathway to warming of 4°C or more, Figure 22 uses the highest SRES scenario, SRESA1FI, and compares it to other, lower scenarios. SRESA1FI is a fossil-fuel intensive, high economic growth scenario that would very likely cause mean the global temperature to exceed a 4°C increase above preindustrial temperatures.

Figure 21: Probabilistic temperature estimates for new (RCP) IPCC scenarios, based on the synthesized carbon-cycle and climate system understanding of the IPCC AR4. Grey ranges show 66 percent ranges, yellow lines are the medians. Under a scenario without climate policy intervention (RCP8.5), median warming could exceed 4°C before the last decade of this century. In addition, RCP6 (limited climate policy) shows a more than 15 percent chance to exceed 4°C by 2100.

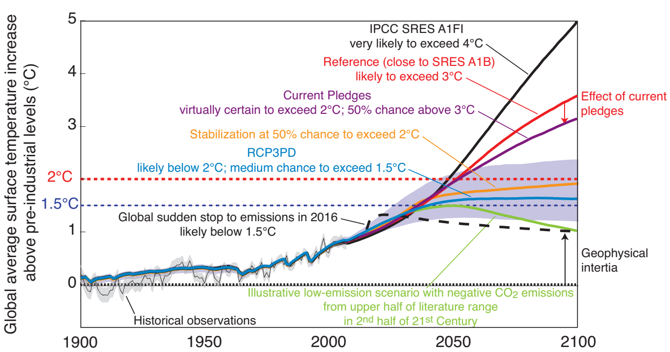


Source: Rogelj, Meinshausen et al. 2012

Most striking in Figure 22 is the large gap between the projections by 2100 of current emissions reduction pledges and the (lower) emissions scenarios needed to limit warming to 1.5–2°C above pre-industrial levels. This large range in the climate change implications of the emission scenarios by 2100 is important in its

10 Probabilities of warming projections are based on the approach of (Meinshausen et al. 2011), which involves running a climate model ensemble of 600 realizations for each emissions scenario. In the simulations each ensemble member is driven by a different set of climate-model parameters that define the climate-system response, including parameters determining climate sensitivity, carbon cycle characteristics, and many others. Randomly drawn parameter sets that do not allow the climate model to reproduce a set of observed climate variables over the past centuries (within certain tolerable "accuracy" levels) are filtered out and not used for the projections, leaving the 600 realizations that are assumed to have adequate predictive skill.

Figure 22: Median estimates (lines) from probabilistic temperature projections for two nonmitigation emission scenarios (SRES A1FI and a reference scenario close to SRESA1B), both of which come close to, or exceed by a substantial margin, 4°C warming by 2100. The results for these emissions are compared to scenarios in which current pledges are met and to mitigation scenarios holding warming below 2°C with a 50 percent chance or more (Hare, Cramer, Schaeffer, Battaglini, and Jaeger 2011; Rogelj et al. 2010; Schaeffer, Hare, Rahmstorf, and Vermeer 2012). The 2 standard deviation uncertainty range is provided for one scenario only to enhance readability. A hypothetical scenario is also plotted for which global emissions stop are ended in 2016, as an illustrative comparison against pathways that are technically and economically feasible. The spike in warming after emissions are cut to zero is due to the removal of the shading effect of sulfate aerosols.



own right, but it also sets the stage for an even wider divergence in the changes that would follow over the subsequent centuries, given the long response times of the climate system, including the carbon cycle and climate system components that contribute to sea-level rise.

The scenarios presented in Figure 22 indicate the likely onset time for warming of 4°C or more. It can be seen that most of the scenarios remain fairly close together for the next few decades of the 21st century. By the 2050s, however, there are substantial differences among the changes in temperature projected for the different scenarios. In the highest scenario shown here (SRES A1FI), the median estimate (50 percent chance) of warming reaches 4°C by the 2080s, with a smaller probability of 10 percent of exceeding this level by the 2060s. Others have reached similar conclusions (Betts et al. 2011). Thus, even if the policy pledges from climate convention in Copenhagen and Cancun are fully implemented, there is still a chance of exceeding 4°C in 2100. If the pledges are not met and present carbon intensity trends continue, then the higher emissions scenarios shown in Figure 22 become more likely, raising the probability of reaching 4°C global mean warming by the last quarter of this century.

Figure 23 shows a probabilistic picture of the regional patterns of change in temperature and precipitation for the lowest and highest RCP scenarios for the AR4 generation of AOGCMS. Patterns are broadly consistent between high and low scenarios. The high latitudes tend to warm substantially more than the global mean.

RCP8.5, the highest of the new IPCC AR5 RCP scenarios, can be used to explore the regional implications of a 4°C or warmer world. For this report, results for RCP8.5 (Moss et al. 2010) from the new IPCC AR5 CMIP5 (Coupled Model Intercomparison Project; Taylor, Stouffer, & Meehl 2012) climate projections have been analyzed. Figure 24 shows the full range of increase of global mean temperature over the 21st century, relative to the 1980–2000 period from 24 models driven by the RCP8.5 scenario, with those eight models highlighted that produce a mean warming of 4–5°C above preindustrial temperatures averaged over the period 2080–2100.

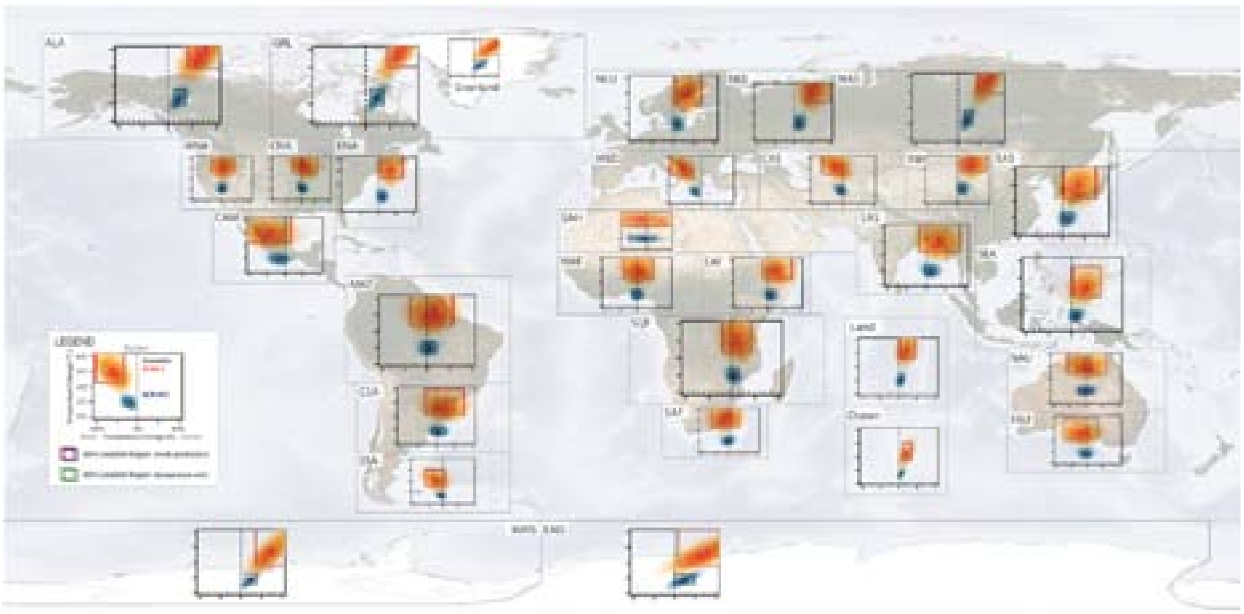
In terms of regional changes, the models agree that the most pronounced warming (between 4°C and 10°C) is likely to occur over land. During the boreal winter, a strong "arctic amplification" effect is projected, resulting in temperature anomalies of over 10°C in the Arctic region. The subtropical region consisting of the Mediterranean, northern Africa and the Middle East and the contiguous United States is likely to see a monthly summer temperature rise of more than 6°C.

CO_2 Concentration and Ocean Acidification

The high emission scenarios would also result in very high carbon dioxide concentrations and ocean acidification, as can be seen in Figure 25 and Figure 26. The increase of carbon dioxide concentration to the present-day value of 390 ppm has caused the pH to drop by 0.1 since preindustrial conditions. This has increased ocean acidity, which because of the logarithmic scale of pH is equivalent to a 30 percent increase in ocean acidity (concentration of hydrogen ions). The scenarios of 4°C warming or more by 2100 correspond to a carbon dioxide concentration of above 800 ppm and lead to a further decrease of pH by another 0.3, equivalent to a 150 percent acidity increase since preindustrial levels.

Ongoing ocean acidification is likely to have very severe consequences for coral reefs, various species of marine calcifying organisms, and ocean ecosystems generally (for example, Vézina & Hoegh-Guldberg 2008; Hofmann and Schellnhuber 2009). A recent review shows that the degree and timescale of ocean acidification resulting from anthropogenic CO_2 emissions appears to be greater than during any of the ocean acidification events identified so far over the geological past, dating back millions of years and including several mass extinction events (Zeebe 2012). If atmospheric CO_2 reaches 450 ppm, coral reef growth around the world is expected to slow down considerably and at 550 ppm reefs are expected to start to dissolve (Cao and Caldeira 2008; Silverman et al. 2009). Reduced growth, coral skeleton weakening,

Figure 23: The correlation between regional warming and precipitation changes in the form of joint distributions of mean regional temperature and precipitation changes in 2100 is shown for the RCP3-PD (blue) and RCP8.5 (orange) scenarios. The latter exceeds 4°C warming globally by 2100. The distributions show the uncertainty in the relationship between warming and precipitation for 20 of the AOGCMs used in the IPCC AR4, and take into account the significant effects of aerosols on regional patterns. The boxes indicate the inner 80 percent of the marginal distributions and the labeling of the axes is the same in all subpanels and given in the legend. The region definitions are based on Giorgi and Bi (2005) and are often used to describe large-scale climate changes over land areas. Here, they are amended by those for the West and East Antarctic Ice Sheets separated by the Transantarctic Mountains.



Source: Frieler, Meinshausen et al. 2012.

and increased temperature dependence would start to affect coral reefs already below 450 ppm. Thus, a CO_2 level of below 350 ppm appears to be required for the long-term survival of coral reefs, if multiple stressors, such as high ocean surface-water temperature events, sea-level rise, and deterioration in water quality, are included (Veron et al. 2009).

Based on an estimate of the relationship between atmospheric carbon dioxide concentration and surface ocean acidity (Bernie, Lowe, Tyrrell, and Legge 2010), only very low emission scenarios are able to halt and ultimately reverse ocean acidification (Figure 26). An important caveat on these results is that the approach used here is likely to be valid only for relatively short timescales. If mitigation measures are not implemented soon to reduce carbon dioxide emissions, then ocean acidification can be expected to extend into the deep ocean. The calculations shown refer only to the response of the ocean surface layers, and once ocean acidification has spread more thoroughly, slowing and reversing this will be much more difficult. This would further add significant stress to marine ecosystems already under pressure from human influences, such as overfishing and pollution.

Figure 24: Simulated historic and 21st century global mean temperature anomalies, relative to the preindustrial period (1880–1900), for 24 CMIP5 models based on the RCP8.5 scenario. The colored (and labeled) curves show those simulations reaching a global mean warming of 4°C–5°C warmer than preindustrial for 2080–2100, which are used for further analysis.

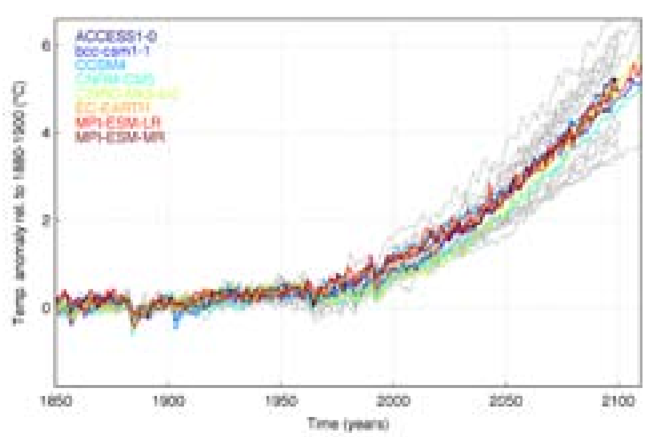
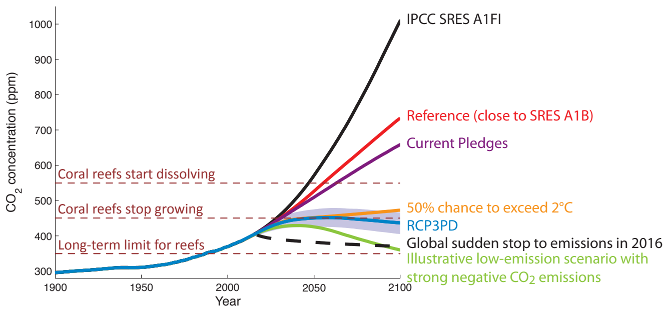
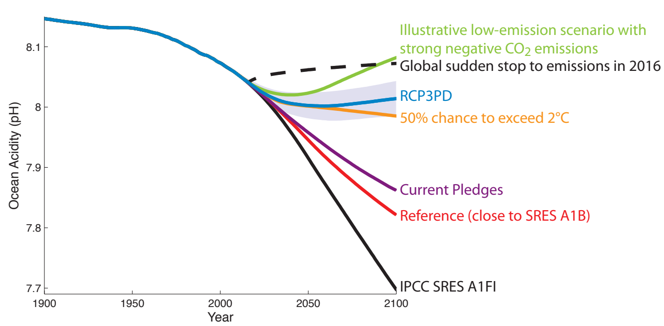


Figure 25: Projected impacts on coral reefs as a consequence of a rising atmospheric CO_2 concentration. Coral reef limits from Silverman et al. (2009) indicate the approximate levels of atmospheric CO_2 concentration at which the reaction of CO_2 with seawater reduces the availability of calcium carbonate to the point that coral reefs stop growing (450 ppm), or even start to resolve (550 ppm). Based on further considerations of coral bleaching resulting from associated warming at high CO_2 while also considering other human influences, Veron et al. (2009) estimated that the CO_2 concentration might have to be reduced to below 350 ppm to ensure the long-term survival of coral reefs. See caption of Figure 22 for legend.



Sources: Hare et al. 2011; Rogelj et al. 2010; Schaeffer et al. 2012.

Figure 26: Ocean surface pH. Lower pH indicates more severe ocean acidification, which inhibits the growth of calcifying organisms, including shellfish, calcareous phytoplankton, and coral reefs. The SRES A1FI scenarios show increasing ocean acidification likely to be associated with 4°C warming. Method for estimating pH from Bernie et al. (2010). Median estimates from probabilistic projections. See Hare et al. 2011; Rogelj et al. 2010; Schaeffer et al. 2012. See caption of Figure 22 for more details.



Droughts and Precipitation

As explained earlier, modeling, observations and theoretical considerations suggest that greenhouse-gas forcing leads to an intensification of the water cycle (Trenberth 2010). This implies that on the planetary scale, in a warmer world generally dry areas will become drier and wet areas wetter, in the absence of additional forcing by aerosols (Chen et al. 2011), which are projected to play a much smaller role relative to greenhouse gases compared to the 20th century. The most robust large-scale feature of climate model projections seems to be an increase in precipitation in the tropics and a decrease in the subtropics, as well as an increase in mid to high latitudes (Trenberth 2010; Allen 2012). On the regional scale, observational evidence suggests soil-moisture feedbacks might lead to increased vertical air transport (convection) triggering afternoon rains over drier soils, hence providing a negative feedback that dampens an increased dryness trend, although it is as yet unclear if and how the small-scale feedbacks involved translate to longer time scales and larger subcontinental spatial scales (Taylor de Jenet 2012).

Using the results from the latest generations of 13 climate models (CMIP5) that will form major input for IPCC AR5, Sillmann et al. (2012) showed that total precipitation on wet days is generally projected to increase by roughly 10 percent. They also found that extreme precipitation events, expressed as total annual precipitation during the five wettest days in the year, is projected to increase by 20 percent in RCP8.5 (4 + °C), indicating an additional risk of flooding. Large increases in mean total precipitation are projected for large parts of the Northern Hemisphere, East Africa, and South and Southeast Asia, as well as Antarctica, while changes are amplified in high northern and southern latitudes for scenarios in which global mean warming exceeds 4°C.

Significant increases in extreme precipitation are projected to be more widespread. The strongest increases of 20–30 percent precipitation during the annually wettest days were found for South Asia, Southeast Asia, western Africa, eastern Africa, Alaska, Greenland, northern Europe, Tibet, and North Asia. The projected increases in extreme precipitation seem to be concentrated in the Northern Hemisphere winter season (December, January, and February) over the Amazon Basin, southern South America, western North America, central North America, northern Europe, and Central Asia.

Overall drier conditions and droughts are caused by net decreases in precipitation and evaporation, the latter enhanced by higher surface temperatures (Trenberth 2010), as explained in Chapter 2 on observations. Since the net change determines soil moisture content, and since increased precipitation might occur in more intense events, an increase in overall precipitation might be consistent with overall drier conditions for some regions. Trenberth (2010) and more recently Dai (2012), who used the CMIP5 model results mentioned above, showed that particularly significant soil moisture decreases are projected to occur over much of the Americas, as well as the Mediterranean, southern Africa, and Australia. He also found that soil moisture content is projected to decrease in parts of the high northern latitudes.

A different indicator of drought is the Palmer Drought Index, which measures the cumulative balance of precipitation and evaporation relative to local conditions, therefore indicating what is normal for a geographical location. The most extreme droughts compared to local conditions are projected over the Amazon, western United States, the Mediterranean, southern Africa, and southern Australia (Dai 2012). Further discussion of droughts and their implications for agriculture appears in section 6.

IMPLICATIONS FOR ECONOMIC GROWTH AND HUMAN DEVELOPMENT

Increasing intensity of extreme dry events appears likely to have adverse implications for poverty, particularly in developing countries in the future. According to models that bring together the biophysical impacts of climate change and economic indicators, food prices can be expected to rise sharply, regardless of the exact amount of warming (Nelson et al. 2010). A recent projection of the change in poverty and changes in extreme dry event intensity in the 2071 to 2100 period under the SRES A2 scenario (with warming of about 4.1°C above preindustrial temperatures) indicates a significant risk of increased climate-induced poverty (Ahmed, Diffenbaugh, and Hertel 2009). The largest increase in poverty because of climate change is likely to occur in Africa, with Bangladesh and Mexico also projected to see substantial climate-induced poverty increases.

Tropical Cyclones

For some regions, the projected increased intensity of tropical cyclones poses substantial risks. The IPCC´s *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX)* reports that the average maximum cyclone intensity (defined by maximum speed) is likely to increase in the future (Field et al. 2012). This is to be expected from both theory and high-resolution modeling (Bender et al. 2010; Knutson et al. 2010), although uncertainty remains as to whether the global frequency of tropical cyclones will decrease or remain essentially the same. Increasing exposure through economic growth and development is likely to lead to higher economic losses in the future, with floodwaters in many locations increasing in the absence of additional protection measures. In the East Asia and Pacific and South Asian regions as a whole, gross domestic product (GDP) has outpaced increased losses because of tropical cyclone damage, but in all other regions the risk of economic losses from tropical cyclones appears to be growing faster than GDP per capita; in other words, the risk of loss of wealth because of tropical cyclone disasters appears to be increasing faster than wealth (UNISDR 2011). Recent work has demonstrated that the mortality risk from tropical cyclones depends on such factors as tropical cyclone intensity, exposure, levels of poverty, and governance structures (Peduzzi et al. 2012). In the short term, over the next 20 years or so, increases in population and development pressure combined with projected increases in tropical cyclone intensity appear likely to greatly increase the number of people exposed to risk and exacerbate disasters (Peduzzi et al. 2012). Mendelsohn, Emanuel, Chonabayashi, and Bakkensen (2012) project that warming reaching roughly 4°C by 2100 is likely to double the present economic damage resulting from the increased projected frequency of high-intensity tropical cyclones accompanying global warming, with most damages concentrated in North America, East Asia, and the Caribbean and Central American region.

Chapter 4

Focus: Sea-level Rise Projections

Projecting sea-level rise as a consequence of climate change is one of the most difficult, complex, and controversial scientific problems. Process-based approaches dominate—i.e the use of numeric models that represent the physical processes at play—and are usually used to project future climate changes such as air, temperature, and precipitation. In the case of Greenland and Antarctic ice sheets however, uncertainties in the scientific understanding about the response to global warming lead to less confidence in the application of ice sheet models to sea-level rise projections for the current century. On the other hand, semi-empirical approaches, which have begun to be used in recent years and take into account the observed relation between past sea level rise and global mean temperature to project future sea level rise, have their own limitations and challenges.

It is now understood that, in addition to global rise in sea levels, a number of factors, such as the respective contribution of the ice sheets or ocean dynamics, will affect what could happen in any particular location. Making estimates of regional sea-level rise, therefore, requires having to make estimates of the loss of ice on Greenland and Antarctica and from mountain glaciers and ice caps.

Furthermore, there is at present an unquantifiable risk of nonlinear responses from the West Antarctic Ice Sheet and possibly from other components of Greenland and Antarctica. In the 1970s, Mercer hypothesized that global warming could trigger the collapse of the West Antarctic Ice Sheet, which is separated from the East Antarctic Ice Sheet by a mountain range. The West Antarctic Ice Sheet is grounded mainly below sea level, with the deepest points far inland, and has the potential to raise eustatic global sea level by about 3.3 m (Bamber, Riva, Vermeersen, and LeBrocq 2009). This estimate takes into account that the reverse bedslope could trigger instability of the ice sheet, leading to an unhalted retreat. Since the first discussion of a possible collapse of the West Antarctic Ice Sheet because of this so-called Marine Ice Sheet Instability (Weertman 1974) induced by global anthropogenic greenhouse gas concentrations (Hughes 1973; Mercer 1968, 1978), the question of if and how this might happen has been debated. In their review of the issue in 2011, Joughin and Alley conclude that the possibility of a collapse of the West Antarctic Ice Sheet cannot be discarded, although it remains unclear how likely such a collapse is and at what rate it would contribute to sea-level rise.

A range of approaches have been used to estimate the regional consequences of projected sea-level rise with both a small and a substantial ice sheet contribution over the 21st century (see Appendix 1 and Table 2 for a summary).

Using a semi-empirical model indicates that scenarios that approach 4°C warming by 2100 (2090–2099) lead to median estimates of sea-level rise of nearly 1 m above 1980–1999 levels on this time frame (Table 2). Several meters of further future sea-level rise would very likely be committed to under these scenarios (Schaeffer et al. 2012). In this scenario, as described in Appendix 1, the Antarctic and Greenland Ice Sheets (AIS and GIS) contributions to the total rise are assumed to be around 26 cm each over this time period. Applying the lower ice-sheet scenario assumption, the total rise is approximately 50 cm, the AIS and GIS contributions to the total rise 0 and around 3 cm, respectively (Table 2). Process-based modeling considerations at the very high end of physically plausible ice-sheet melt, not used in this report, suggest that sea-level rise of as much as 2 m by 2100 might be possible at maximum (Pfeffer et al. 2008).

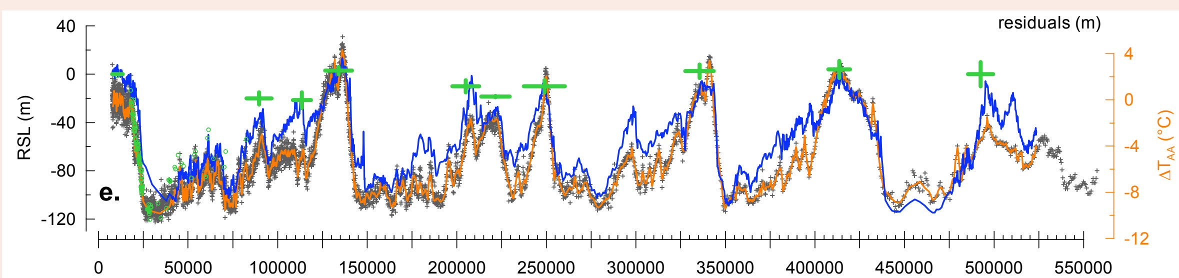
For a 2°C warming by 2100 (2090–99), the median estimate of sea-level rise from the semi-empirical model is about 79 cm above 1980–99 levels. In this case, the AIS and GIS contributions to the total rise are assumed to be around 23 cm each. Applying the lower ice-sheet scenario assumption, the median estimate of the total rise is about 34 cm, with the AIS and GIS contributing 0 and around 2 cm respectively (Table 2).

Box 2: Predictability of Future Sea-level Changes

Future sea-level rise can be described as the sum of global mean change (as if the ocean surface as a whole were to undergo a uniform vertical displacement, because of heating or addition of mass) and local deviations from this mean value (readjustment of the ocean surface resulting from gravity forces, winds, and currents). The components of both global and regional sea-level rise are known with varying levels of confidence. Global mean thermal expansion is relatively well simulated by climate models, as it depends on the total amount of atmospheric warming and the rate of downward mixing of heat in the oceans. The spread in existing climate model projections is, therefore, well understood and probably gives an adequate estimate of the uncertainty. Projected melt in mountain glaciers and ice caps is also considered reliable, or at least its potential contribution to sea-level rise is limited by their moderate total volume, equal to 0.60 ±0.07 m sea-level equivalent, of which a third is located at the margin of the large Greenland and Antarctic ice sheets (Radić and Hock 2010).

The Greenland and Antarctic ice sheets themselves constitute a markedly different problem. Their potential contributions to future global mean sea-level rise is very large, namely 7 m and 57 m, respectively, for complete melting. While a recent study (Robinson et al. 2012) suggests that a critical threshold for complete disintegration of the Greenland ice sheet might be 1.6°C, it should not be forgotten that this applies to an ice sheet that can reach its equilibrium state in a world where temperature stays at levels above that threshold for a long time. The time frame for such a complete disintegration, is of the order of at least several centuries or even millennia, even though it is not precisely known. This means, that a world that crosses that threshold but returns to lower levels thereafter, is not necessarily doomed to lose the Greenland ice sheet. Although the question of committed sea-level rise is important, currently projections of the nearer future are needed. However, the physics of the large ice sheets is poorly understood. There are indications that current physical models do not capture these fast timescales: model

Figure 27. Sea level (blue, green: scale on the left) and Antarctic air temperature (orange, gray: scale on the right) over the last 550,000 years, from paleo-records (from right to left: present-day on the left). Sea level varied between about 110 m below and 10 m above present, while air temperature in Antarctica varied between about 10°C below and 4°C above present, with a very good correlation between both quantities. Variations in Antarctic air temperature are about two-fold those of global mean air temperature. Low sea-level stands correspond to glacial periods and high stands to interglacials (see main text).



Source: Rohling et al. 2009.

simulations are so far not able to reproduce their presently observed contribution to current sea-level rise (Rahmstorf et al. 2007). This casts doubt on their ability to project changes into the future (see discussion below and throughout the main text).

Regional variations of future sea-level also have uncertainties, but—concerning ocean dynamics—they remain within reach of the current generation of coupled ocean-atmosphere models, in the sense that an ensemble of model projections may be a good approach to estimate future changes and their associated uncertainties. Concerning changes in gravitational patterns, however, they are inherently linked to ice-sheet projections. Nevertheless, several attempts have been made to project regional sea-level changes (Katsman et al. 2008, 2011; Perrette, Landerer, Riva, Frieler, and Meinshausen 2012; Slangen, Katsman, Wal, Vermeersen, and Riva 2011).

Past sea-level records indicate that it has varied by about 120 m between glacial periods and warmer interglacials (Figure 27), most of which is due to ice-sheet melt and regrowth. The most recent deglaciation has been accompanied by very rapid rates of rise (~40 mm/year) (Deschamps et al. 2012). However, that is not directly applicable to anthropogenic climate change because present-day ice sheets are much smaller than they were during the last ice age, and less numerous (the Laurentide and Fenno-scandinavian ice sheets do not exist anymore). A more relevant period to look at is the last warm, or interglacial, period (120,000 years ago). The global mean temperature was then likely 1–2°C above current values, and sea level was 6.6–9.4 m above the present level (Kopp, Simons, Mitrovica, Maloof, and Oppenheimer 2009),

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as revealed by a compilation of various proxy data around the world. Important caveats in the study of paleo-climate as analog for future climate change are the nature of the forcing, which leads to sea-level rise (Ganopolski and Robinson 2011), and the rate of sea-level rise. The latter is often very poorly known due to a lack of temporal resolution in the data. Despite the various caveats associated with the use of paleo-climatic data, a lesson from the past is that ice sheets may have been very sensitive to changes in climate conditions and did collapse in the past. That is a strong motivation to better understand what leads to these changes and to pursue the efforts to assess the risk of large ice-sheet contributions to sea-level rise in the future.

The benefit of choosing a 2°C pathway rather than a 4°C pathway can be to limit up to about 20 cm of total global sea-level rise by the end of the century.

Schaeffer et al. (2012) report, with a semi-empirical model, significant potential to reduce the rate of sea-level rise by 2100 with deep mitigation scenarios, such as RCP3PD, and even more so with a scenario consistent with limiting warming to 1.5°C by 2100 (Figure 28). For example, under deep mitigation scenarios the rate of sea-level rise could be either stabilized (albeit at three times the present level under RCP3PD) or reduced from peak levels reached at mid-century (under a 1.5°C consistent scenario). Under emissions scenarios that reach or exceed 4°C warming by 2100 the rate of sea-level rise would continue to increase throughout the 21st century (Figure 29).

Regional Sea-level Rise Risks

Sea level is not "flat" nor uniformly distributed over the Earth. The presence of mountains, deep-ocean ridges, and even ice sheets perturb the gravity field of the Earth and give the ocean surface mountains and valleys. Wind and ocean currents further shape the sea surface (Yin, Griffies, and Stouffer 2010), with strong currents featuring a cross-current surface slope (because of Earth rotation). This effect results in a so-called "dynamic" sea-level pattern (Figure 30), which describes local deviations from the gravity-shaped surface (also called geoid), which the ocean would have if it were at rest. This dynamic topography also adjusts to the temperature and salinity structure, and thereby the local density distribution of the underlying water. Apart from those changes in the sea level itself (or in the absolute sea level, as measured from the center of the Earth), the vertical motion of the Earth's crust also influences the perceived sea level at the coast (also called relative sea level, as measured from the coast). The elevation of the land surface responds to current and past changes in ice loading, in particular the glacial isostatic adjustment since the last deglaciation (Peltier and Andrews 1976). Local land subsidence can also occur in response to mining (Poland and Davis 1969), leading to a perceived sea-level rise. In what follows, this publication refers to sea-level changes regardless of whether they are absolute or relative changes.

Table 2: Global Mean Sea-Level Projections between Present-Day (1980–99) and the 2090–99 Period

The numbers in bracket for the 2°C and 4°C scenarios indicate the 16th and the 84th percentiles, as an indication of the assessed uncertainty. Components are thermal expansion, mountain glaciers, and ice caps (MGIC), Greenland Ice Sheet (GIS), and Antarctic Ice Sheet (AIS). All scenarios apply the same method of calculating the contributions from thermal expansion and mountain glaciers and ice caps, but differ in assumptions regarding the Greenland and Antarctica ice sheets. The "GIS AR4 and zero AIS" method assumes no contribution from the Antarctic ice sheet and a limited contribution from Greenland, using methods dating back to IPCC's AR4 (see text box). The semi-empirical method derives relations between warming and total sea-level rise from observations over the past 2,000 years and uses this relation for projections into the future. In addition, the table presents in the last row extrapolations in the future of present-day rates of sea-level rise (SLR Current Trend) for comparison with the projections (indicative purpose only). The two numbers indicated there represent a linear and an accelerated trend. The ice-sheet trends are derived from 1992–2009 observations (Rignot et al. 2011). For total SLR (last column), the lower estimate assumes a fixed 3.3 mm/yr annual rate of SLR, equal to the mean trend in satellite observations over the period 1993–2007 (Cazenave and Llovel 2010). The accelerated trend estimate only accounts for acceleration resulting from ice sheet melting (Rignot et al. 2011), added on top of the fixed-rate estimate of total sea-level rise.

Scenario		Thermal expansion (cm)	MGIC (cm)	Thermal +MGIC (cm)	GIS (cm)	AIS (cm)	Total (cm)
2°C	Lower ice sheet	19 (12, 26)	13 (9, 16)		2 (1, 3)	0 (0, 0)	34 (27, 42)
	Semi-empirical			32 (25, 40)	23 (14, 33)	23 (14, 33)	79 (65, 96)
4°C	Lower ice sheet	27 (17, 38)	16 (12, 20)	43 (33, 53)	3 (2, 5)	0 (0, 0)	47 (37, 58)
	Semi-empirical				26 (15, 39)	26 (16, 39)	96 (82, 123)
SLR Current Trend linear-accelerated					6–33	7–23	35–77

Figure 28: As for Figure 22 but for global mean sea-level rise using a semi-empirical approach. The indicative/fixed present-day rate of 3.3 mm.yr-1 is the satellite-based mean rate 1993–2007 (Cazenave and Llovel 2010). Median estimates from probabilistic projections. See Schaeffer et al. (2012) and caption of Figure 22 for more details.

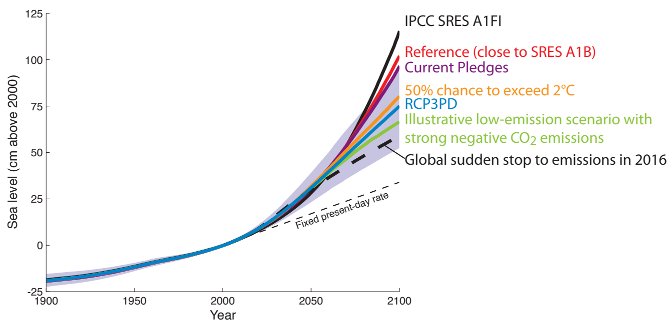


Figure 29: As for Figure 22 but for annual rate of global mean sea-level rise. The indicative/fixed present-day rate of 3.3 mm.yr-1 is the satellite based mean rate 1993–2007 (Cazenave and Llovel 2010). Median estimates from probabilistic projections. See Schaeffer et al. (2012 and caption of Figure 22 for more details.

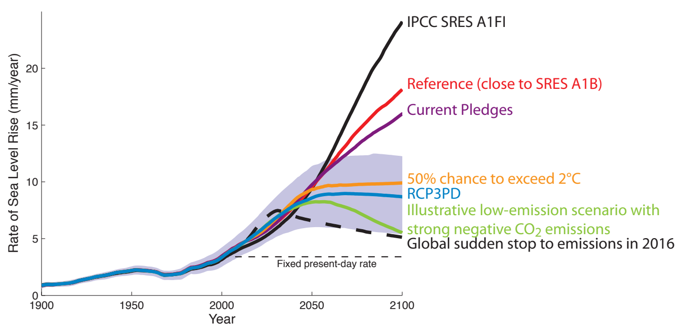
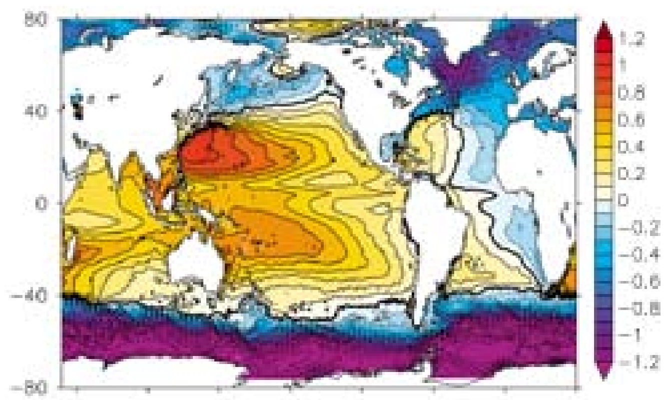


Figure 30: Present-day sea-level dynamic topography. This figure shows the sea-level deviations from the geoid (that is, the ocean surface determined by the gravity field, if the oceans were at rest). Above-average sea-level is shown in orange/red while below-average sea level is indicated in blue/purple. The contour lines indicate 10 cm intervals. This "dynamic topography" reflects the equilibrium between the surface slope and the ocean current systems. Noteworthy is the below-average sea level along the northeastern coast of the United States, associated with the Gulf Stream. Climate change is projected to provoke a slow-down of the Gulf Stream during the 21st century and a corresponding flattening of the ocean surface. This effect alone would, in turn, cause sea level to rise in that area. Note however that there is no systematic link between present-day dynamic topography (shown in this figure) and the future sea-level rise under climate warming.



Source: Yin et al. 2010.

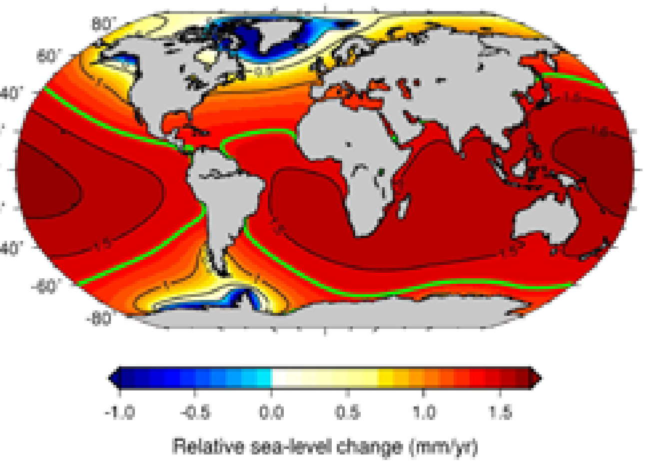
Climate change perturbs both the geoid and the dynamic topography. The redistribution of mass because of melting of continental ice (mountain glaciers, ice caps, and ice sheets) changes the gravity field (and therefore the geoid). This leads to above-average rates of rise in the far field of the melting areas and to below-average rise—sea-level drop in extreme cases—in the regions surrounding shrinking ice sheets and large mountain glaciers (Farrell and Clark 1976) (Figure 31). That effect is accentuated by local land uplift around the melting areas. These adjustments are mostly instantaneous.

Changes in the wind field and in the ocean currents can also—because of the dynamic effect mentioned above—lead to strong local sea-level changes (Landerer, Jungclaus, and Marotzke 2007; Levermann, Griesel, Hofmann, Montoya, and Rahmstorf 2005). In certain cases, however, these large deviations from the global mean rate of rise are caused by natural variability (such as the El Niño phenomenon) and will not be sustained in the future. The very high rates of rise observed in the western tropical Pacific since the 1960s (Becker et al. 2012) likely belong to this category (B. Meyssignac, Salas y Melia, Becker, Llovel, and Cazenave 2012).

In the following, the authors apply two scenarios (lower ice-sheet and higher ice-sheet) in a 4°C world to make regional sea-level rise projections. For methods, please see Appendix 1 and Table 2 for global-mean projections.

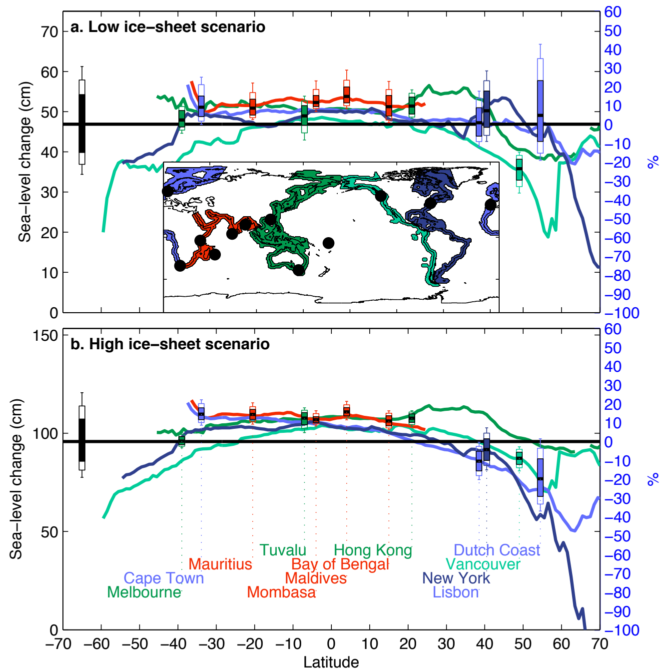
A clear feature of the regional projections for both the lower and higher ice-sheet scenarios is the relatively high sea-level rise at low latitudes (in the tropics) and below-average sea-level rise at higher latitudes (Figure 32). This is primarily because of the polar location of ice masses whose reduced gravitational pull accentuates the rise in their far-field, the tropics, similarly to present-day ice-induced pattern of rise (Figure 31). Close to the main ice-melt sources (Greenland, Arctic Canada, Alaska, Patagonia, and Antarctica), crustal uplift and reduced self-attraction cause a below-average rise, and even a sea-level fall in the very

Figure 31: Present-day rates of regional sea-level rise due to land-ice melt only (modeled from a compilation of land-ice loss observations). This features areas of sea-level drop in the regions close to ice sheets and mountain glaciers (in blue) and areas of sea-level rise further away (red), as a consequence of a modified gravity field (reduced self-attraction from the ice masses) or land uplift. The thick green contour indicates the global sea-level rise (1.4 mm/yr): locations inside the contour experience above-average rise, while locations outside the contour experience below-average sea-level rise or even drop. Compare Figure A1.3 for projected sea-level contribution from land ice in a 4°C world



Source: Bamber and Riva 2010.

Figure 32: Sea-level rise in a 4°C warmer world by 2100 along the world's coastlines, from South to North. Each color line indicates an average over a particular coast as shown in the inlet map in the upper panel. The scale on the right-hand side represents the ratio of regional sea-level compared to global-mean sea level (units of percent), and the vertical bars represent uncertainty thereof, showing 50 percent, 68 percent, and 80 percent ranges.



near-field of a mass source. Further away, the eastern Asian coast and the Indian Ocean experience above-average contribution from land-ice melt.

While this is clearly the dominant effect in the higher ice-sheet case, where the median land-ice contribution makes up around 70 percent of the total, it explains only part of the pattern in the lower ice-sheet case, where land ice accounts for only 40 percent of the total median. Ocean dynamics also shape the pattern of projected sea-level. In particular, above-average contribution from ocean dynamics is projected along the northeastern North American and eastern Asian coasts, as well as in the Indian Ocean (Figure A1.3). In the northeastern North American coast, gravitational forces counteract dynamic effects because of the nearby location of Greenland. Along the eastern Asian coast and in the Indian Ocean, however, which are far from melting glaciers, both gravitational forces and ocean dynamics act to enhance sea-level rise, which can be up to 20 percent higher than the global mean.

In summary, projected sea-level rise by 2100 presents regional variations, which are generally contained within ± 20 percent of the global mean rise, although higher values are also possible (Figure 32). Sea-level rise tends to be larger than the global mean at low latitudes, such as in vulnerable locations in the Indian Ocean or in the western Pacific, and less than the global mean at high latitudes, for example along the Dutch coast, because of the polar location of the ice sheets and their reduced gravitational pull after melting. On top of ice-induced patterns, changes in ocean currents can also lead to significant deviations from the global mean rise. The northeastern North American coast has indeed been identified as a "hotspot" where the sea level is rising faster than the global mean (Sallenger et al. 2012), and might continue to do so (Yin et al. 2009), if the gravitational depression from the nearby melting Greenland and Canadian glaciers is moderate.

The biggest uncertainties in regional projections of sea-level rise are caused by insufficient knowledge of the contributions from the large ice sheets, especially from dynamic changes in the Antarctic ice sheet. So far, semi-empirical models or approaches using kinematic constraints[11] have been used to bridge the gap

11 A kinematic constraint is, for example, estimating the maximum ice flux that can in total pass through the narrow fjords around the Greenland ice sheet assuming an upper limit of a physically reasonable speed of the glaciers.

between the few available projections of ice-sheet contribution and the need to provide estimates of future sea-level rise. It should be noted that warming of 4°C above preindustrial temperatures by 2100 implies a commitment to further sea-level rise beyond this point, even if temperatures were stabilized.

RISKS OF SEA-LEVEL RISE

While a review of the regional impacts of sea level rise has not been undertaken here, it is useful to indicate some particular risks.

Because of high population densities and often inadequate urban planning, coastal cities in developing regions are particularly vulnerable to sea-level rise in concert with other impacts of climate change. Coastal and urban migration, with often associated unplanned urban sprawl, still exacerbates risks in the future. Sea-level rise impacts are projected to be asymmetrical even within regions and countries. Of the impacts projected for 31 developing countries, only ten cities account for two-thirds of the total exposure to extreme floods. Highly vulnerable cities are to be found in Mozambique, Madagascar, Mexico, Venezuela, India, Bangladesh, Indonesia, the Philippines, and Vietnam (Brecht et al. 2012)

Because of the small population of small islands and potential problems with adaptation implementation, Nicholls et al. (2011) conclude that forced abandonment seems a possible outcome even for small changes in sea level. Similarly, Barnett and Adger (2003) point out that physical impacts might breach a threshold that pushes social systems into complete abandonment, as institutions that could facilitate adaptation collapse. Projecting such collapses, however, can potentially lead to self-fulfilling prophecies, if foreign aid decreases. Barnett and Adger cite Tuvalu as a case in which negotiations over migration rights to New Zealand might have undermined foreign aid investor confidence and thereby indirectly undermined the potential for adaptive capacity.

A recent detailed review (Simpson et al. 2010) of the consequences for 1 m sea-level rise in the Caribbean illustrates the scale of the damage that could be caused to small island developing states by the 2080s. Total cumulative capital GDP loss was estimated at US$68.2 billion equivalent to about 8.3 percent of projected GDP in 2080, including present value of permanently lost land, as well as relocation and reconstruction costs. Annual GDP costs were estimated by the 2080s at $13.5 billion (1.6 percent of GDP), mainly in the tourism and agricultural sectors. These estimates do not include other potential factors, such as water supply costs, increased health care costs, nonmarket damages, and increased tropical cyclone damages. The tourism industry, a major source of economic growth in these regions, was found to be very sensitive to sea-level rise. Large areas of important wetlands would be lost, affecting fisheries and water supply for many communities: losses of 22 percent in Jamaica, 17 percent in Belize, and 15 percent in the Bahamas are predicted.

Nicholls and Cazenave (2010) stress that geological processes also drive sea-level rise and, therefore, its impacts. In additional, human activities, such as drainage and groundwater fluid withdrawal, exacerbate subsidence in regions of high population density and economic activity. River deltas are particularly susceptible to such additional stresses. These observations highlight the potential for coastal management to alleviate some of the projected impacts. At the same time, they hint at the double challenge of adapting to climate change induced sea-level rise and impacts of increasing coastal urbanization, particularly in developing regions. It thus appears paramount to include sea-level rise projections in coastal planning and decisions on long-term infrastructure developments.


Chapter
5

Focus: Changes in Extreme Temperatures

A thorough assessment of extreme events by Field et al. (2012) concludes that it is very likely that the length, frequency, and intensity of heat waves will increase over most land areas, with more warming resulting in more extremes. Zwiers and Kharin (1998) report, when examining simulations with doubled CO_2, (which typically results in about 3°C global mean warming), that the intensity of extremely hot days, with a return time of 20 years, increases between 5°C and 10°C over continents, with the larger values over North and South America and Eurasia, related to substantial decreases in regional soil moisture.

Meehl and Tebaldi (2004) found significant increases in intensity, duration, and frequency of three-day heat events under a business-as-usual scenario. The intensity of such events increases by up to 3°C in the Mediterranean and the western and southern United States. Based on the SRES A2 transient greenhouse-gas scenario, Schär et al. (2004) predict that toward the end of the century about every second European summer could be as warm as or warmer than the summer of 2003. Likewise, Stott et al. (2004) show that under unmitigated emission scenarios, the European summer of 2003 would be classed as an anomalously cold summer relative to the new climate by the end of the century. Barnett et al. (2006) show that days exceeding the present-day 99th percentile occur more than 20 times as frequently in a doubled CO_2 climate. In addition, extremely warm seasons are robustly predicted to become much more common in response to doubled CO_2 (Barnett et al. 2006). Based on the same ensemble of simulations, Clark, Brown, and Murphy (2006) conclude that the intensity, duration, and frequency of summer heat waves are expected to be substantially greater over all continents, with the largest increases over Europe, North and South America, and East Asia.

These studies, which analyze extreme weather events in simulations with a doubling of CO_2 and those following a business-as-usual emissions path, can provide useful insights. Without exception, such studies show that heat extremes, whether on daily or seasonal time scales, greatly increase in climates more than 3°C warmer than today.

To the authors' knowledge, no single study has specifically analyzed the number of extremes in a world beyond 4°C warmer than preindustrial conditions. The authors address this gap in the science and provide statistical analysis of heat extremes in CMIP5 (Coupled Model Intercomparison Project) climate projections that reach a 4°C world by the end of the 21st century (Taylor et al. 2012). Methods are described in Appendix 2.

A Substantial Increase in Heat Extremes

The authors' statistical analysis indicates that monthly heat extremes will increase dramatically in a world with global mean temperature more than 4°C warmer than preindustrial temperatures. Temperature anomalies that are associated with highly unusual heat extremes today (namely, 3-sigma events occurring only once in several hundreds of years in a stationary climate)[12] will have become the norm over most (greater than 50 percent) continental areas by the end of the 21st century. Five-sigma events, which are now essentially

[12] In general, the standard deviation (sigma) shows how far a variable tends to deviate from its mean value. In the authors' study it represents the possible year-to-year changes in local monthly temperature because of natural variability. For a normal distribution, events warmer than 3 sigma away from the mean have a return time of 740 years and events warmer than 5 sigma have a return time of several million years. Monthly temperature data do not necessarily follow a normal distribution (for example, the distribution can have "long" tails making warm events more likely) and the return times can be different. Nevertheless, 3-sigma events are extremely unlikely and 4-sigma events almost certainly have not occurred over the lifetime of key infrastructure. A warming of 5 sigma means that the average change in the climate is 5 times larger than the normal year-to-year variation experienced today.

absent, will become common, especially in the tropics and in the Northern Hemisphere (NH) mid-latitudes during summertime.

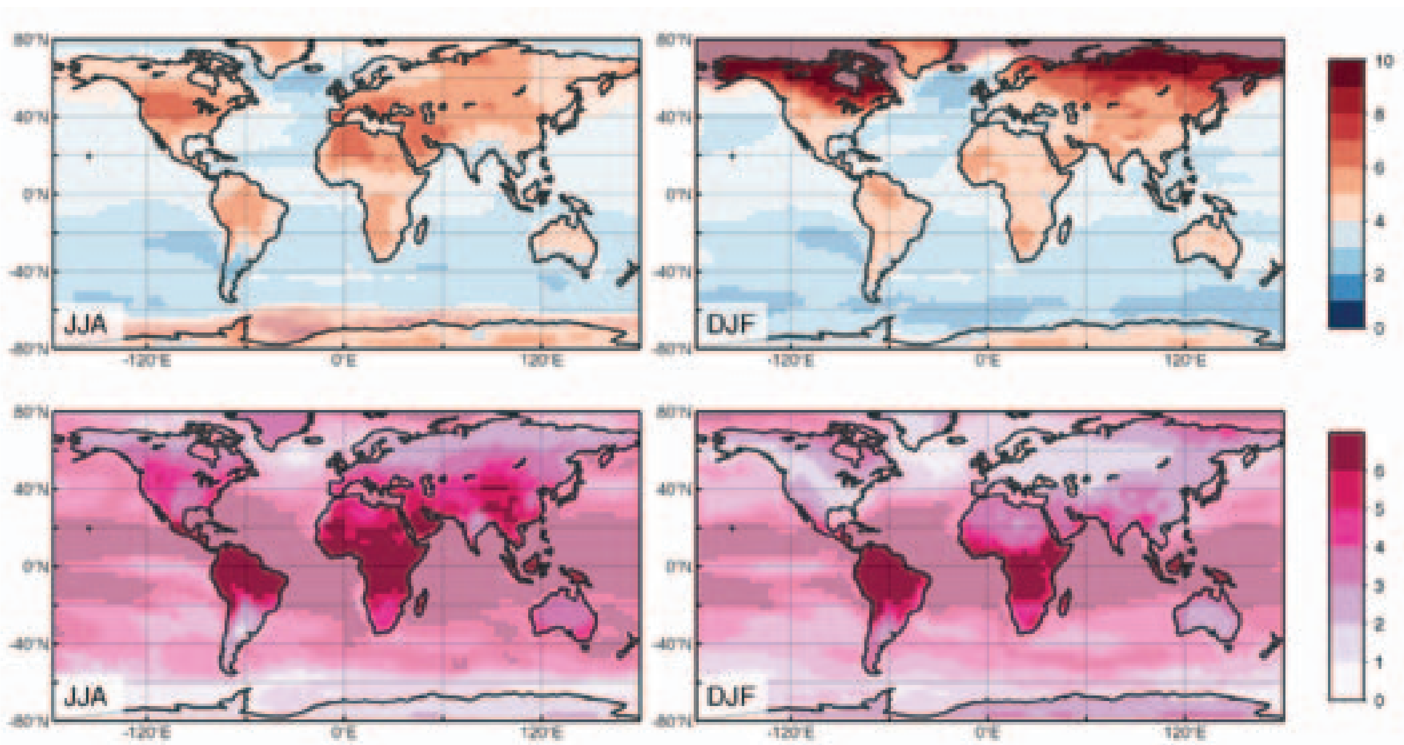
According to the authors' analysis, the most pronounced warming will occur over land (see Figure 33, top row). Monthly mean temperatures over oceans will increase between 0°C and 4°C and over continents between 4°C and 10°C. Warming over continental regions in the tropics and in the Southern Hemisphere (SH) is distributed rather evenly without strong spatial and seasonal variations. The only exception is Argentina, which is expected to see less wintertime (JJA) warming. In the NH, much stronger spatial and seasonal variations in continental warming patterns are observed. During the boreal winter, strong warming in the near Arctic region is observed due to the so-called "arctic amplification" effect, resulting in temperature anomalies of over 10°C. Two NH regions can be identified that are expected to see more warming in summertime than in wintertime: The subtropical region consisting of the Mediterranean, northern Africa, and the Middle East, as well as the contiguous United States, are likely to see monthly summer temperatures rise by more than 6°C.

All land areas show a mean warming of at least 1-sigma above the present-day mean and most land areas (greater than 80 percent) show warming of at least 2-sigma. Roughly half of the land area will likely experience a mean warming of more than 3-sigma during the boreal winter and more than 4-sigma during the boreal summer. This seasonal difference is due to enhanced warming over NH mid-latitudinal land areas during the boreal summer.

Shifts in Temperature by Region

In the authors' analysis, a 4°C warmer world will consistently cause temperatures in the tropics to shift by more than 6 standard deviations for all months of the year (Figure 33 bottom panels). Particularly, countries in tropical South America, Central Africa, and all tropical islands in the Pacific will see unprecedented extreme temperatures become the new norm in all months of the year. In fact, a temperature shift of 6 standard deviations or more implies a new climatic regime with the coolest months in 2080–2100 being substantially warmer than the warmest months in the end of the 20th century. In the SH mid-latitudes, monthly temperatures over the continents by the end of the 21st century lie in the range of 2- to 4-sigma above the present-day mean in both seasons. Over large regions of the NH mid-latitudes, the continental warming (in units of sigma) is much stronger in summer,

Figure 33: Multimodel mean of monthly warming over the 21st century (2080–2100 relative to present day) for the months of JJA (left) and DJF (right) in units of degrees Celsius (top) and in units of local standard deviation of temperature (bottom). The intensity of the color scale has been reduced over the oceans for distinction.



reaching 4- to 5-sigma, than in winter. This includes large regions of North America, southern Europe, and central Asia, including the Tibetan plateau.

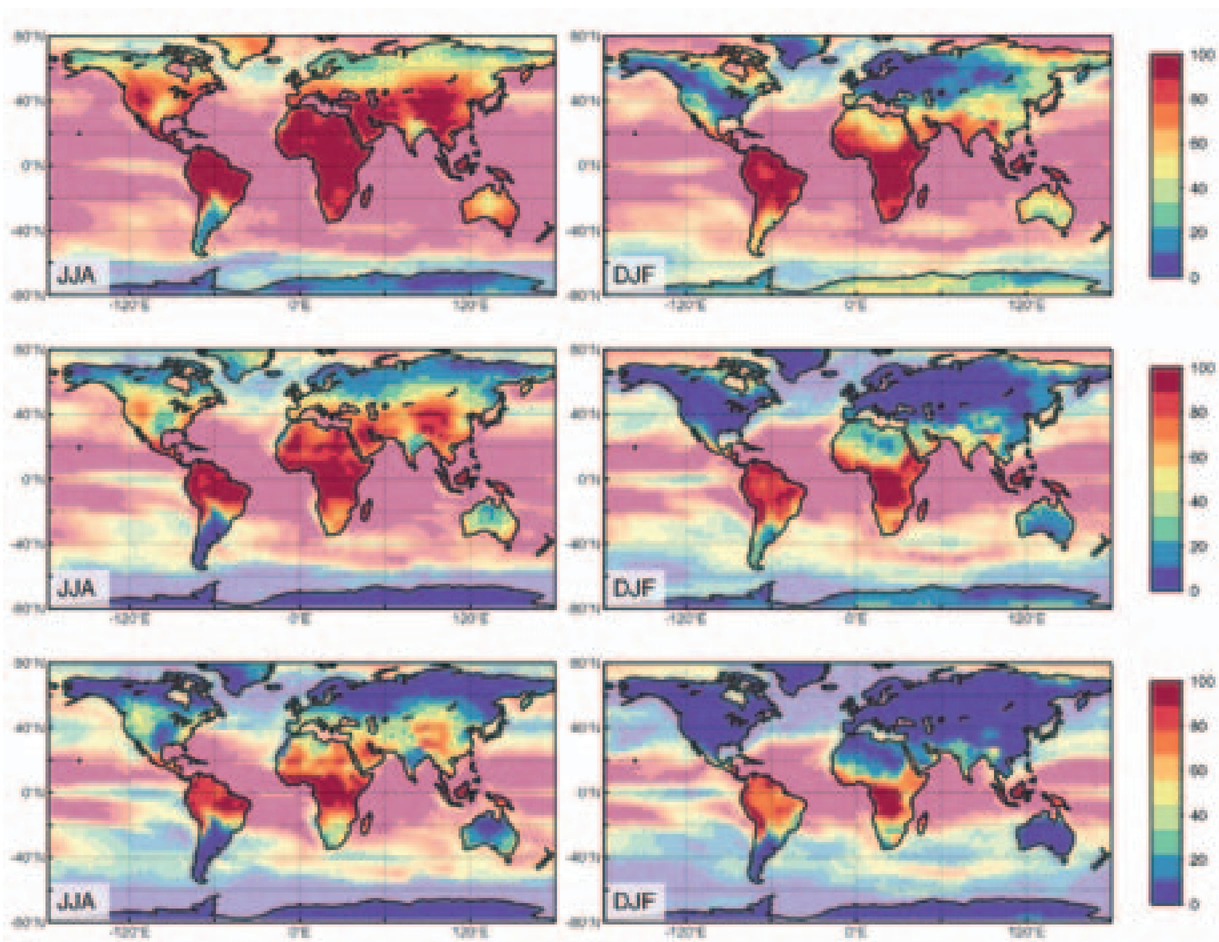
From this analysis, the tropics can be identified as high impact regions, as highlighted in previous studies (Diffenbaugh and Scherer 2011). Here, continental warming of more than 4°C shifts the local climate to a fundamentally new regime. This implies that anomalously cold months at the end of the 21st century will be substantially warmer than record warm months experienced today.

Outside the tropics, the NH subtropics and mid-latitudes are expected to experience much more intense heat extremes during the boreal summer. In the Mediterranean, North Africa, the Middle East, the Tibetan plateau, and the contiguous United States, almost all (80 percent to 100 percent) summer months will be warmer than 3-sigma and approximately half (about 50 percent) will be warmer than 5-sigma. This implies that temperatures of the warmest July within the period 2080–2100 in the Mediterranean region, for example, are expected to approach 35°C, which is about 9°C warmer than the warmest July estimated for the present day. This strong increase in the intensity of summertime extremes over NH continental regions is likely because of soil moisture feedbacks (Schär and et al. 2004; Zwiers and Kharin 1998). Once the soil has completely dried out due to strong evaporation during heat waves, no more heat can be converted into latent heat, thus further increasing temperatures. This effect is much more important during summers (Schär and et al. 2004) and has been a characteristic of major heat and drought events in Europe and North America.

Frequency of Significantly Warmer Months

Figure 34 shows the frequency of months warmer than 3-, 4-, and 5-sigma occurring during 2080–2100 for JJA and DJF. This figure clearly shows that the tropics would move to a new

Figure 34: Multimodel mean of the percentage of months during 2080–2100 that are warmer than 3- (top), 4- (middle) and 5-sigma (bottom) relative to the present-day climatology, for the months of JJA (left) and DJF (right). The intensity of the color scale has been reduced over the oceans for distinction.

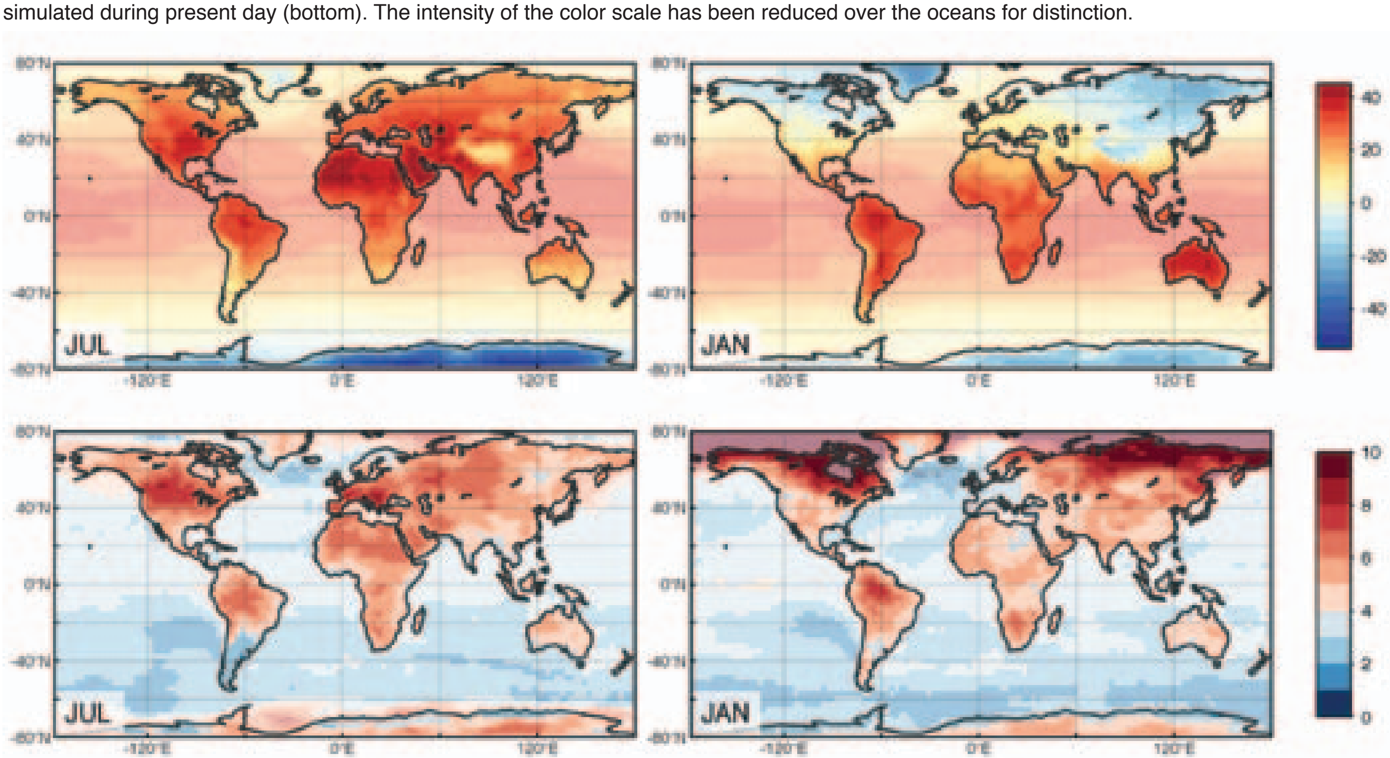


climatic regime. In the authors' analysis, even months warmer than 5-sigma are very common over tropical regions, reaching 100 percent frequencies in central Africa and parts of tropical South America. In addition, the tropical ocean maintains anomalies above 3-sigma 100 percent of the time for all months. Over SH extra-tropical land areas, the patterns are again broadly similar between the warm and cold season. Australia and Argentina are expected to see summer months (DJF) warmer than 3-sigma about 50 percent of the time, but 5-sigma events will still be rare. In the NH mid-latitudes, especially summertime extremes (3-, 4- and 5-sigma events) will increase dramatically. In the Mediterranean, North Africa, and Middle East almost all (80 percent to 100 percent) summer months will be warmer than 3-sigma and about half (about 50 percent) will be warmer than 5-sigma. The same approximate values hold for summer extremes over the contiguous United States and the Tibetan plateau. For the Mediterranean, North Africa, and Middle East, the strong increase in summertime extremes is directly related to the enhanced summertime warming trends in these areas (Figure 33). In contrast, the high number of summertime extremes over the Tibetan plateau is due to much smaller standard deviations here in JJA in combination with a moderate warming. Over the continental both effects play a role. Warm extremes during the boreal winter hardly increase over some areas of NH continents, including the eastern United States and central Europe.

Figure 35 plots the multi-model mean of the warmest July and January temperatures encountered during the period 2080–2100. The warmest July month in the Sahara and the Middle East will see temperatures as high as 45°C, or 6–7°C above the warmest July simulated for the present day. In the Mediterranean and central United States, the warmest July in the period 2080–2100 will see temperatures close to 35°C, or up to 9°C above the warmest July for the present day. Finally, in the Southern Hemisphere, record monthly summer extremes (namely, January) will be as warm as 40°C in Australia, or about 5°C warmer than the most extreme present-day January. Note that temperatures presented here are monthly averages, which include night-time temperatures. Daytime temperatures can be expected to significantly exceed the monthly average.

Monthly heat extremes exceeding 3 standard deviations or more that occur during summer months are associated with the most prolonged, and therefore high-impact, heat waves. The authors' results show that the number of such prolonged heat waves will increase dramatically in a 4°C warmer world over essentially all continental regions, with the tropics and the NH subtropics and mid-latitudes most severely impacted. This is consistent with

Figure 35: Multimodel mean compilation of the most extreme warm monthly temperature experienced at each location in the period 2080–2100 for the months of July (left) and January (right) in absolute temperatures (top) and anomalies compared to the most extreme monthly temperature simulated during present day (bottom). The intensity of the color scale has been reduced over the oceans for distinction.



modeling studies on the increase of heat wave intensity over the 21st century based on business-as-usual emission scenarios (Meehl and Tebaldi 2004; Schär and et al. 2004; Stott et al. 2004) or doubled CO_2 simulations (Barnett et al. 2005; Clark et al. 2006; Zwiers and Kharin 1998). These results also corroborate recent modeling studies indicating that the tropics are especially vulnerable to unprecedented heat extremes in the next century (Beaumont et al. 2011; Diffenbaugh and Scherer 2011).

The Impacts of More Frequent Heat Waves

Given the humanitarian impacts of recent extreme heat waves, the strong increase in the number of extreme heat waves in a 4°C world as reported here would pose enormous adaptation challenges for societies. Prolonged heat waves are generally the most destructive as mortality and morbidity rates are strongly linked to heat wave duration, with excess deaths increasing each additional hot day (Kalkstein and Smoyer 1993; Smoyer 1998; Tan et al. 2006; Fouillet et al. 2006). Temperature conditions experienced during these recent events would become the new norm in a 4°C warmer world and a completely new class of heat waves, with magnitudes never experienced before in the 20th century, would occur regularly. Societies and ecosystems can be expected to be especially vulnerable to the latter as they are not adapted to extremes never experienced before. In particular, the agricultural sector would be strongly impacted as extreme heat can cause severe yield losses (Lobell et al. 2012) (see Section 6). Ecosystems in tropical and sub-tropical regions would be particularly vulnerable to climate change. The authors' analysis show that the increase in absolute temperatures relative to the past variability is largest in these regions and thus the impacts on ecosystems would become extreme here (see Section 6).

Chapter 6

Sectoral Impacts

The following presents a brief overview of the most recent findings on impacts within a selection of sectors. Neither the selection of sectors nor of literature cited claims to be exhaustive. Furthermore, the comparability between studies within sectors or across sectors is complicated by differences in underlying emission scenarios and associated temperatures. Where possible, attempts have been made to relate degrees of warming to preindustrial levels. Temperature increases relative to preindustrial levels have been calculated based on the Climate Research Unit Temperature Data[13] (Jones et al. 2012).

In light of the knowledge gaps with respect to future effects of climate change, there are two international research projects that were recently initiated to quantify impacts within a sector and across sectors at different levels of global warming, including high-end scenarios. First, the Agriculture Model Intercomparison and Improvement Project AgMIP (launched in October 2010) is bringing together a large number of biophysical and agro-economic modelling groups explicitly covering regional to global scales to compare their results and improve their models with regard to observations (Rötter, Carter, Olesen, and Porter 2011). Second, the first Inter-Sectoral Model Intercomparison Project (ISI-MIP) was launched in December 2011 with a fast-track phase designed to provide a synthesis of cross-sectoral global impact projections at different levels of global warming (Schiermeier 2012). Both projects will profit from the new RCPs where the highest reaches about 5°C of global warming.

Agriculture

The overall conclusions of IPCC AR4 concerning food production and agriculture included the following:

- Crop productivity is projected to increase slightly at mid- to high latitudes for local mean temperature increases of up to 1 to 3°C depending on the crop, and then decrease beyond that in some regions (medium confidence) {WGII 5.4, SPM}.
- At lower latitudes, especially in seasonally dry and tropical regions, crop productivity is projected to decrease for even small local temperature increases (1 to 2°C) which would increase the risk of hunger (medium confidence) {WGII 5.4, SPM}.
- Globally, the potential for food production is projected to increase with increases in local average temperature over a range of 1 to 3°C, but above this it is projected to decrease (medium confidence) {WGII 5.4, 5.5, SPM}.

These findings clearly indicate a growing risk for low-latitude regions at quite low levels of temperature increase and a growing risk for systemic global problems above a warming of a few degrees Celsius. While a comprehensive review of literature is forthcoming in the IPCC AR5, the snapshot overview of recent scientific literature provided here illustrates that the concerns identified in the AR4 are confirmed by recent literature and in important cases extended. In particular, impacts of extreme heat waves deserve mention here for observed agricultural impacts (see also Chapter 2).

This chapter will focus on the latest findings regarding possible limits and risks to large-scale agriculture production because of climate change, summarizing recent studies relevant to this risk assessment, including at high levels of global warming approaching 4°C. In particular, it will deliberately highlight important

[13] (http://www.cru.uea.ac.uk/cru/data/temperature/ – October 17, 2012.

findings that point to the risks of assuming a forward projection of historical trends.

Projections for food and agriculture over the 21st century indicate substantial challenges irrespective of climate change. As early as 2050, the world's population is expected to reach about 9 billion people (Lutz and Samir 2010) and demand for food is expected to increase accordingly. Based on the observed relationship between per capita GDP and per capita demand for crop calories (human consumption, feed crops, fish production and losses during food production), Tilman et al. (2011) project a global increase in the demand for crops by about 100 percent from 2005 to 2050. Other estimates for the same period project a 70 percent increase of demand (Alexandratos 2009). Several projections suggest that global cereal and livestock production may need to increase by between 60 and 100 percent to 2050, depending on the warming scenario (Thornton et al. 2011).

The historical context can on the one hand provide reassurance that despite growing population, food production has been able to increase to keep pace with demand and that despite occasional fluctuations, food prices generally stabilize or decrease in real terms (Godfray, Crute, et al. 2010). Increases in food production have mainly been driven by more efficient use of land, rather than by the extension of arable land, with the former more widespread in rich countries and the latter tending to be practiced in poor countries (Tilman et al. 2011). While grain production has more than doubled, the area of land used for arable agriculture has only increased by approximately 9 percent (Godfray, Beddington, et al. 2010).

However, although the expansion of agricultural production has proved possible through technological innovation and improved water-use efficiency, observation and analysis point to a significant level of vulnerability of food production and prices to the consequences of climate change, extreme weather, and underlying social and economic development trends. There are some indications that climate change may reduce arable land in low-latitude regions, with reductions most pronounced in Africa, Latin America, and India (Zhang and Cai 2011). For example, flooding of agricultural land is also expected to severely impact crop yields in the future: 10.7 percent of South Asia´s agricultural land is projected to be exposed to inundation, accompanied by a 10 percent intensification of storm surges, with 1 m sea-level rise (Lange et al. 2010). Given the competition for land that may be used for other human activities (for example, urbanization and biofuel production), which can be expected to increase as climate change places pressure on scarce resources, it is likely that the main increase in production will have to be managed by an intensification of agriculture on the same—or possibly even reduced—amount of land (Godfray, Beddington et al. 2010; Smith et al. 2010). Declines in nutrient availability (for example, phosphorus), as well as the spread in pests and weeds, could further limit the increase of agricultural productivity. Geographical shifts in production patterns resulting from the effects of global warming could further escalate distributional issues in the future. While this will not be taken into consideration here, it illustrates the plethora of factors to take into account when thinking of challenges to promoting food security in a warming world.

New results published since 2007 point to a more rapidly escalating risk of crop yield reductions associated with warming than previously predicted (Schlenker and Lobell 2010; Schlenker and Roberts 2009). In the period since 1980, patterns of global crop production have presented significant indications of an adverse effect resulting from climate trends and variability, with maize declining by 3.8 percent and wheat production by 5.5 percent compared to a case without climate trends. A significant portion of increases in crop yields from technology, CO_2 fertilization, and other changes may have been offset by climate trends in some countries (Lobell et al. 2011). This indication alone casts some doubt on future projections based on earlier crop models.

In relation to the projected effects of climate change three interrelated factors are important: temperature-induced effect, precipitation-induced effect, and the CO_2-fertilization effect. The following discussion will focus only on these biophysical factors. Other factors that can damage crops, for example, the elevated levels of tropospheric ozone (van Groenigen et al. 2012), fall outside the scope of this report and will not be addressed.

Largely beyond the scope of this report are the far-reaching and uneven adverse implications for poverty in many regions arising from the macroeconomic consequences of shocks to global agricultural production from climate change. It is necessary to stress here that even where overall food production is not reduced or is even increased with low levels of warming, distributional issues mean that food security will remain a precarious matter or worsen as different regions are impacted differently and food security is further challenged by a multitude of nonclimatic factors.

TEMPERATURE-INDUCED EFFECTS

One of the significant developments since the IPCC AR4 relates to improvements in understanding of the effect of an increase in temperature on crop production. In broad terms, the overall pattern of expected responses to temperature increases has been well established for some time. Rising temperature may increase yields at higher latitudes where low temperatures are a limiting factor on growth; for example, winter wheat varieties become suitable in comparison to lower-yielding summer varieties (Müller et al. 2009). At lower latitudes, increases in temperature alone are expected to reduce yields from grain crops. The effect is due to the fact that grain crops mature earlier at higher temperatures, reducing the critical growth period and leading to lower yields, an effect that is well studied and documented. A reduction of 8 percent per 1°C of regional mean warming during the growing season is estimated from U.K. field conditions (Mitchell et al. 1995), which is in line with estimated 3 to 10 percent reduction per 1°C for wheat yields in China (You et al. 2009).

Between 2000 and 2050, and for warming levels of between 1.8°C and 2.8°C (2.2°C and 3.2°C compared to preindustrial temperatures), Deryng et al. (2011) project decreases in yields of 14 to 25 percent for wheat, 19 to 34 percent for maize, and 15 to 30 percent for soybean (without accounting for possible CO_2 fertilization effects). These authors also show that when adaptive measures are taken into account, overall losses can be significantly reduced. By simulating adaptation with respect to changes in planting and harvesting date, as well as changes in cultivar type in terms of rates of maturation, they find that adaptation can reduce losses by about a factor of two for spring wheat and maize and by 15 percent for soybeans (Table 3).

Not included in the analysis of Deryng et al. (2011) are cultivar adaptations for heat and drought tolerance. However, Challinor et al. (2010) indicate that the negative effects of climate change on spring wheat yields in northeastern China can be averted through either developing cultivars with greater drought or heat tolerance, or that yields can even possibly be increased if both are pursued. These results suggest that crop adaptation could conceivably play a major role in ensuring food security in a changing climate, although realization of this potential will likely require substantial investment in developing suitable cultivars.

Recent research also indicates that there may be larger negative effects at higher and more extreme temperatures, giving rise to a growing concern with respect to the sensitivity of crop yields to temperature increases and, in particular, extreme temperature events. There seem to be larger negative effects at higher temperatures (Semenov et al. 2012), as documented in higher yield losses per degree of regional mean warming in Australia (Asseng et al. 2011) and India (Lobell et al. 2012). In particular, there is an emerging risk of nonlinear effects on crop yields because of the damaging effect of temperature extremes. Field experiments have shown that crops are highly sensitive to temperatures above certain thresholds (see also Chapter 2). This effect is expected to be highly relevant in a 4°C world. Most current crop models do not account for this effect, leading to recent calls for an "overhaul" of current crop-climate models (Rötter et al. 2011).

PRECIPITATION-INDUCED EFFECTS

Recent projections and evaluations against historical records point to a substantially increased risk of drought affecting large parts of the world (see also Chapter 3). The total "drought disaster-affected" area is predicted to increase from currently 15.4 percent of global cropland to 44 ±6 percent by 2100 based on a modified Palmer Drought Severity Index. The largest fractions of affected sown areas are expected for Africa and Oceania, reaching about 59 percent by 2100 in each region. Climate projections of 20 General Circulation Models were used to estimate the change in drought disaster affected area under different emission scenarios. In the considered scenarios, global mean temperature change in 2100 reaches 4.1°C relative to 1990 temperatures or 4.9°C relative to preindustrial values (Li et al. 2009).

The regions expected to see increasing drought severity and extent over the next 30 to 90 years are in southern Africa, the United States, southern Europe, Brazil, and Southeast Asia (Dai 2012). Increasing temperatures (with higher evaporation) in combination with decreasing precipitation in already drought prone areas, particularly in the tropics and subtropics, mean a greater threat to food security.

Table 3: Projected Impacts on Different Crops Without and With Adaptation

	Without adaptation	With adaptation
Spring wheat	–14 to –25%	–4 to –10%
Maize	–19 to –34%	–6 to –18%
Soybean	–15 to –30%	–12 to –26%

Source: Deryng et al. 2011.

UNCERTAINTY IN CO_2-FERTILIZATION EFFECT

The effects of the increasing CO_2 concentrations on crop yields represent one of the most critical assumptions with respect to biophysical crop modeling. However, there is ongoing debate about the magnitude of this effect under field conditions (Ainsworth et al. 2009). In broad terms, if the effects of CO_2 fertilization occurs to the extent assumed in laboratory studies, then global crop production could be increased; if not, then a decrease is possible. Different assumptions about the efficiency of this process have the potential to change the direction and sign of the projected yield changes between 2000 and 2050 on the global level for a temperature increase in the range of 1.8°C to 3.4°C (SRES A1b, A2, B1, equivalent to 2.5°C to 4.1°C). For example, Müller et al. (2010) simulate a global mean increase in yields of 13 percent when fully accounting for the CO_2 fertilization effect, while without CO_2 fertilization effect a decrease of 7 percent is projected by 2050. Even if such a yield increase resulting from CO_2 fertilization were achieved, Müller et al. (2010) conclude that increased crop yields may not be sufficient to balance population increases in several regions, including Sub-Saharan Africa, the Middle East, North Africa, South Asia, and Latin America and the Caribbean.

When considering risks to future crop production and attempting to account for the effects of CO_2 fertilization, it is also important to recall that a key constraint of the carbon fertilization effect is that it would operate in situations where enough nutrients (for example, phosphorus and nitrogen) are available. While the response to enhanced CO_2 varies across crop types, optimal temperatures for a selection of crop types (C4, for example maize) are higher than others (C3, for example rice), so that response to temperature varies as well.[14] The fertilization effect is therefore likely to be more or less offset due to higher temperatures depending on what crop is sown. The magnitude of the CO_2 fertilization effect in a 4°C world thus remains uncertain.

COMBINED EFFECTS

While the preceding sections have looked at risks arising from individual factors, the combined effect of different factors can complicate the picture to a considerable extent. A recent study by Tao and Zhang (Tao and Zhang 2010) of maize production in China at different levels of warming illustrates some of the complexities here, while still pointing to a substantial level of risk. In the study, regional changes in climate were linked to global mean temperature increases of 1, 2, and 3°C above 1961–1990 levels (1.4°C, 2.4°C and 3.4°C above preindustrial temperatures, respectively). These authors adopted a probabilistic approach using different climate models to predict regional climatic changes over the next century to drive a process-based crop model to project maize yields. The results shown in Table 4 indicate that for the high end of yield losses there is a consistent increase with increasing global mean warming for both rainfed and irrigated maize, with the loss larger without the CO_2 fertilization effect. However, precipitation changes turn out to be more positive at one end of the probability distribution, as the loss in yield might be reduced above 2°C warming. The median estimates in all cases show increasing losses.

Another study for China (Challinor et al. 2010), involving wheat and also taking a probabilistic approach, finds a significant increase in the risk of crop failure in the future arising from a combination of increased heat and water stress, after taking into account the CO_2 fertilization effect. This study shows that adaptation measures may be able to ameliorate many of the risks.

IMPLICATIONS FOR ECONOMIC GROWTH AND HUMAN DEVELOPMENT

Hertel et al. (2010) use updated estimates of the effects of climate change on crop yields to explore the consequences for poverty and welfare of climate change using the Global Trade Analysis Project model. In a scenario that results in a 1.5°C temperature increase as soon as 2030, Hertel et al. (2010) report that effects on welfare as a result of the direct impact of climate change on crops will be felt most in Sub-Saharan Africa, followed by China and the United States. In addition, adverse effects on future cereal yields and reduced food security potentially increase the risk of hunger or undernutrition, often differentially affecting children. It is well established that child undernutrition has adverse implications for lifetime economic earning potential and health. Recent projections of the consequences of a warming of 2°C to 2.5°C (2.7°C to 3.2°C relative to preindustrial temperatures) by the 2050s for childhood

[14] C3 plants include more than 85% of plants on Earth (e.g. most trees, wheat and rice) and respond well to moist conditions and to additional carbon dioxide in the atmosphere. C4 plants (for example, sugarcane) are more efficient in water and energy use and outperform C3 plants in hot and dry conditions. C3 and C4 plants differ in the way they assimilate CO_2 into their system to perform photosynthesis. During the first steps in CO_2 assimilation, C3 plants form a pair of three carbon-atom molecules. C4 plants, on the other hand, initially form four carbon-atom molecules.

Table 4. Projected Changes in Median Maize Yields under Different Management Options and Global Mean Warming Levels

Experiment	1°C (1.4°C) above 1961–1990	2°C (2.4°C) above 1961–1990	3°C (3.4°C) above 1961–1990
Irrigated maize No CO_2 fertilization	–1.4% to –10.9%	–9.8% to –21.7%	–4.3% to –32.1%
Irrigated maize With CO_2 fertilization	–1.6% to –7.8%	–10.2% to –16.4%	–3.9% to –26.6%
Rainfed maize No CO_2 fertilization	–1.0% to –22.2%	–7.9% to –27.6%	–4.6% to –33.7%
Rainfed maize With CO_2 fertilization	0.7% to –10.8%	–5.6% to –18.1%	–1.6% to –25.9%

Source: Tao & Zhang 2010.

stunting indicate substantial increases, particularly in severe stunting in Sub-Saharan Africa (23 percent) and South Asia (62 percent) (Lloyd, Kovats, and Chalabi 2011).

Water Resources

It is well established that climate change will bring about substantial changes in precipitation patterns, as well as in surface temperature and other quantities that govern evapotranspiration (see for example, Meehl, Stocker, and Collins 2007). The associated changes in the terrestrial water cycle are likely to affect the nature and availability of natural water resources and, consequently, human societies that rely on them. As agriculture is the primary water consumer globally, potential future water scarcity would put at risk many societies' capacity to feed their growing populations. However, other domestic and industrial water uses, including cooling requirements, for example, for thermal power plants, as well as the functioning of natural ecosystems also depend on the availability of water. The magnitude and timing of surface water availability is projected to be substantially altered in a warmer world. It is very likely that many countries that already face water shortages today will suffer from increased water stress in a 4°C world and that major investments in water management infrastructure would be needed in many places to alleviate the adverse impacts, and tap the potential benefits, of changes in water availability. In the following, recent model predictions are referenced in order to provide an outline of the nature and direction of change expected for warming of 4°C and beyond.

CHANGES TO LEVELS OF PRECIPITATION AND WATER STRESS IN A 2°C WORLD AND IN A 4°C+ WORLD

Fung et al. (2011) explicitly investigate the difference between a 4°C world and a 2°C world, using the MacPDM hydrological model, which is driven by a large perturbed-physics climate model ensemble based on the HadCM3L climate model. Because they define the 1961–1990 average temperature as their baseline, their 4°C world is actually about 4.4°C warmer than the preindustrial one.

The bottom line of this study is that globally changes in annual runoff are expected to be amplified once warming has reached 4°C compared to one in which it has reached 2°C; that is, on a large scale, the hydrological response to global warming appears rather linear. Regions experiencing drier conditions —namely, generating less runoff—under 2°C warming are projected to become even drier under 4°C (and vice versa). Drier conditions are projected for southern Europe, Africa (except some areas in the northeast), large parts of North America and South America, and Australia, among others. Wetter conditions are projected for the northern high latitudes, that is, northern North America, northern Europe, and Siberia. In the ensemble average, mean annual runoff decreases in a 2°C world by around 30, 20, 40, and 20 percent in the Danube, Mississippi, Amazon, and Murray Darling river basins, respectively, while it increases by around 20 percent in both the Nile and the Ganges basins, compared to the 1961–190 baseline period. Thus, according to Fung et al. (2011), all these changes are approximately doubled in magnitude in a 4°C world.

Fung et al. (2011) also look at a simple water stress index, using the ratio of annual mean runoff to population in a given basin as a measure of water resources per capita. The SRES A1B emissions scenario, from which the 2°C and 4°C climate projections are derived, is set in relation to a scenario of future population growth based on a medium UN population projection. In a 2°C world, relatively small runoff changes combined with large population growth over the next few decades mean that changes in water stress would mostly be dominated by population changes, not climate changes. Increasing water demand would exacerbate water stress in most regions, regardless of the direction of change in runoff. However, in a 4°C world, climate changes would become large enough to dominate changes in water stress in many cases. Again, water stress is expected to increase in southern Europe, the United States, most parts of South America, Africa, and Australia, while it is expected to decrease in high latitude regions. A fragmented picture emerges for South and East Asia, where increased runoff from monsoon rainfall in some areas competes with population-driven increases in demand (while other areas may see reduced monsoon runoff).

There are complexities beyond this large-scale, annual mean picture. In five of the six major river basins studied in detail by Fung et al. (2011), the seasonality of runoff increases along with global warming, that is, wet seasons become wetter and dry seasons become drier. This means that while an increase in annual mean runoff, for example, in the Nile or the Ganges basin may appear beneficial at first sight, it is likely to be distributed unevenly across the seasons, possibly leading to increased flooding in the high-flow season, while hardly improving water stress in the low-flow season. This would have severe adverse consequences for affected populations, especially if the seasonality of runoff change would be out of phase with that of demand, such as for crop growing or the cooling of thermal power plants. Major investments in storage facilities would be required in such cases in order to control water availability across the year and actually reap the local benefits of any increases in runoff. For such basins as the Ganges, another reason to strengthen water management capacities is that hydrological projections for the Indian monsoon region are particularly uncertain because of the inability of most climate models to simulate accurately the Indian monsoon. Quantitative results for this region based on a single climate model (as used by

Fung et al. [2011]) must be taken with great caution. Substantial improvement of climate models is needed to be able to make more robust statements about future water stress in this region.

The uncertainty related to the disagreement among climate model projections is highlighted in the study of Arnell et al. (2011), who contrast a reference scenario approaching 4°C warming (above preindustrial temperatures) by 2100 with a mitigation scenario that stabilizes below 2°C. They employ the same hydrological model as in the study described above, but use projections by four different climate models, which all exhibit different patterns of precipitation change under global warming, resulting in different patterns of runoff change produced by the hydrological model. While in all four cases an increase in annual mean runoff is projected for the high northern latitudes and a decrease for the eastern Mediterranean and southern Africa, there is no consensus on the direction of change for most other regions. Despite this disagreement in spatial patterns, however, the difference between a 2°C world and a 4°C world is similar in all four cases. According to Arnell et al. (2011) about 50 percent of the runoff changes in either direction expected with warming of 4°C could be avoided if warming were constrained to 2°C.

In terms of water stress, however, the difference appears to be smaller. In a 2°C world, about 20 to 30 percent less people globally are expected to be affected by increased water stress, based on per-capita availability, than in a 4°C world. Moreover, based on the ratio of water withdrawals to availability, about 15 to 47 percent less people would be affected. The large range of this estimate is due to differences between the four climate change patterns. Thus, when it comes to the difference between a 2°C world and a 4°C world, much more uncertainty is associated with the actual societal impacts of climate change than with the physical change in runoff. This is partly because the geographical distribution of runoff changes, which determines what proportion of the global population will be affected by runoff increases or decreases, is very uncertain. In addition, it is hard to assess which of the simplified metrics used in these studies better reflects the actual water stress that people experience. Although such simplified metrics as per-capita availability or the ratio of withdrawals to availability are useful for a large-scale impact assessment, actual water stress in a given location depends on many other factors that are not reflected in these metrics (Rijsberman 2006).

THE AVAILABILITY OF WATER FOR FOOD PRODUCTION

Arguably one of the most important of these other factors when it comes to direct impacts on humans is the amount of water actually required to produce a certain amount and type of food in a given location. Gerten et al. (2011) attempt to take this factor into account and, for this purpose, develop an indicator that not only reflects the availability of "blue water" contained in rivers, lakes, reservoirs, and other open water bodies, but also that of the "green water" contained in the soil. The latter is globally more important for sustaining agricultural productivity. Moreover, Gerten et al. (2011) use a combined vegetation and hydrology model (LPJmL) to consistently evaluate water availability and water requirements for crop production. As the efficiency of crops in utilizing available water differs greatly among regions—depending on regional climate, but also management practices—the spatially explicit comparison of agricultural water requirements to green-blue water (GWBW) availability yields a more accurate pattern of water scarcity than the application of a globally uniform threshold.

In their projections for the 2080s under the SRES A2 scenario (which implies a warming by approximately 4°C compared to preindustrial temperatures), Gerten et al. (2011) find that 43 to 50 percent of the global population will be living in water-scarce countries, compared to 28 percent today. Water scarcity (defined as the ratio between the GWBW availability and the water requirement for producing a balanced diet) is very likely to be amplified due to climate change in many countries that are already water scarce today, mainly in Northern and Eastern Africa and South Asia. However, compared to this climate-change only signal, the (uncertain) direct effect of rising CO_2 concentrations on lowering plant water requirements might ease water scarcity over East Africa and South Asia. Additional countries, particularly in Sahelian and equatorial Africa, are projected to become water scarce because of projected population changes, rather than climate change.

A NOTE OF CAUTION: LIMITS TO ANTICIPATING WATER INSECURITY IN A 4°C WORLD

There are some common results among the few recent studies that assess the impact of 4°C warming on global water resources that have been referenced above. Studies that compare different levels of warming conclude that changes found at lower levels of warming are expected to be amplified in a 4°C world, while the direction and spatial patterns of change would be similar. The climate impact on global water resources will likely be spatially heterogeneous, with increasing water availability mainly in the high latitudes of the Northern Hemisphere, and decreasing water availability in many regions across the tropics and subtropics, including large parts of Africa, the Mediterranean, the Middle East, and parts of Asia. Regardless of which indicator of water scarcity is used, it is clear that many world regions are at risk of being more severely impacted under strong climate change, but some regions are expected to experience advantages because of such factors as regional precipitation increases, low population, or high agricultural water use efficiency. Another factor that will likely complicate the picture in terms of which regions will see increased demand for water, is related to water use in energy production. Increased demand in different parts of the world could lead to greater tensions and conflicts over claims to water sources and priority of water uses.

However, the exact spatial patterns of change in water stress remain uncertain, mainly because of the persistent shortcomings of global climate models in simulating future precipitation patterns. This is particularly relevant in the Indian monsoon domain, where a large share of the world's population depends highly on natural water resources, which are already under significant stress today, while up to now no robust statement can be made about the future response of monsoon rainfall to climate change. Moreover, while this climate model uncertainty is apparent from the studies discussed here, it should also be noted that each of these studies only uses a single hydrological model. As hydrological models have many structural differences, systematic comparison of different models is necessary to quantify the associated uncertainty, but has hardly been carried out, particularly for scenarios near 4°C warming.

The above studies also highlight the difficulty of assessing on-the-ground water stress or scarcity on a global scale. Locations around the world differ greatly in water management practices, water-use efficiency of agriculture and other water users, and adaptation options to changing water availability, among other factors. Moreover, looking only at long-term averages of seasonal-mean water availability neglects the importance of subseasonal processes. Climate change is expected to alter the seasonal distribution of runoff and soil water availability, likely increasing the number of such extreme events as floods and droughts, both of which can have devastating effects, even if annual mean numbers remain unchanged. In order to better estimate climate change impacts on water resources at potentially vulnerable locations, future water resources research will thus increasingly have to consider finer spatial and temporal scales. Besides changes in runoff and soil moisture, there are many other physical processes that are important for a comprehensive assessment of water related climate change impacts, including groundwater extraction and recharge, salination of aquifers and estuaries, melting glaciers, water temperatures, sediment fluxes, and the ability of existing hydrological features—both natural (for example, river beds) and artificial (for example, dams and reservoirs)—to handle changed water flows. Glacial runoff, for example, is critical in the dry season in India, China, and South America. Global-scale studies of these factors are rare, let alone for temperatures at or above 4°C.

Finally, one major outcome of the above studies is that it is primarily the combination of climate change, population change, and changes in patterns of demand for water resources that will determine future water stress around the world, rather than climate change alone. This will be further shaped by levels of adaptive capacity. In many countries, particularly in the developing world, the adverse impacts of decreasing runoff and total water availability would probably be greatly exacerbated by high rates of population growth and by the fact that many of these countries are already water scarce and thus have little capacity to satisfy the growing demand for water resources. Conversely, positive impacts of climate change are expected to occur primarily in countries that have higher adaptive capacities and lower population growth rates. In the context of a 4°C world, the strong dependence of water stress on population also means that the timing of the warming is important. Depending on the scenario, world population is projected to grow until the second half of this century, but this trend is expected to reverse towards the year 2100 and beyond, shrinking the world population. Thus, in a rapidly warming world, the most adverse impacts on water availability associated with a 4°C world may coincide with maximum water demand as world population peaks (Fung et al. 2011).

Ecosystems and Biodiversity

Ecosystems and their species provide a range of important goods and services for human society. These include water, food, cultural and other values. In the AR4 an assessment of climate change effects on ecosystems and their services found the following:

- If greenhouse gas emissions and other stresses continue at or above current rates, the resilience of many ecosystems is likely to be exceeded by an unprecedented combination of change in climate, associated disturbances (for example, flooding, drought, wildfire, insects, and ocean acidification) and other stressors (global change drivers) including land use change, pollution and over-exploitation of resources.
- Approximately 20 to 30 percent of plant and animal species assessed so far are likely to be at increased risk of extinction, if increases in global average temperature exceed of 2–3° above preindustrial levels.
- For increases in global average temperature exceeding 2 to 3° above preindustrial levels and in concomitant atmospheric CO_2 concentrations, major changes are projected in ecosystem structure and function, species' ecological interactions and shifts in species' geographical ranges, with predominantly negative consequences for biodiversity and ecosystem goods and services, such as water and food supply.

It is known that past large-scale losses of global ecosystems and species extinctions have been associated with rapid climate change combined with other ecological stressors. Loss and/or degradation of ecosystems, and rates of extinction because of human pressures over the last century or more, which have intensified in recent decades, have contributed to a very high rate of extinction by geological standards. It is well established that loss or degradation of ecosystem services occurs as a consequence of species extinctions, declining species abundance, or widespread shifts in species and biome distributions (Leadley et al. 2010).

Climate change is projected to exacerbate the situation. This section outlines the likely consequences for some key ecosystems and for biodiversity. The literature tends to confirm the conclusions from the AR4 outlined above.

Despite the existence of detailed and highly informative case studies, upon which this section will draw, it is also important to recall that there remain many uncertainties (Bellard, Bertelsmeier, Leadley, Thuiller, and Courchamp, 2012). However, threshold behavior is known to occur in biological systems (Barnosky et al. 2012) and most model projections agree on major adverse consequences for biodiversity in a 4°C world (Bellard et al., 2012). With high levels of warming, coalescing human induced stresses on ecosystems have the potential to trigger large-scale ecosystem collapse (Barnosky et al. 2012). Furthermore, while uncertainty remains in the projections, there is a risk not only of major loss of valuable ecosystem services, particularly to the poor and the most vulnerable who depend on them, but also of feedbacks being initiated that would result in ever higher CO_2 emissions and thus rates of global warming.

Significant effects of climate change are already expected for warming well below 4°C. In a scenario of 2.5°C warming, severe ecosystem change, based on absolute and relative changes in carbon and water fluxes and stores, cannot be ruled out on any continent (Heyder, Schaphoff, Gerten, & Lucht, 2011). If warming is limited to less than 2°C, with constant or slightly declining precipitation, small biome shifts are projected, and then only in temperate and tropical regions. Considerable change is projected for cold and tropical climates already at 3°C of warming. At greater than 4°C of warming, biomes in temperate zones will also be substantially affected. These changes would impact not only the human and animal communities that directly rely on the ecosystems, but would also exact a cost (economic and otherwise) on society as a whole, ranging from extensive loss of biodiversity and diminished land cover, through to loss of ecosystems services such as fisheries and forestry (de Groot et al., 2012; Farley et al., 2012).

Ecosystems have been found to be particularly sensitive to geographical patterns of climate change (Gonzalez, Neilson, Lenihan, and Drapek, 2010). Moreover, ecosystems are affected not only by local changes in the mean temperature and precipitation, along with changes in the variability of these quantities and changes by the occurrence of extreme events. These climatic variables are thus decisive factors in determining plant structure and ecosystem composition (Reu et al., 2011).

Increasing vulnerability to heat and drought stress will likely lead to increased mortality and species extinction. For example, temperature extremes have already been held responsible for mortality in Australian flying-fox species (Welbergen, Klose, Markus, and Eby 2008), and interactions between phenological changes driven by gradual climate changes and extreme events can lead to reduced fecundity (Campbell et al. 2009; Inouye, 2008).

Climate change also has the potential to facilitate the spread and establishment of invasive species (pests and weeds) (Hellmann, Byers, Bierwagen, & Dukes, 2008; Rahel & Olden, 2008) with often detrimental implications for ecosystem services and biodiversity.

Human land-use changes are expected to further exacerbate climate change driven ecosystem changes, particularly in the tropics, where rising temperatures and reduced precipitation are expected to have major impacts (Campbell et al., 2009; Lee & Jetz, 2008). Ecosystems will be affected by the increased occurrence of extremes such as forest loss resulting from droughts and wildfire exacerbated by land use and agricultural expansion (Fischlin et al., 2007).

Climate change also has the potential to catalyze rapid shifts in ecosystems such as sudden forest loss or regional loss of agricultural productivity resulting from desertification (Barnosky et al., 2012). The predicted increase in extreme climate events would also drive dramatic ecosystem changes (Thibault and Brown 2008; Wernberg, Smale, and Thomsen 2012). One such extreme event that is expected to have immediate impacts on ecosystems is the increased rate of wildfire occurrence. Climate change induced shifts in the fire regime are therefore in turn powerful drivers of biome shifts, potentially resulting in considerable changes in carbon fluxes over large areas (Heyder et al., 2011; Lavorel et al., 2006)

It is anticipated that global warming will lead to global biome shifts (Barnosky et al. 2012). Based on 20th century observations and 21st century projections, poleward latitudinal biome shifts of up to 400 km are possible in a 4°C world (Gonzalez et al., 2010). In the case of mountaintop ecosystems, for example, such a shift is not necessarily possible, putting them at particular risk of extinction (La Sorte and Jetz, 2010). Species that dwell at the upper edge of continents or on islands would face a similar impediment to adaptation, since migration into adjacent ecosystems is not possible (Campbell, et al. 2009; Hof, Levinsky, Araújo, and Rahbek 2011).

The consequences of such geographical shifts, driven by climatic changes as well as rising CO_2 concentrations, would be found in both reduced species richness and species turnover (for example, Phillips et al., 2008; White and Beissinger 2008). A study by (Midgley and Thuiller, 2011) found that, of 5,197 African plant species studied, 25–42 percent could lose all suitable range by 2085. It should be emphasized that competition for space with human agriculture over the coming century is likely to prevent vegetation expansion in most cases (Zelazowski et al., 2011)

Species composition changes can lead to structural changes of the entire ecosystem, such as the increase in lianas in tropical and temperate forests (Phillips et al., 2008), and the encroachment of woody plants in temperate grasslands (Bloor et al., 2008, Ratajczak et al., 2012), putting grass-eating herbivores at risk of extinction because of a lack of food available—this is just one example of the sensitive intricacies of ecosystem responses to external perturbations. There is also an increased risk of extinction for herbivores in regions of drought-induced tree dieback, owing to their inability to digest the newly resident C4 grasses (Morgan et al., 2008).

The following provides some examples of ecosystems that have been identified as particularly vulnerable to climate change. The discussion is restricted to ecosystems themselves, rather than the important and often extensive impacts on ecosystems services.

Boreal-temperate ecosystems are particularly vulnerable to climate change, although there are large differences in projections, depending on the future climate model and emission pathway studied. Nevertheless there is a clear risk of large-scale forest dieback in the boreal-temperate system because of heat and drought (Heyder et al., 2011). Heat and drought related die-back has already been observed in substantial areas of North American boreal forests (Allen et al., 2010), characteristic of vulnerability to heat and drought stress leading to increased mortality at the trailing edge of boreal forests. The vulnerability of transition zones between boreal and temperate forests, as well as between boreal forests and polar/tundra biomes, is corroborated by studies of changes in plant functional richness with climate change (Reu et al., 2011), as well as analyses using multiple dynamic global vegetation models (Gonzalez et al., 2010). Subtle changes within forest types also pose a great risk to biodiversity as different plant types gain dominance (Scholze et al., 2006).

Humid tropical forests also show increasing risk of major climate induced losses. At 4°C warming above pre-industrial levels, the land extent of humid tropical forest, characterized by tree species diversity and biomass density, is expected to contract to approximately 25 percent of its original size [see Figure 3 in (Zelazowski et al., 2011)], while at 2°C warming, more than 75 percent of the original land can likely be preserved. For these ecosystems, water availability is the dominant determinant of climate suitability (Zelazowski et al., 2011). In general, Asia is substantially less at risk of forest loss than the tropical Americas. However, even at 2°C, the forest in the Indochina peninsula will be at risk of die-back. At 4°C, the area of concern grows to include central Sumatra, Sulawesi, India and the Philippines, where up to 30 percent of the total humid tropical forest niche could be threatened by forest retreat (Zelazowski et al., 2011).

There has been substantial scientific debate over the risk of a rapid and abrupt change to a much drier savanna or grassland ecosystem under global warming. This risk has been identified as a possible planetary tipping point at around a warming of 3.5–4.5°C, which, if crossed, would result in a major loss of biodiversity, ecosystem services and the loss of a major terrestrial carbon sink, increasing atmospheric CO_2 concentrations (Lenton et al., 2008)(Cox, et al., 2004) (Kriegler, Hall, Held, Dawson, and Schellnhuber, 2009). Substantial uncertainty remains around the likelihood, timing and onset of such risk due to a range of factors including uncertainty in precipitation changes, effects of CO_2 concentration increase on water use efficiency and the CO_2 fertilization effect, land-use feedbacks and interactions with fire frequency and intensity, and effects of higher temperature on tropical tree species and on important ecosystem services such as pollinators.

While climate model projections for the Amazon, and in particular precipitation, remain quite uncertain recent analyses using IPCC AR4 generation climate indicates a reduced risk of a major basin wide loss of precipitation compared to some earlier work. If drying occurs then the likelihood of an abrupt shift to a drier, less biodiverse ecosystem would increase. Current projections indicate that fire occurrence in the Amazon could double by 2050, based on the A2 SRES scenario that involves warming of approximately 1.5°C above pre-industrial levels (Silvestrini et al., 2011), and can therefore be expected to be even higher in a 4°C world. Interactions of climate change, land use and agricultural expansion increase the incidence of fire (Aragão et al., 2008), which plays a major role in the (re)structuring of vegetation (Gonzalez et al., 2010; Scholze et al., 2006). A decrease in precipitation over the Amazon forests may therefore result in forest retreat or transition into a low biomass forest (Malhi et al., 2009). Moderating this risk is a possible increase in ecosystem water use efficiency with increasing CO_2 concentrations is accounted for, more than 90 percent of the original humid tropical forest niche in Amazonia is likely to be preserved in the 2°C case, compared to just under half in the 4°C warming case (see Figure 5 in Zelazowski et al., 2011) (Cook, Zeng, and Yoon, 2012; Salazar & Nobre, 2010).

Recent work has analyzed a number of these factors and their uncertainties and finds that the risk of major loss of forest due to climate is more likely to be regional than Amazon basin-wide, with the eastern and southeastern Amazon being most at risk (Zelazowski et al., 2011). Salazar and Nobre (2010) estimates a transition from tropical forests to seasonal forest or savanna in the eastern Amazon could occur at warming at warming of 2.5–3.5°C when CO_2 fertilization is not considered and 4.5–5.5°C when it is considered. It is important to note, as Salazar and Nobre (2010) point out, that the effects of deforestation and increased fire risk interact with the climate change and are likely to accelerate a transition from tropical forests to drier ecosystems.

Increased CO_2 concentration may also lead to increased plant water efficiency (Ainsworth and Long, 2005), lowering the risk of plant die-back, and resulting in vegetation expansion in many regions, such as the Congo basin, West Africa and Madagascar (Zelazowski et al., 2011), in addition to some dry-land ecosystems (Heyder et al., 2011). The impact of CO_2 induced 'greening' would, however, negatively affect biodiversity in many ecosystems. In particular encroachment of woody plants into grasslands and savannahs in North American grassland and savanna communities could lead to a decline of up to 45 percent in species richness ((Ratajczak and Nippert, 2012) and loss of specialist savanna plant species in southern Africa (Parr, Gray, and Bond, 2012).

Mangroves are an important ecosystem and are particularly vulnerable to the multiple impacts of climate change, such as: rise in sea levels, increases in atmospheric CO_2 concentration, air and water temperature, and changes in precipitation patterns. Sea-level rise can cause a loss of mangroves by cutting off the flow of fresh water and nutrients and drowning the roots (Dasgupta, Laplante et al. 2010). By the end of the 21st century, global mangrove cover is projected to experience a significant decline because of heat stress and sea-level rise (Alongi, 2008; Beaumont et al., 2011). In fact, it has been estimated that under the A1B emissions scenario (3.5°C relative to pre-industrial levels) mangroves would need to geographically move on average about 1 km/year to remain in suitable climate zones (Loarie et al., 2009). The most vulnerable mangrove forests are those occupying low-relief islands such as small islands in the Pacific where sea-level rise is a dominant factor. Where rivers are lacking and/ or land is subsiding, vulnerability is also high. With mangrove losses resulting from deforestation presently at 1 to 2 percent per annum (Beaumont et al., 2011), climate change may not be the biggest immediate threat to the future of mangroves. However if conservation efforts are successful in the longer term climate change may become a determining issue (Beaumont et al., 2011).

Coral reefs are acutely sensitive to changes in water temperatures, ocean pH and intensity and frequency of tropical cyclones. Mass coral bleaching is caused by ocean warming and ocean acidification, which results from absorption of CO_2 (for example, Frieler et al., 2012a). Increased sea-surface temperatures and a reduction of available carbonates are also understood to be driving causes of decreased rates of calcification, a critical reef-building process (De'ath, Lough, and Fabricius, 2009). The effects of climate change on coral reefs are already apparent. The Great Barrier Reef, for example, has been estimated to have lost 50 percent of live coral cover since 1985, which is attributed in part to coral bleaching because of increasing water temperatures (De'ath et al., 2012). Under atmospheric CO_2 concentrations that correspond to a warming of 4°C by 2100, reef erosion will likely exceed rates of calcification, leaving coral reefs as "crumbling frameworks with few calcareous corals" (Hoegh-Guldberg et al., 2007). In fact, frequency of bleaching events under global warming in even a 2°C world has been projected to exceed the ability of coral reefs to recover. The extinction of coral reefs would be catastrophic for entire coral reef ecosystems and the people who depend on them for food, income and shoreline. Reefs provide coastal protection against coastal floods and rising sea levels, nursery grounds and habitat for a variety of currently fished species, as well as an invaluable tourism asset. These valuable services to often subsistence-dependent coastal and island societies will most likely be lost well before a 4°C world is reached.

The preceding discussion reviewed the implications of a 4°C world for just a few examples of important ecosystems. The section below examines the effects of climate on biological diversity Ecosystems are composed ultimately of the species and interactions between them and their physical environment. Biologically rich ecosystems are usually diverse and it is broadly agreed that there exists a strong link between this biological diversity and ecosystem productivity, stability and functioning (McGrady-Steed, Harris, and Morin, 1997; David Tilman, Wedin, and Knops, 1996)(Hector, 1999; D Tilman et al., 2001). Loss of species within ecosystems will hence have profound negative effects on the functioning and stability of ecosystems and on the ability of ecosystems to provide goods and services to human societies. It is the overall diversity of species that ultimately characterizes the biodiversity and evolutionary legacy of life on Earth. As was noted at the outset of this discussion, species extinction rates are now at very high levels compared to the geological record. Loss of those species presently classified as 'critically endangered' would lead to mass extinction on a scale that has happened only five times before in the last 540 million years. The loss of those species classified as 'endangered' and 'vulnerable' would confirm this loss as the sixth mass extinction episode (Barnosky 2011).

Loss of biodiversity will challenge those reliant on ecosystems services. Fisheries (Dale, Tharp, Lannom, and Hodges, 2010), and agronomy (Howden et al., 2007) and forestry industries (Stram & Evans, 2009), among others, will need to match species choices to the changing climate conditions, while devising new strategies to tackle invasive pests (Bellard, Bertelsmeier, Leadley, Thuiller, and Courchamp, 2012). These challenges would have to be met in the face of increasing competition between natural and agricultural ecosystems over water resources.

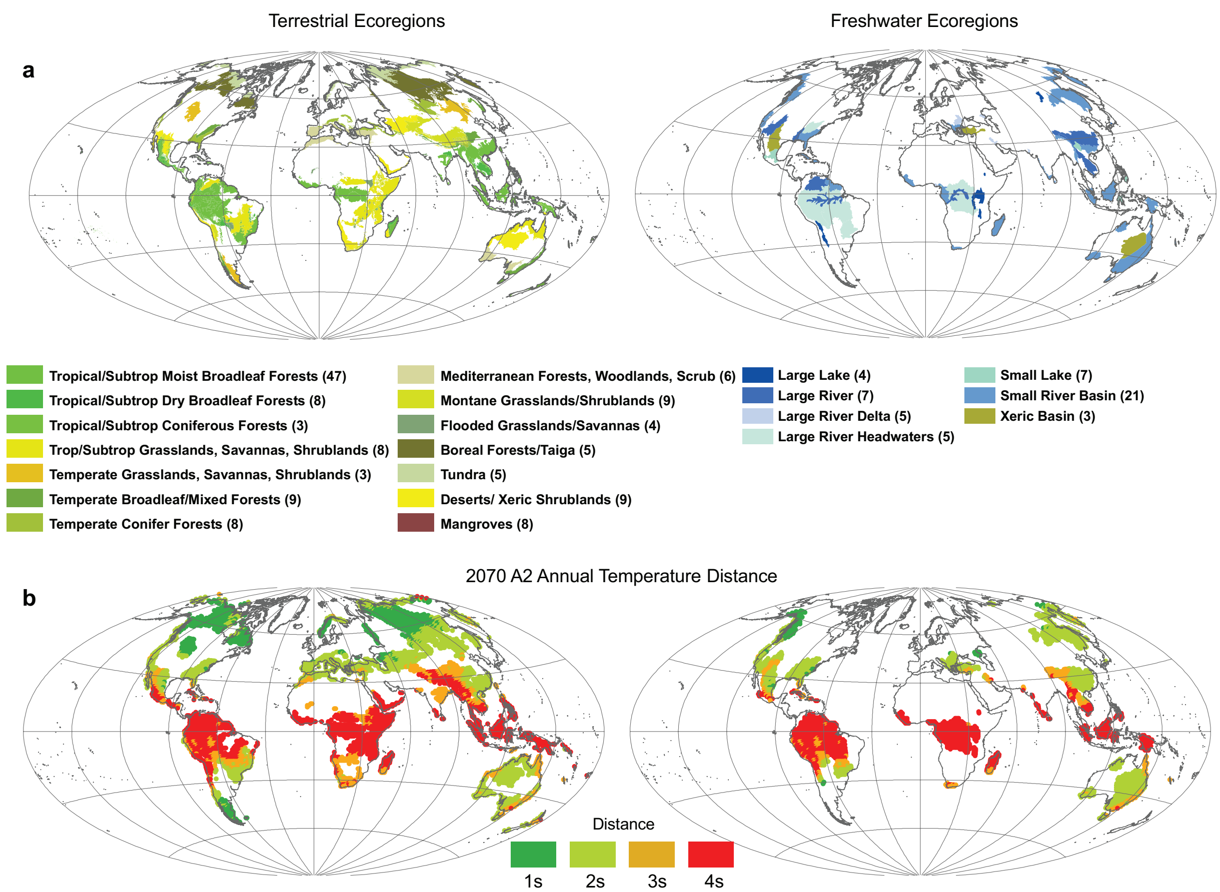
Over the 21st-century climate change is likely to result in some bio-climates disappearing, notably in the mountainous tropics and in the poleward regions of continents, with new, or novel, climates developing in the tropics and subtropics (Williams, Jackson, and Kutzbach, 2007). In this study novel climates are those where 21st century projected climates do not overlap with their 20th century analogues, and disappearing climates are those 20th century climates that do not overlap with 21st century projected climates. The projections of Williams et al (2007) indicate that in a 4°C world (SRES A2), 12–39 percent of the Earth's land surface may experience a novel climate compared to 20th century analogues. Predictions of species response to novel climates are difficult because researchers have no current analogue to rely upon. However, at least such climates would give rise to disruptions, with many current species associations being broken up or disappearing entirely.

Under the same scenario an estimated 10–48 percent of the Earth's surface including highly biodiverse regions such as the Himalayas, Mesoamerica, eastern and southern Africa, the Philippines and the region around Indonesia known as Wallacaea would lose their climate space. With limitations on how fast species can disperse, or move, this indicates that many species may find themselves without a suitable climate space and thus face a high risk of extinction. Globally, as in other studies, there is a strong association apparent in these projections between regions where the climate disappears and biodiversity hotspots. Limiting warming to lower levels in this study showed substantially reduced effects, with the magnitude of novel and disappearing climates scaling linearly with global mean warming.

More recent work by Beaumont and colleagues using a different approach confirms the scale of this risk (Beaumont et al., 2011, Figure 36). Analysis of the exposure of 185 eco-regions of exceptional biodiversity (a subset of the so-called Global 200) to extreme monthly temperature and precipitation conditions in the 21st century compared to 1961–1990 conditions shows that within 60 years almost all of the regions that are already exposed to substantial environmental and social pressure, will experience extreme temperature conditions based on the A2 emission scenario (4.1°C global mean temperature rise by 2100) (Beaumont et al., 2011). Tropical and sub-tropical eco-regions in Africa and South America are particularly vulnerable. Vulnerability to such extremes is particularly acute for high latitude and small island biota, which are very limited in their ability to respond to range shifts, and to those biota, such as flooded grassland, mangroves and desert biomes, that would require large geographical displacements to find comparable climates in a warmer world.

The overall sense of recent literature confirms the findings of the AR4 summarized at the beginning of the section, with a number

Figure 36: Distribution of monthly temperature projected for 2070 (2.9°C warming) across the terrestrial and freshwater components of WWF's Global 200. (A) The distribution of 132 terrestrial and 53 freshwater ecosystems, grouped by biomes. (B) Average distance (measured in number of standard deviations from the mean) of 21st century monthly temperatures from that of the baseline period (1961–1990).



Source: Beaumont et al., 2011.

of risks such as those to coral reefs occurring at significantly lower temperatures than estimated in that report. Although non-climate related human pressures are likely to remain a major and defining driver of loss of ecosystems and biodiversity in the coming decades, it is also clear that as warming rises so will the predominance of climate change as a determinant of ecosystem and biodiversity survival. While the factors of human stresses on ecosystems are manifold, in a 4°C world, climate change is likely to become a determining driver of ecosystem shifts and large-scale biodiversity loss (Bellard et al., 2012; New et al., 2011). Recent research suggests that large-scale loss of biodiversity is likely to occur in a 4°C world, with climate change and high CO_2 concentration driving a transition of the Earth´s ecosystems into a state unknown in human experience. Such damages to ecosystems would be expected to dramatically reduce the provision of ecosystem services on which society depends (e.g., hydrology—quantity flow rates, quality; fisheries (corals), protection of coastline (loss of mangroves).

Barnosky has described the present situation facing the biodiversity of the planet as "the perfect storm" with multiple high intensity ecological stresses because of habitat modification and degradation, pollution and other factors, unusually rapid climate change and unusually high and elevated atmospheric CO_2 concentrations. In the past, as noted above, this combination of circumstances has led to major, mass extinctions with planetary consequences. Thus, there is a growing risk that climate change, combined with other human activities, will cause the irreversible transition of the Earth´s ecosystems into a state unknown in human experience (Barnosky et al., 2012).

Human Health

Climatic changes have in the past affected entire societies on various time scales, often leading to social upheavals and unrest (McMichael, 2012). In what follows, a brief overview of possible adverse effects of warming on human health is presented.

UNDERNOURISHMENT AND MALNOURISHMENT

The "Great Famine" in Europe in the 14th century is an example of an event related to extreme climatic conditions. While the event can be attributed to the complex interplay of several factors, including socio-economic conditions, the fact that the famine coincided with dire weather conditions worsened its impacts as the floods, mud and cold that accompanied the famine helped diseases spread and undermined social coping capacity (McMichael, 2012).

Famine is caused or exacerbated by a variety of factors, many of which are environmental in nature. In the future, malnutrition and under-nutrition, which are major contributors to child mortality in developing countries, are likely to increase as an effect of potential crop failure resulting from extreme weather events and changing climate patterns. Undernourishment in turn is known to increase vulnerability to illness and infection severity (World Health Organization, 2009; World Bank, 2010), thereby indirectly producing further health impacts. One instance of such a causal chain was reported in the World Development Report 2010: drought, which is one extreme weather event that can trigger famine, has been shown to be strongly correlated to past meningitis epidemics in Sub-Saharan Africa (World Bank Group, 2010).

HEALTH IMPACTS OF EXTREME EVENTS

Extreme events have affected health not only in developing regions. The death toll of the 2003 heat wave in Europe is estimated at 70,000. Impacts of warming could include deaths, injuries, and mental health trauma because of extreme weather events, and, in high-vulnerability settings, increases in respiratory and diarrheal infections. Heat amplified levels of some urban-industrial air pollutants could cause respiratory disorders and exacerbate heart and blood vessel disease ('cardiovascular disease'), while in some regions increases in concentrations of aeroallergens (pollens, spores) are likely to amplify rates of allergic respiratory disorders (McMichael and Lindgren, 2011). Heat extremes have been shown to contribute to mortality rates of circulatory diseases (WHO, 2009). In addition, catastrophic events can cause damage to facilities that provide health related services (UN Habitat, 2011), potentially undermining the capacity to meet the challenges of excess illness and injury.

Applying a set of coherent, high-resolution climate change projections and physical models within an economic modeling framework, (Ciscar et al., 2011) project climate impacts for different levels of global warming. Within this framework, the LISFLOOD hydrological model provides estimates for the impacts of river floods (Tables 5. The authors project that, with no additional adaptation measures other than those already in place, with 4.1°C (relative to 1961–1990; 4.5°C relative to pre-industrial) warming in the 2080s, 251,000 people per year in Europe are likely to be affected by river flooding; and with a 5.4 °C (5.8°C relative to pre-industrial) warming in the 2080s 396,000 people per year are projected to be affected by river flooding. With a 2.5°C (2.9°C relative to pre-industrial) warming, in the 2080s, 276,000 people would be affected by river flooding. The river flood damages are expected to mostly affect western Europe, the British Isles, and Central and South Central European regions. The projections assume no growth in exposed value and population. The same study quantifies the effects of heat and cold related mortality. In the 2080s, without adaptation measures and physiological acclimatization, the annual increase mortality caused by heat in Europe is between 60,000 and 165,000. The decrease in cold-related mortality in Europe is projected to be between 60,000 and 250,000.

Table 5: Number of People Affected by River Flooding in European Regions (1000s)

People affected (1,000s/y)‡	Southern Europe	Central Europe	South Central Europe	North British Isles	Northern Europe	EU
2.5°C (2.9°C)	46	117	103	12	–2	276
3.9°C (4.3°C)	49	101	110	48	9	318
4.1°C (4.5°C)	9	84	119	43	–4	251
5.4°C (5.8°C)	–4	125	198	79	–3	396

Source: Ciscar *et al.* 2011.
Note: Estimated by the river flooding, given no adaptive measures in addition to what is in place today and projections assume no growth in exposed value and population. Temperatures in parentheses indicate warming above pre-industrial levels.
‡ Differences compared with the 1961–1990 period.

The number of people affected by weather extremes can be expected to be higher in developing countries than in the industrialized world, as has been also seen with extreme events in the past (for example, Cyclone Nargis in Myanmar in 2008). However, the authors are not aware of any studies that project weather extremes related health risks in developing countries for different levels of global warming.

Heat related mortality particularly affects the old, the young and those with pre-existing cardiovascular or other illnesses. With population ageing and an increasing proportion of people living in urban areas, combined with climate change, it is anticipated that the effects of heat stress will increase considerably. Heat waves and heat extremes are projected to increase as a consequence of climate change, as reported earlier in this report. Effects on human comfort and well-being are linked to a combination of increase in temperature and humidity. Recent projections of changes in the wet-bulb global temperature (WBGT) indicate a substantial increase in exposure to extreme heat conditions, taking into account both temperature and humidity changes. (Willett and Sherwood, 2012) project that heat events may become worse in the humid tropical and mid-latitude regions, even though these regions warm less in absolute terms than the global average because of greater absolute humidity increases. In this study, significant increases in WBGT are projected by the 2050s for all regions examined: India, China, and the Caribbean region in the developing world and for the United States, Australia and parts of Europe in the developed world.

MENTAL HEALTH AND LIFESTYLE-RELATED HEALTH DISORDERS

Another dimension of the impact of climate change on human health is that of the complex and often indirect repercussions for the quality of life of affected populations. It can be expected that warmer temperatures and exposure to extreme weather events will have negative effects on psychological and mental health, as well as increase the occurrence of conflict and violence (for example, McMichael and Lindgren, 2011; (World Bank Group, 2009). This remains, however, an under-researched area and there are very few studies that quantify these relationships. (Zivin and Neidell, 2010) point out that increased temperatures could also affect lifestyle by reducing the time spent on outdoor recreational activities, which in turn could potentially affect obesity, diabetes, and cardiovascular disease rates. In their study based on the American Time Use Survey, temperatures over 100°F (37.7°C) lead to a statistically significant decrease in outdoor leisure of 22 minutes compared to 76–80°F (24.4–26.6°C). On the other hand, temperatures in autumn, winter and spring more conducive to outdoor activity could produce the opposite effect in some areas. A further point arguably contributing to mental stress might be that changes to climatic regimes and associated environments will have ramifications for national identification and alter the dynamics of traditional cultures.

THE SPREAD OF PATHOGENS AND VECTOR BORNE DISEASES

According to (McMichael and Lindgren, 2011), climate change affects the rates of spread and multiplication of pathogens and changes the ranges and survival of non-human host species. Changes in temperature, precipitation and humidity influence vector-borne diseases (for example, malaria and dengue fever), as well as hantaviruses, leishmaniasis, Lyme disease and schistosomiasis (World Health Organization, 2009). In the Northern Hemisphere, the risk of tick-borne diseases in particular is expected to increase with higher temperatures. The tick species studied can transmit Mediterranean-spotted fever, Lyme borreliosis, and tick-borne encephalitis in Europe (Gray et al., 2009). (Reyburn et al. 2011) find a correlation between temperature increase and an increased cholera risk. Furthermore, flooding can introduce contaminants and diseases into water supplies and can increase the incidence of diarrheal and respiratory illnesses in both developed and developing countries (UN Habitat, 2011); (World Bank Group, 2009). Increased transmission of disease because of favorable conditions on the one hand, and undernourishment because of famine on the other, can be more likely to coincide under higher levels of warming, potentially compounding the overall health impact.

Malaria is an example of a vector borne disease whose distribution is likely to be influenced by climate change. Climate conditions including rainfall patterns, temperature and humidity affect the amount and the survival of mosquitoes, the vector of malaria. For instance, the peak of transmission often occurs during and just after the rain seasons (World Health Organization, 2012). Sudden changes to climatic conditions can lead to the outbreak of malaria in areas in which there is rarely malaria and people have little or no immunity (World Health Organization, 2012). For example, (Peterson, 2009) forecasts an increased malaria risk in East Africa and southern Africa where annual mean temperatures are increasing at such a rate as to permit new species of mosquitoes to establish populations.

However, according to (Gollin et al., 2010), in a scenario in which temperature increases by 3°C, the impact on malaria transmission can be minimized somewhat if the protection measures (including vaccines, bed nets and screens in houses) that may be taken up by some individuals are taken into account. This study finds that with a protection efficacy ranging from 90 percent to 70 percent (based on the assumption that these measures may not be effective all of the time), the increase in people affected oscillates between 0.32 and 2.22 percent.

In another study, (Béguin et al., 2011) estimate that the increased population at risk of contracting malaria in 2050 is over 200 million, under the IPCC´s A1B scenario (2.8°C relative to 1980–1999; 3.5°C relative to pre-industrial levels). The total population at risk in 2050 is projected to be about 5.2 billion if only climate impacts are considered and decreases to 2 billion if the effects of climate change and socio-economic development are considered. Furthermore, considering the effects of climate change only, some areas in South America, Sub-Saharan Africa and China would be exposed to a 50 percent higher malaria transmission probability rate (Béguin et al., 2011).

FURTHER FACTORS OF VULNERABILITY

Vulnerability toward health impacts of temperature extremes varies from different subgroups of population. Mid and low income countries face more challenges compared to OECD countries. Children and women are generally expected to be affected more severely (WHO, 2009; (EACC Synthesis World Bank Group, 2010)). The World Health Organization (2009) identifies Small Island Developing States and low lying regions as particularly vulnerable towards health impacts, because of salinization of fresh water and arable land as well as exposure to storm surges. The vulnerability of indigenous people in the Arctic region is likely be increased due to a decrease in food sources as reduced sea ice causes the animals on which they depend to decline, disrupting their hunting and food sharing culture (Arctic Climate Impact Assessment (ACIA), 2004; Crowley, 2010).Furthermore, urban populations are at greater risk of suffering from increasing temperatures because of a combination of higher inner-city temperatures, population densities and inadequate sanitation and freshwater services (WHO, 2009). Furthermore, health risks associated with climate change are closely linked to as yet unclear climate impacts in other fields, such as agriculture (Pandey, 2010).

Although future vulnerability toward climate change induced health impacts is therefore likely to heavily depend on future socioeconomic developments, quantitative assessments of various climate change related health impacts allow for a first understanding of the scope of future risks. However, quantitative assessments of health risks and different future temperature increase levels are rare to find. Moreover, studies that carry out such an analysis often focus on a single health risk rather than a comprehensive assessment of various interrelated risks at different levels of global warming. It can, however, plausibly be argued that the risks overviewed here will increase with rising temperatures, disproportionally affecting the poor and thus most vulnerable.

Chapter 7

System Interaction and Non-linearity—The Need for Cross-sector Risk Assessments

The preceding sections presented new analyses of regional sea-level rise projections and increases in extreme heat waves. They have given a snapshot of what some sectoral impacts of global mean warming of 4°C or more above preindustrial temperatures may mean. This review indicates very substantial issues in a number of critical sectors.

It is important to also consider how the impacts, risks, and vulnerabilities scale with increasing levels of global mean warming and CO_2 concentration. Many of the impacts identified for a 4°C world can be avoided with high confidence by limiting warming to lower levels. Other risks cannot be eliminated, but they can be very substantially reduced with lower levels of warming and CO_2 concentration. A comprehensive assessment of these issues has not been undertaken in this report.

In its Fourth Assessment Synthesis Report, the IPCC found it very likely that the net economic damages and costs of climate change would increase over time as global temperatures increase. The IPCC pointed out that responding to climate change involves an iterative risk management process, including adaptation and mitigation that takes into account climate damages, cobenefits, sustainability equity, and attitudes to risk. Another finding of the AR4 Synthesis Report (IPCC 2007), relating to the question of avoiding 4°C warming, is also relevant here: "mitigation efforts and investment over the next two to three decades will have a large impact on opportunities to achieve lower stabilization levels. Delayed emission reductions significantly constrain the opportunities to achieve lower levels and increase the risk of more severe climate change impacts." Earlier sections of this report pointed to recent literature that reinforces and extends these findings, and in particular, shows that it is still possible to hold warming below 2°C.

One of the striking conclusions one can draw from the projected impacts and risks is that the high level of risk and damages for temperature increases when approaching 4°C, and for some systems even well below 2°C. Findings from the AR4 Synthesis Report and from additional research are indicating that the risks of climate change are tending to become larger in magnitude or occur at lower increases in global temperature than found in earlier assessments (for example, Smith et al. 2009).

If one considers the impacts in a 4°C world from a risk planning perspective, some of the questions that immediately arise include the following:

- How will the impacts unfold? How fast and how will the likely impacts and adaptation needs differ from those expected for 2°C warming?
- Will the impacts and adaptation costs expected from a 4°C warming be twice as high as from a 2°C warming? Are there likely to be nonlinear increases in impacts and costs, or conversely a saturation of damages after 2°C or 3°C warming?
- Will the consequences of climate change be qualitatively similar independent of the temperature increase? Will investments made to adapt to 2°C warming be scalable to 4°C warming or is there a chance that these investments may be wasted, or at least become useless? Is such a targeted adaptation feasible at all, given the uncertainties associated with the impacts of high levels of global warming?
- Will increasing wealth in the future be sufficient to reduce vulnerability to acceptable levels, or will climate change reduce economic development prospects and exacerbate vulnerabilities?

For many of these questions there is no readily available quantitative modeling assessment that can provide reliable answers.

The climate modeling community can provide projections of global mean warming and even regional climatic changes up to at least a 4–5°C warming, albeit with increasing uncertainty. For most regions, the patterns of climate change projected for 2°C warming are expected to be roughly similar, but substantially greater for warming of 4°C. However, lurking in the tails of the probability distributions are likely to be many unpleasant surprises. The new projections for unprecedented heat waves and temperature extremes for 4°C warming are one illustration of this. Many systems and changes in the extremes have much more impact than changes in the mean. Researchers expect that many extremes, including heat waves, droughts, extreme rainfall, flooding events, and tropical cyclone intensity, are likely to respond nonlinearly to an increase in global mean warming itself. They are already observing some of these effects, which are forcing a recalibration of important impact parameters, such as the responses of crops and the agricultural system to climate change. Warming to these levels of risks commits the climate system to very long-term warming (Solomon, Plattner, Knutti, and Friedlingstein 2009; Hare and Meinshausen 2006) and to impacts, such as very long-term, multimeter sea-level rise, because of the response of the ice sheets over thousands of years (Huybrechts et al. 2011)

The scale and rapidity of climate change will not be occurring in a vacuum. It will occur in the context of economic growth and population increases that will place increasing stresses and demands on a planetary ecosystem already approaching, or even exceeding, important limits and boundaries (Barnosky et al. 2012; Rockström et al. 2009). The resilience of many natural and managed ecosystems is likely to be adversely affected by both development and growth, as well as the consequences of climate change.

Although systems interact, sometimes strongly, present tools for projecting impacts of climate change are not yet equipped to take into account strong interactions associated with the interconnected systems impacted by climate change and other planetary stresses, such as habitat fragmentation, pollution, and invasive species (Warren 2011). Scientific findings are starting to indicate that some of these interactions could be quite profound, rather than second-order effects. Impacts projected for ecosystems, agriculture, and water supply in the 21st century could lead to large-scale displacement of populations, with manifold consequences for human security, health, and economic and trade systems. Little is understood regarding the full human and economic consequences of a collapse of coral reef ecosystems, combined with the likely concomitant loss of marine production because of rising ocean temperatures and increasing acidification, and the large-scale impacts on human settlements and infrastructure in low-lying fringe coastal zones of a 1 m sea-level rise within this century. While each of these sectors have been examined, as yet researchers do not fully understand the consequences for society of such wide ranging and concomitant impacts, many of which are likely before or close to 4°C warming.

An aspect of the risks arising from climate change that requires further research to better understand the consequences for society is how nonlinear behavior in the Earth and human systems will alter and intensify impacts across different levels of warming. This is discussed in the following sections.

Risks of Nonlinear and Cascading Impacts

In the outline of impacts presented in this report, an implicit assumption in nearly all of the modeling and assessment exercises is that the climate system and affected sectors will respond in a relatively linear manner to increases in global mean temperature. Large-scale and disruptive changes in the climate system, or its operation, are generally not included in modeling exercises, and not often in impact assessments. However, given the increasing likelihood of threshold crossing and tipping points being reached or breached, such risks need to be examined in a full risk assessment exercise looking at the consequences of 4°C warming, especially considering that even further warming and sea-level rise would be expected to follow in the centuries ahead. What follows is a sketch of potential mechanisms that point to a nonlinearly evolving cascade of risks associated with rising global mean temperature. The list does not claim to be exhaustive; for a more extensive discussion, see, for example, Warren (2011).

NONLINEAR RESPONSES OF THE EARTH SYSTEM

With global warming exceeding 2°C, the risk of crossing activation thresholds for nonlinear tipping elements in the Earth System and irreversible climate change impacts increases (Lenton et al. 2008), as does the likelihood of transitions to unprecedented climate regimes. A few examples demonstrate the need for further examination of plausible world futures.

Amazon Rain Forest Die-back

There is a significant risk that the rain forest covering large areas of the Amazon basin will be lost as a result of an abrupt transition in climate toward much drier conditions and a related change in the vegetation system. Once the collapse occurs, conditions would likely prevent rain forest from re-establishing. The tipping point for this simulation is estimated to be near 3–5°C global warming (Lenton et al. 2008; Malhi et al. 2009; Salazar and Nobre 2010). A collapse would have devastating consequences for biodiversity, the livelihoods of indigenous people, Amazon basin hydrology and water security, nutrient cycling, and other ecosystem services.

Continuing deforestation in the region enhances the risks of reductions in rainfall and warming (Malhi et al. 2009) and exacerbates climate change induced risks.

Ocean Ecosystems

Disruption of the ocean ecosystems because of warming and ocean acidification present many emerging high-level risks (Hofmann and Schellnhuber 2009). The rising atmospheric carbon dioxide concentration is leading to rapid acidification of the global ocean. Higher acidity (namely, lower pH) of ocean waters leads to reduced availability of calcium carbonate (aragonite), the resource vital for coral species and ecosystems to build skeletons and shells.

The combination of warming and ocean acidification is likely to lead to the demise of most coral reef ecosystems (Hoegh-Guldberg 2010). Warm-water coral reefs, cold-water corals, and ecosystems in the Southern Ocean are especially vulnerable. Recent research indicates that limiting warming to as little as 1.5°C may not be sufficient to protect reef systems globally (Frieler et al. 2012). This is a lower estimate than included in earlier assessments (for example, the IPCC AR4 projected widespread coral reef mortality at 3–4°C above preindustrial). Loss of coral reef systems would have far-reaching consequences for the human societies that depend on them. Moreover, their depletion would represent a major loss to Earth's biological heritage.

A particularly severe consequence of ocean warming could be the expansion of ocean hypoxic zones, ultimately interfering with global ocean production and damaging marine ecosystems. Reductions in the oxygenation zones of the ocean are already being observed, and, in some ocean basins, these losses are reducing the habitat for tropical pelagic fishes, such as tuna (Stramma et al. 2011). Loss of oceanic food production could have very negative consequences for international food security as well as lead to substantial economic costs.

West Antarctic Ice Sheet

It has long been hypothesized that the West Antarctic Ice Sheet, which contains approximately 3 m of sea-level rise equivalent in ice, is especially vulnerable to global warming (Mercer 1968; 1978). The observed acceleration in loss of ice from the West Antarctic Ice Sheet is much greater than projected by modeling studies and appears to be related to deep ocean warming causing the retreat of vulnerable ice streams that drain the interior of this region (Rignot and Thomas 2002; Pritchard, Arthern, Vaughan, and Edwards 2009; Scott, Schell, St-Onge, Rochon, and Blaso 2009; Velicogna 2009). While scientific debate on the subject remains vigorous and unresolved, the risk cannot be ignored because an unstable retreat could lead over the next few centuries to significantly higher rates of sea level rise than currently projected.

Greenland Ice Sheet

New estimates for crossing a threshold for irreversible decay of the Greenland ice sheet (which holds ice equivalent to 6 to 7 m of sea level) indicate this could occur when the global average temperature increase exceed roughly 1.5°C above preindustrial (range of 0.8 to 3.2°C) (Robinson et al. 2012). This value is lower than the earlier AR4 range of 1.9 to 4.6°C above preindustrial. Irreversible decay of this ice sheet would likely occur over many centuries, setting the world on a course to experience a high rate of sea-level rise far into the future.

Significant uncertainty remains about the timing and onset of such tipping points. However, such singularities could lead to drastic and fundamental change and, therefore, deserve careful attention with regard to identifying potential adaptation options for the long term. While the risk of more rapid ice sheet response appears to be growing, there remains an open question as to whether risk planning should be oriented assuming 1 meter rise by 2100 or a substantially larger number, such as, 2 meters. The onset of massive transitions of coral reefs to much simpler ecosystems could happen quite soon and well before even 2°C warming is reached. Along with the uncertainty regarding onset and associated human impact of these and other nonlinearities, the extent of human coping capacity with these impacts also remains uncertain.

NONLINEARITY WITHIN SECTORS AND SOCIAL SYSTEMS

Within individual sectors and systems there can be nonlinear responses to warming when critical system thresholds are crossed. One such nonlinearity arises because of a threshold behavior in crop growth. In different regions of the world, including the United States, Africa, India, and Europe, nonlinear temperature effects have been found on important crops, including maize, wheat, soya, and cassava (see Chapter 2). For example, in the United States, significant nonlinear effects have been observed when local temperature rises to greater than 29°C for corn, 30°C for soybeans, and 32°C for cotton. Under the SRES A1F scenario, which exceeds 4°C warming by 2100, yields are projected to decrease by 63 to 82 percent (Schlenker and Roberts 2009). The potential for damages to crops because of pests and diseases plus nonlinear temperature effects is likely to grow as the world warms toward 2°C and above. Most current crop models do not account for such effects—one reason that led Rötter et al. (2011) to call for an "overhaul" of current crop-climate models. In light of the analysis of temperature extremes presented in this report, adverse impacts on agricultural yields may prove to be greater than previously projected. For example, in the Mediterranean and central United States the warmest July in the latter decades of the 21st century are projected to lead to temperatures

Box 3: Sub-Saharan Africa

Sub-Saharan Africa is a region of the world exposed to multiple stresses and has been identified as particularly vulnerable to the impacts of climate change. It is an example of an environment where impacts across sectors may interact in complex ways with one another, producing potentially cascading effects that are largely unpredictable.

For example, in a 4°C world, Sub-Saharan Africa is projected to experience temperatures that are well above currently experienced extreme heat waves. In coastal areas, an additional problem will be sea-level rise, which is projected to displace populations, and particularly in combination with severe storms, could cause freshwater resources to become contaminated with saltwater (Nicholls and Cazenave 2010). Projected heat extremes and changes in the hydrological cycle would in turn affect ecosystems and agriculture.

Tropical and subtropical ecoregions in Sub-Saharan Africa are particularly vulnerable to ecosystem damage (Beaumont et al. 2011). For example, with 4°C warming, of 5,197 African plant species studied, 25 percent–42 percent are projected to lose all suitable range by 2085 (Midgley and Thuiller 2011). Ecosystem damage would have the flow-on effect of reducing the ecosystem services available to human populations.

At present, food security is one of the most daunting challenges facing Sub-Saharan Africa. The economies of the region are highly dependent on agriculture, with agriculture typically making up 20–40 percent of gross domestic product (Godfray et al. 2010a). Climate change will likely cause reductions in available arable land (Brown, Hammill, and McLeman 2007). Because agriculture in Sub-Saharan Africa is particularly sensitive to weather and climate variables (for example, 75 percent of Sub-Saharan African agriculture is rainfed), it is highly vulnerable to fluctuations in precipitation (Brown, Hammel, and McLeman 2007) and has a low potential for adaptation (Kotir 2011). With 4°C or more of warming, 35 percent of cropland is projected to become unsuitable for cultivation (Arnell 2009). In a 5°C world, much of the crop and rangeland of Sub-Saharan Africa can be expected to experience major reductions in the growing season length (Thornton et al. 2011b). For example, in the event of such warming, crop yields for maize production are projected to be reduced 13–23 percent across different African regions (not taking into account the uncertain effect of CO_2 fertilization) (Thornton et al. 2011). Crop losses for beans are expected to be substantially higher.

Human health in Sub-Saharan Africa will be affected by high temperatures and reduced availability of water, especially as a result of alterations in patterns of disease transmission. Some areas in Sub-Saharan Africa may face a 50 percent increase in the probability for malaria transmission (Béguin 2011) as a result of new species of mosquitoes becoming established (Peterson 2009). The impacts on agriculture and ecosystems outlined above would further compound the direct impacts on human health by increasing the rates of undernutrition and reduced incomes, ultimately producing negative repercussions for economic growth. These conditions are expected to increase the scale of population displacement and the likelihood of conflict as resources become more scarce. Africa is also considered particularly vulnerable to increasing threats affecting human security. Long-term shifts in the climate seem likely to catalyze conflict by creating or exacerbating food, water and energy scarcities, triggering population movements, and placing larger groups of people in competition for more and more limited resources. Increased climate variability, including the greater frequency of extreme weather events, will also complicate access to resources, thereby exacerbating conditions that are conducive to promoting conflict (Brown, Hammer and McLeman 2007; Hendrix and Glaser 2007). Like many other effects of climate change discussed in this report, instances of conflict could unfold "in a way that could roll back development across many countries"(Brown, Hammer and McLeman 2007).

It is important to emphasize here that each of these impacts would undermine the ability of populations in Sub-Saharan Africa that are often already facing poverty and precarious conditions to adapt to the challenges associated with impacts in other sectors. In this context, the potential for climate change to act as a "threat multiplier," potentially making such existing challenges as water scarcity and food insecurity more complex and irresolvable, is cause for particular concern.

rising close to 35°C, or up to 9°C above the warmest July for the past two decades. However, more research is required to better understand the repercussions for agriculture in a 4°C world given the uncertainty in both temperature and impact projections, as well as the potential for adaptive responses and the possibility of breeding high temperature crop varieties.

Similarly, social systems can be pushed beyond thresholds that existing institutions could support, leading to system collapse (Kates et al. 2012). The risk of crossing such thresholds is likely to grow with pressures increasing as warming progresses toward 4°C and combines with nonclimate related social, ecological, economic, and population stresses. Barnett and Adger (2003) point to the risks of sea-level rise in atoll countries pushing controlled, adaptive migration to collapse, resulting in complete abandonment. Similarly, stresses on human health—such as heat waves, malnutrition, decreasing quality of drinking water resulting from salt water intrusion, and more—could overburden health-care systems to the point where adaptation to given stresses is no longer possible. Immediate physical exposure of facilities such as hospitals to extreme weather events, storm surge, and sea-level rise may also contribute to this pressure on health care systems.

Where a system responds linearly and proportionately to warming, there is a better basis for systematic planning. A non-linear response in a sector or human system is likely instead to raise far greater challenges and should be taken into account for adaptation planning.

NONLINEARITIES BECAUSE OF INTERACTIONS OF IMPACTS

Potential interactions of sectoral impacts can introduce a further dimension of nonlinearity into analyses of the potential for significant consequences from global warming.

If changes were to be small, it is plausible that there would be few interactions between sectors. For example, a small change in agricultural production might be able to be compensated for elsewhere in another region or system. However, as the scale and number of impacts grow with increasing global mean temperature, interactions between them seem increasingly likely, compounding the overall impact. A large shock to agricultural production resulting from extreme temperatures and drought across many regions would, for example, likely lead to substantial changes in other sectors and in turn be impacted by them. For example, substantial pressure on water resources and changes of the hydrological cycle could ultimately affect water availability for agriculture. Shortages in water and food could in turn impact human health and livelihoods. Diversion of water from ecosystem maintenance functions to meet increased human needs could have highly adverse effects on biodiversity and vital ecosystem services derived from the natural environment. This could cascade into effects on economic development by reducing a population´s work capacity that could, in turn, diminish GDP growth.

Nonclimatic factors can interact with impacts to increase vulnerability. For example, increasing demands on resources needed to address the population increase could lead to reduced resilience, if resources are not distributed adequately and equitably. As another example, an aging population will experience higher vulnerability to particular impacts, such as health risks. Furthermore, such mitigation measures as land-use change to provide for biomass production and incremental adaptation designed for a 2°C world could increase—perhaps exponentially—vulnerability to a 4°C world by increasing land and resource value without guarding against abrupt climate change impacts (Kates et al. 2012). Warren (2011) further stresses that future adaptation measures to projected high impacts, such as changes in irrigation practices to counteract crop failures, might exacerbate impacts in other sectors, such as water availability.

NONLINEARITIES BECAUSE OF CASCADING IMPACTS

With the possibility of installed adaptation capacities failing in a 4°C world, infrastructure that plays a key role in the distribution of goods is more exposed to climate change impacts. This could lead to impacts and damages cascading into areas well beyond the initial point of impact. Thus, there is a risk that vulnerability is more widely dispersed and extensive than anticipated from sectoral impact assessment.

Projections of damage costs for climate change impacts typically assess the costs of directly damaged settlements, without taking surrounding infrastructure into account. However, in a more and more globalized world that experiences further specialization in production systems and higher dependency on infrastructure to deliver produced goods, damages to infrastructure can lead to substantial indirect impacts. For example, breakdowns or substantial disruption of seaport infrastructure could trigger impacts inland and further down the distribution chain.

A better understanding of the potential for such cascading effects, their extent, and potential responses is needed. To date, impacts on infrastructure and their reach has not been sufficiently investigated to allow for a quantitative understanding of the full scope and time frame of total impacts. Such potential examples present a major challenge for future research.

Concluding Remarks

A 4°C world will pose unprecedented challenges to humanity. It is clear that large regional as well as global scale damages and risks are very likely to occur well before this level of warming is reached. This report has attempted to identify the scope of these challenges driven by responses of the Earth system and various human and natural systems. Although no quantification of the full scale of human damage is yet possible, the picture that emerges challenges an often-implicit assumption that climate change will not significantly undermine economic growth.[15] It seems clear that climate change in a 4°C world could seriously undermine poverty alleviation in many regions. This is supported by past observations of the negative effects of climate change on economic growth in developing countries. While developed countries have been and are projected to be adversely affected by impacts resulting from climate change, adaptive capacities in developing regions are weaker. The burden of climate change in the future will very likely be borne differentially by those in regions already highly vulnerable to climate change and variability. Given that it remains uncertain whether adaptation and further progress toward development goals will be possible at this level of climate change, the projected 4°C warming simply must not be allowed to occur—the heat must be turned down. Only early, cooperative, international actions can make that happen.

15 The Stern Report being a notable exception, Stern, N. 2007. *The Economics of Climate Change: The Stern Review.* Cambridge and New York, Cambridge University Press.

Appendix 1

Methods for Modeling Sea-level Rise in a 4°C World

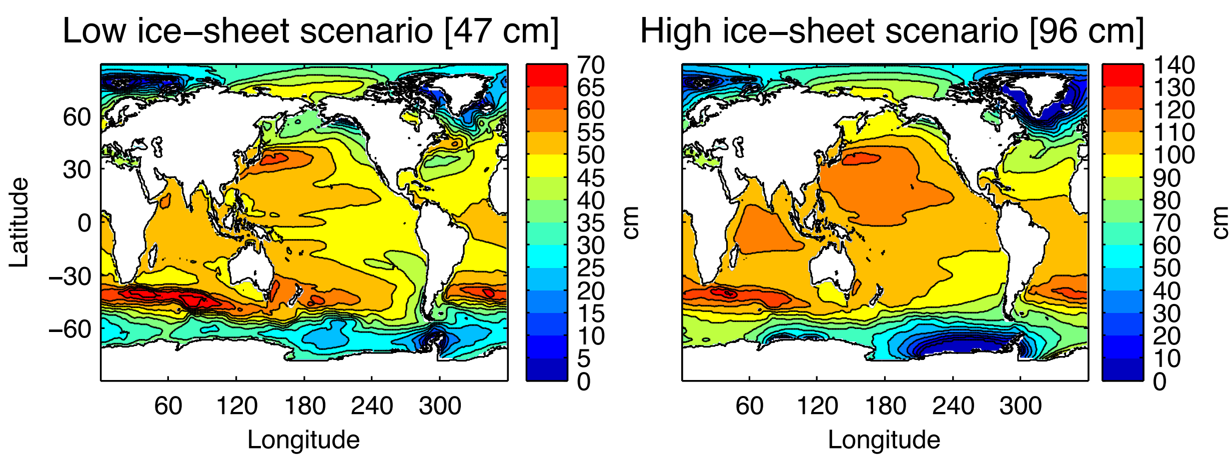
The authors developed sea-level scenarios using a combination of approaches, acknowledging the fact that both physically-based numerical ice sheet modeling and semi-empirical methods have shortcomings, but also recognizing the need to provide ice sheet loss estimates to be able to estimate regional sea-level rise. They did not attempt to characterize the full range of uncertainties, either at the low or high end. Future contributions from groundwater mining are also not included in the projections, and could account for another 10 cm (Wada et al. 2012). The scenario construction is as follows.

For the upper end of the sea-level scenario construction, the authors apply a semi-empirical sea-level rise model (Rahmstorf, Perrette, and Vermeer 2011; Schaeffer et al. 2012), giving a global estimate for specific emission scenarios leading to a 2°C or 4°C increase in global mean temperature by 2100. As the semi-empirical sea-level rise models do not separately calculate the individual terms giving rise to sea-level increases, further steps are needed to characterize plausible ice sheet contributions. The authors calculate the contribution from thermal sea-level rise and from mountain glaciers and icecaps and deduct this from the total global sea-level rise and assign this difference to the ice sheets, half to Greenland and the other half to Antarctica. The resulting contributions from the ice sheets are significantly above those estimated by most process based ice sheet models and approximates the ice sheet contribution that would arise, if the rates of acceleration of loss observed since 1992 continued unchanged throughout the 21st century.

For the lower end of the scenario construction, the authors use as a starting point the calculated thermal sea level-rise and the contribution from mountain glaciers and ice caps. To this, they add a surface mass balance contribution from the Greenland ice sheet (GIS; excluding ice dynamics) and assume that the Antarctic ice sheet (AIS) is in balance over the 21st century. Most AIS models project that this ice sheet would lower sea-level rise in the 21st century as it does not warm sufficiently to lose more ice than it gains because of enhanced precipitation over this period. On the other hand, observations indicate that the ice sheet is losing ice at a slowly increasing rate close to that of the Greenland ice sheet at present. Setting the AIS contribution to zero is, thus, a way of leaving open the possibility that short-term processes may have been at work over the last 20 years. This very low ice sheet contribution scenario approaches the levels of some process-based model projections, where the projected net uptake of ice by Antarctica is balanced by ice melting from Greenland over the 21st century.

In the lower ice-sheet scenario (47 cm sea-level rise in the global mean), eastern Asian and northeastern American coasts both experience above-average sea-level rise, about 20 percent and 15 percent, respectively above the global mean (for example, –3 percent to +23 percent around New York City, 68 percent range). In the higher ice-sheet scenario (96 cm sea-level rise in the global mean), where ocean dynamic effects are relatively less significant, the eastern Asian coast clearly stands out as featuring the highest projected coastal sea-level rise of 20 percent above the global mean. In that scenario, sea-level rise is projected to be slightly below the global mean in northeast America, and 20 percent (5–33 percent, 68 percent range) below the global mean along the Dutch coast (Figure A1.1, Figure 32). It is important to note the likely weakening in the Atlantic Meridional Overturning Circulation (AMOC) with increasing warming could be exacerbated by rapid ice sheet melt from Greenland. That effect, which is not included in the authors' projections, could potentially add another 10 cm to the local sea-level rise around New York City, as currently discussed in the scientific literature (Sallenger et al. 2012; Slangen et al. 2011; Stammer, Agarwal, Herrmann, Köhl and Mechoso 2011; Yin et al. 2009). Post-glacial adjustment would also add another 20 cm, albeit with large uncertainties (Slangen et al. 2011).

Figure A1.1: Regional sea-level projection for the lower ice-sheet scenario (left) and the higher ice sheet scenario (right). The numbers in brackets denote the corresponding global mean value for sea-level rise, of 47 cm and 96 cm, respectively.



The difference in regional sea-level rise patterns between 4°C and 2°C warming above preindustrial temperatures is indicated in Figure A1.2 for both ice-sheet scenarios by the end of the century. In both ice-sheet scenarios, the spatially variable component of the difference is closely related to ocean dynamics (see Figure A1.3). The benefit of choosing a 2°C pathway, rather than a 4°C pathway can be to limit more than 20 cm of local sea-level rise (Figure A1.2). Note that the authors do not exclude higher benefits of mitigation: in particular, potential (but uncertain) crossing of tipping points with respect to ice-sheet collapse could increase the impact of a 4°C world compared to a 2°C world.

The regional projections presented here incorporate the uncertainties from the methods that were applied to estimate global mean sea-level rise. In order to reduce these uncertainties, further research on the dynamic changes in the ice sheets is needed, using reconstruction of past responses to climate and observations of

Figure A1.2: Difference in sea-level rise between a 4°C world and a 2°C world for the lower (left) and higher (right) ice-sheet scenario. The numbers in brackets indicate the difference in global mean sea-level rise. Grey shaded areas indicate regions where sea-level is higher in a 2°C world: they correspond to regions where sea level is actually projected to drop in the coming century because of land uplift and gravitational effects.

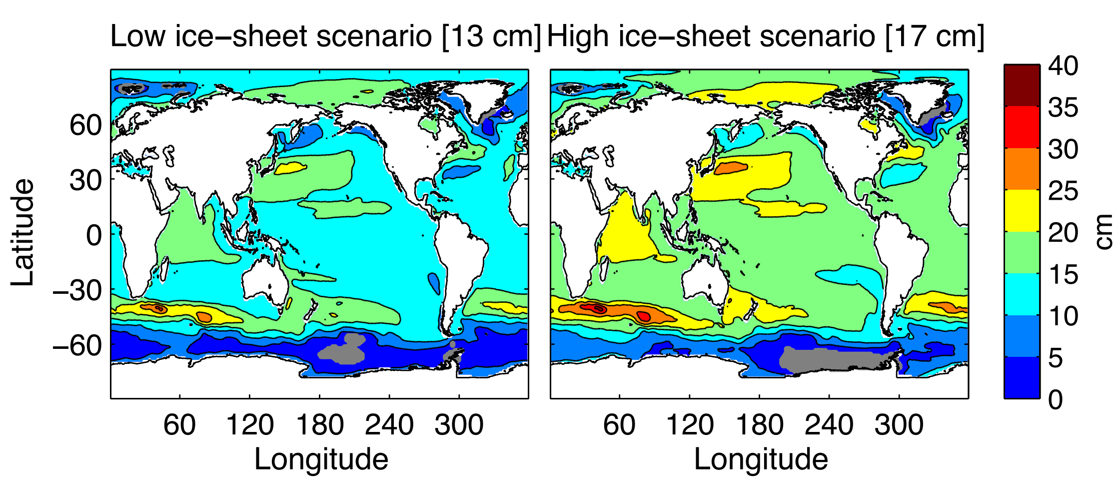
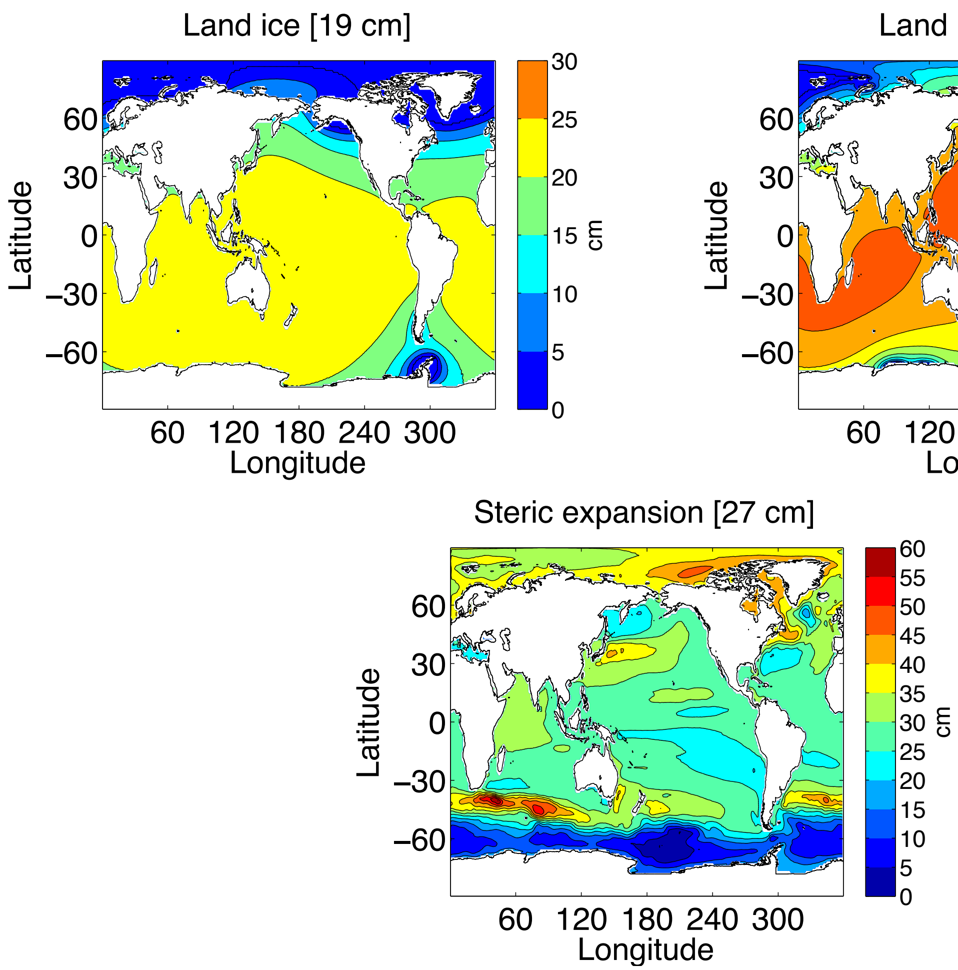


Figure A1.3: Individual contributions to sea-level rise by 2100 in a 4°C world: land-ice (mountain glaciers and ice caps + ice sheets) contribution fromå the lower (top-left) and higher (top-right) ice-sheet scenario; global mean thermal expansion plus dynamic sea-level changes (together termed steric expansion) (bottom-left). Global averages are indicated in brackets in figure. Grey shading indicates sea-level drop (negative values). Note that the authors do not exclude higher benefits of mitigation: in particular, potential (but uncertain) crossing of tipping points with respect to ice-sheet collapse which could increase the impact of a 4°C world compared to a 2°C world.



ongoing changes, as well as numerical modeling. Another need, which is more specific to regional sea-level projections, is to combine projections such as those presented in this report with local, specific information about uplift or subsidence rates because of nonclimatic processes, such as sediments accretion, mining, or long-term glacial isostatic adjustment ongoing since the last deglaciation.

This report considered regional sea-level rise by 2100, but shorter time scales are also of high societal relevance. Decadal rates of sea-level change can, indeed, vary significantly at the regional level because of the superimposed effect of natural variability. On subannual time scales, storm surges and waves can inundate and erode coastlines even for a small rise of the annual mean sea level.

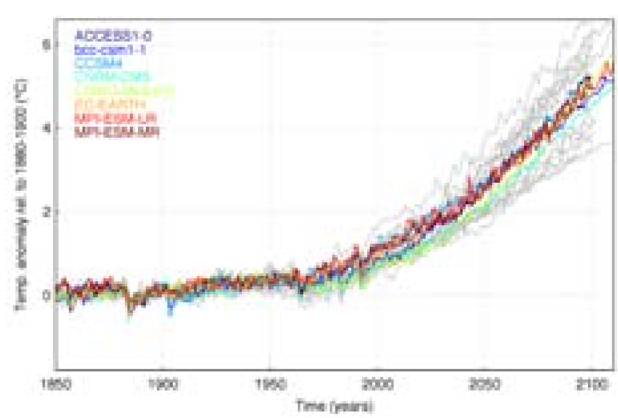
Appendix 2

Methods for Analyzing Extreme Heat Waves in a 4°C World

For the analysis of extreme heat waves in a 4°C world, those CMIP5 simulation runs were selected that project a four-degree warmer world by the end of the 21st century. Figure A2.1 shows the increase of global mean temperature over the 21st century, relative to pre-industrial conditions (averaged over the period 1880–1900), for 24 models based on the RCP8.5 scenario. Only with the high-emission scenario RCP8.5 (Moss et al. 2010) do the models produce climates that are around 4°C warmer than pre-industrial before the end of the 21st century. From these RCP8.5 model runs, those simulations that show 4.0 ±0.5°C of global mean warming averaged over the period 2080–2100 (colored curves in Figure A2.1) relative to present-day conditions (1980–2000) were selected. This, thus, implies 4°C–5°C warmer compared to pre-industrial conditions (Figure A2.1), (Betts et al. 2011).). The eight simulations selected this way exhibit a rate of warming in the middle of the range of those produced by the RCP8.5 scenario runs, compared with several models that reach a four-degree world sooner and others only into the 22nd century (grey curves).

For each of the selected 4°C world simulations, the local monthly standard deviation because of due to natural variability over the entire 20th century (1901–2000) for each individual month was determined. To do so, first a singular spectrum analysis to extract the long-term, non-linear warming trend (namely, the climatological warming signal) was used. Next the 20th century monthly time series was detrended by subtracting the long-term trend, which provides the monthly year-to-year variability. From this detrended signal, monthly standard deviations were calculated, which were then averaged seasonally (that is, seasonally averaged monthly-standard deviations). In the present analysis, the standard deviation calculated for the entire 20th century (1901–2000) was employed;, however, it was found that this estimate was robust with respect to shorter time periods. All results concerning extreme events are presented in terms of standard deviation, which allows for a calculation of multi-model means, even though natural variability might be different between the models.

Figure A2.1: Simulated historic and 21st century global mean temperature anomalies, relative to the pre-industrial period (1880–1900), for 24 CMIP5 models based on the RCP8.5 scenario. The colored (and labeled) curves show those simulations reaching a global mean warming of 4°C–5°C warmer than pre-industrial for 2080–2100, which are used for further analysis.



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