4° Turn Down the Heat

Climate Extremes, Regional Impacts, and the Case for Resilience

THE WORLD BANK

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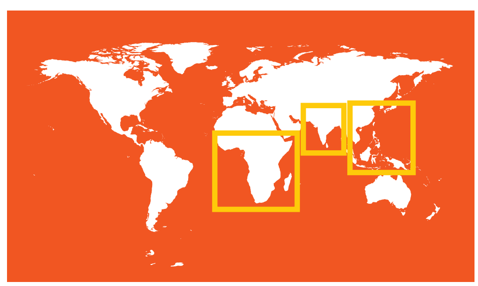

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A Report for the World Bank by the Potsdam Institute for Climate Impact Research and Climate Analytics

THE WORLD BANK

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Acknowledgments

The report ***Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience*** is a result of contributions from a wide range of experts from across the globe. The report follows *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided*, released in November 2012. We thank everyone who contributed to its richness and multidisciplinary outlook.

The report has been written by a team from the Potsdam Institute for Climate Impact Research and Climate Analytics, including Hans Joachim Schellnhuber, Bill Hare, Olivia Serdeczny, Michiel Schaeffer, Sophie Adams, Florent Baarsch, Susanne Schwan, Dim Coumou, Alexander Robinson, Marion Vieweg, Franziska Piontek, Reik Donner, Jakob Runge, Kira Rehfeld, Joeri Rogelj, Mahé Perette, Arathy Menon, Carl-Friedrich Schleussner, Alberte Bondeau, Anastasia Svirejeva-Hopkins, Jacob Schewe, Katja Frieler, Lila Warszawski and Marcia Rocha.

The ISI-MIP projections were undertaken by modeling groups at the following institutions: ORCHIDEE[1] (Institut Pierre Simon Laplace, France); JULES (Centre for Ecology and Hydrology, UK; Met Office Hadley Centre, UK; University of Exeter, UK); VIC (Norwegian Water Resources and Energy Directorate, Norway; Wageningen University, Netherlands); H08 (Institute for Environmental Studies, Japan); WaterGAP (Kassel University, Germany; Universität Frankfurt, Germany); MacPDM (University of Reading, UK; University of Nottingham, UK); WBM (City University of New York, USA); MPI-HM (Max Planck Institute for Meteorology, Germany); PCR-GLOBWB (Utrecht University, Netherlands); DBH (Chinese Academy of Sciences, China); MATSIRO (University of Tokyo, Japan); Hybrid (University of Cambridge, UK); Sheffield DGVM (University of Sheffield, UK; University of Bristol, UK); JeDi (Max Planck Institut für Biogeochemie, Germany); ANTHRO-BGC (Humboldt University of Berlin, Germany; Leibniz Centre for Agricultural Landscape Research, Germany); VISIT (National Institute for Environmental Studies, Japan); GEPIC (Eawag, Switzerland); EPIC (University of Natural Resources and Life Sciences, Vienna, Austria); pDSSAT (University of Chicago, USA); DAYCENT (Colorado State University, USA); IMAGE (PBL Netherlands Environmental Assessment Agency, Netherlands); PEGASUS (Tyndall Centre, University of East Anglia, UK); LPJ-GUESS (Lunds Universitet, Sweden); MAgPIE (Potsdam Institute, Germany); GLOBIOM (International Institute for Applied Systems Analysis, Austria); IMPACT (International Food Policy Research Institute, USA; International Livestock Research Institute, Kenya); DIVA (Global Climate Forum, Germany); MARA (London School of Hygiene and Tropical Medicine, UK); WHO CCRA Malaria (Umea University, Sweden); LMM 205 (The University of Liverpool, UK); MIASMA (Maastricht University, Netherlands); and VECTRI (Abdus Salam International Centre for Theoretical Physics, Italy).

1 A full list of ISI-MIP modeling groups is given in Appendix 2.

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Foreword

The work of the World Bank Group is to end extreme poverty and build shared prosperity. Today, we have every reason to believe that it is within our grasp to end extreme poverty by 2030. But we will not meet this goal without tackling the problem of climate change.

Our first *Turn Down the Heat* report, released late last year, concluded the world would warm by 4°C by the end of this century if we did not take concerted action now.

This new report outlines an alarming scenario for the days and years ahead—what we could face in our lifetime. The scientists tell us that if the world warms by 2°C—warming which may be reached in 20 to 30 years—that will cause widespread food shortages, unprecedented heat-waves, and more intense cyclones. In the near-term, climate change, which is already unfolding, could batter the slums even more and greatly harm the lives and the hopes of individuals and families who have had little hand in raising the Earth's temperature.

Today, our world is 0.8°C above pre-industrial levels of the 18th century. We could see a 2°C world in the space of one generation.

The first *Turn Down the Heat* report was a wake-up call. This second scientific analysis gives us a more detailed look at how the negative impacts of climate change already in motion could create devastating conditions especially for those least able to adapt. The poorest could increasingly be hit the hardest.

For this report, we turned again to the scientists at the Potsdam Institute for Climate Impact Research and Climate Analytics. This time, we asked them to take a closer look at the tropics and prepare a climate forecast based on the best available evidence and supplemented with advanced computer simulations.

With a focus on Sub-Saharan Africa, South East Asia and South Asia, the report examines in greater detail the likely impacts for affected populations of present day, 2°C and 4°C warming on critical areas like agricultural production, water resources, coastal ecosystems and cities.

The result is a dramatic picture of a world of climate and weather extremes causing devastation and human suffering. In many cases, multiple threats of increasing extreme heat waves, sea-level rise, more severe storms, droughts and floods will have severe negative implications for the poorest and most vulnerable.

In Sub-Saharan Africa, significant crop yield reductions with 2°C warming are expected to have strong repercussions on food security, while rising temperatures could cause major loss of savanna grasslands threatening pastoral livelihoods. In South Asia, projected changes to the monsoon system and rising peak temperatures put water and food resources at severe risk. Energy security is threatened, too. While, across South East Asia, rural livelihoods are faced with mounting pressures as sea-level rises, tropical cyclones increase in intensity and important marine ecosystem services are lost as warming approaches 4°C.

Across all regions, the likely movement of impacted communities into urban areas could lead to ever higher numbers of people in informal settlements being exposed to heat waves, flooding, and diseases.

The case for resilience has never been stronger.

This report demands action. It reinforces the fact that climate change is a fundamental threat to economic development and the fight against poverty.

At the World Bank Group, we are concerned that unless the world takes bold action now, a disastrously warming planet threatens to put prosperity out of reach of millions and roll back decades of development.

In response we are stepping up our mitigation, adaptation, and disaster risk management work, and will increasingly look at all our business through a "climate lens."

But we know that our work alone is not enough. We need to support action by others to deliver bold ideas that will make the biggest difference.

I do not believe the poor are condemned to the future scientists envision in this report. In fact, I am convinced we can reduce poverty even in a world severely challenged by climate change.

We can help cities grow clean and climate resilient, develop climate smart agriculture practices, and find innovative ways to improve both energy efficiency and the performance of renewable energies. We can work with countries to roll back harmful fossil fuel subsidies and help put the policies in place that will eventually lead to a stable price on carbon.

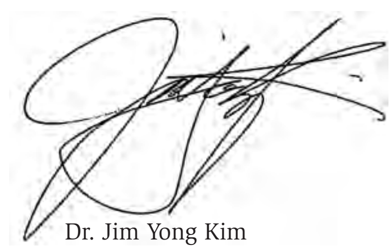
We are determined to work with countries to find solutions. But the science is clear. There can be no substitute for aggressive national emissions reduction targets.

Today, the burden of emissions reductions lies with a few large economies. Not all are clients of the World Bank Group, but all share a commitment to ending poverty.

I hope this report will help convince everyone that the benefits of strong, early action on climate change far outweigh the costs.

We face a future that is precarious because of our warming planet. We must meet these challenges with political will, intelligence, and innovation. If we do, I see a future that eases the hardships of others, allows the poor to climb out of poverty, and provides young and old alike with the possibilities of a better life.

Join us in our fight to make that future a reality. Our successes and failures in this fight will define our generation.



Dr. Jim Yong Kim
President, World Bank Group

Executive Summary

Executive Summary

This report focuses on the risks of climate change to development in Sub-Saharan Africa, South East Asia and South Asia. Building on the 2012 report, *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided*[2], this new scientific analysis examines the likely impacts of present day, 2°C and 4°C warming on agricultural production, water resources, and coastal vulnerability for affected populations. It finds many significant climate and development impacts are already being felt in some regions, and in some cases multiple threats of increasing extreme heat waves, sea-level rise, more severe storms, droughts and floods are expected to have further severe negative implications for the poorest. Climate-related extreme events could push households below the poverty trap threshold. High temperature extremes appear likely to affect yields of rice, wheat, maize and other important crops, adversely affecting food security. Promoting economic growth and the eradication of poverty and inequality will thus be an increasingly challenging task under future climate change. Immediate steps are needed to help countries adapt to the risks already locked in at current levels of 0.8°C warming, but with ambitious global action to drastically reduce greenhouse gas emissions, many of the worst projected climate impacts could still be avoided by holding warming below 2°C.

Scope of the Report

The first *Turn Down the Heat* report found that projections of global warming, sea-level rise, tropical cyclone intensity, aridity and drought are expected to be felt disproportionately in the developing countries around the equatorial regions relative to the countries at higher latitudes. This report extends this previous analysis by focusing on the risks of climate change to development in three critical regions of the world: Sub-Saharan Africa, South East Asia and South Asia.

While covering a range of sectors, this report focuses on how climate change impacts on agricultural production, water resources, coastal zone fisheries, and coastal safety are likely to increase, often significantly, as global warming climbs from present levels of 0.8°C up to 1.5°C, 2°C and 4°C above pre-industrial levels. This report illustrates the range of impacts that much of the developing world is already experiencing, and would be further exposed to, and it indicates how these risks and disruptions could be felt differently in other parts of the world. Figure 1 shows projections of temperature and sea-level rise impacts at 2°C and 4°C global warming.

The Global Picture

Scientific reviews published since the first *Turn Down the Heat* report indicate that recent greenhouse gas emissions and future emissions trends imply higher 21st century emission levels than previously projected. As a consequence, the likelihood of 4°C warming being reached or exceeded this century has increased, in the absence of near-term actions and further commitments to reduce emissions. This report reaffirms the International Energy Agency's 2012 assessment that in the absence of further mitigation action there is a 40 percent chance of warming exceeding 4°C by 2100 and a 10 percent chance of it exceeding 5°C in the same period.

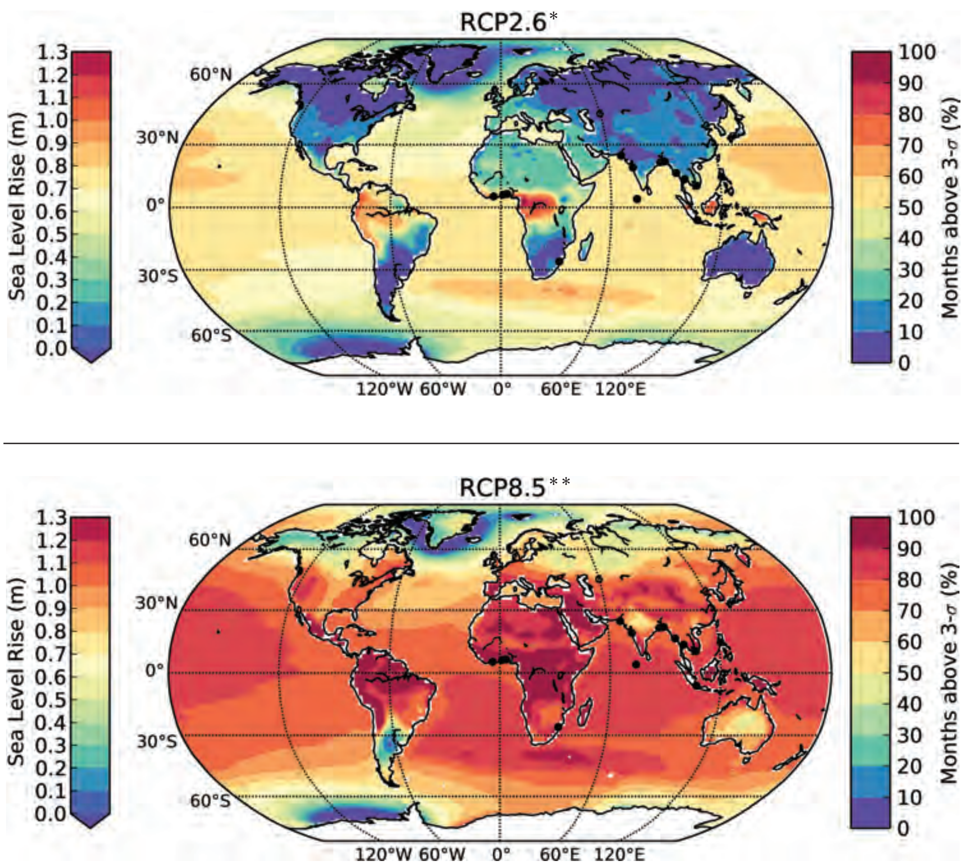
The 4°C scenario does not suggest that global mean temperatures would stabilize at this level; rather, emissions scenarios leading to such warming would very likely lead to further increases in both temperature and sea-level during the 22nd century. Furthermore,

2 *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided*, launched by the World Bank in November 2012.

even at present warming of 0.8°C above pre-industrial levels, the observed climate change impacts are serious and indicate how dramatically human activity can alter the natural environment upon which human life depends.

The projected climate changes and impacts are derived from a combined approach involving a range of climate models of varying complexity, including the state of the art Coupled Model Intercomparison Project Phase 5 (CMIP5), semi-empirical modeling, the "Simple Climate Model" (SCM), the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC; see Appendix 1) and a synthesis of peer reviewed literature.

Figure 1 Projected sea-level rise and northern-hemisphere summer heat events over land in a 2°C World (upper panel) and a 4°C World (lower panel)



Upper panel: In a 2°C world, sea-level rise is projected to be less than 70 cm (yellow over oceans) and the likelihood that a summer month's heat is unprecedented is less than 30 percent (blue/purple colors over land)

Lower panel: In a 4°C world, sea-level rise is projected to be more than 100 cm (orange over oceans) and the likelihood that a summer month's heat is unprecedented is greater than 60 percent (orange/red colors over land)

*RCP2.6, IPCC AR5 scenario aiming to limit the increase of global mean temperature to 2°C above the pre-industrial period.

**RCP8.5, IPCC AR5 scenario with no-climate-policy baseline and comparatively high greenhouse gas emissions. In this report, this scenario is referred to as a 4°C World above the pre-industrial period.

Key Findings Across the Regions

Among the key issues highlighted in this report are the early onset of climate impacts, uneven regional distribution of climate impacts, and interaction among impacts which accentuates cascade effects. For example:

1. **Unusual and unprecedented heat extremes[3]:** Expected to occur far more frequently and cover much greater land areas, both globally and in the three regions examined. For example, heat extremes in South East Asia are projected to increase substantially in the near term, and would have significant and adverse effects on humans and ecosystems under 2°C and 4°C warming.

2. **Rainfall regime changes and water availability:** Even without any climate change, population growth alone is expected to put pressure on water resources in many regions in the future. With projected climate change, however, pressure on water resources is expected to increase significantly.
    - Declines of 20 percent in water availability are projected for many regions under a 2°C warming and of 50 percent for some regions under 4°C warming. Limiting warming to 2°C would reduce the global population exposed to declining water availability to 20 percent.
    - South Asian populations are likely to be increasingly vulnerable to the greater variability of precipitation changes, in addition to the disturbances in the monsoon system and rising peak temperatures that could put water and food resources at severe risk.

3. **Agricultural yields and nutritional quality:** Crop production systems will be under increasing pressure to meet growing global demand in the future. Significant crop yield impacts are already being felt at 0.8°C warming.
    - While projections vary and are uncertain, clear risks emerge as yield reducing temperature thresholds for important crops have been observed, and crop yield improvements appear to have been offset or limited by observed warming (0.8°C) in many regions. There is also some empirical evidence that higher atmospheric levels of carbon dioxide (CO_2) could result in lower protein levels of some grain crops.
    - For the regions studied in this report, global warming above 1.5°C to 2°C increases the risk of reduced crop yields and production losses in Sub-Saharan Africa, South East Asia and South Asia. These impacts would have strong repercussions on food security and are likely to negatively influence economic growth and poverty reduction in the impacted regions.

4. **Terrestrial ecosystems:** Increased warming could bring about ecosystem shifts, fundamentally altering species compositions and even leading to the extinction of some species.
    - By the 2030s (with 1.2–1.3°C warming), some ecosystems in Africa, for example, are projected to experience maximum extreme temperatures well beyond their present range, with all African eco-regions exceeding this range by 2070 (2.1–2.7°C warming).
    - The distribution of species within savanna ecosystems are projected to shift from grasses to woody plants, as CO_2 fertilization favors the latter, although high temperatures and precipitation deficits might counter this effect. This shift will reduce available forage for livestock and stress pastoral systems and livelihoods.

5. **Sea-level rise:** Has been occurring more rapidly than previously projected and a rise of as much as 50 cm by the 2050s may be unavoidable as a result of past emissions: limiting warming to 2°C may limit global sea-level rise to about 70 cm by 2100.
    - As much as 100 cm sea-level rise may occur if emission increases continue and raise the global average temperature to 4°C by 2100 and higher levels thereafter. While the unexpectedly rapid rise over recent decades can now be explained by the accelerated loss of ice from the Greenland and Antarctic ice sheets, significant uncertainty remains as to the rate and scale of future sea-level rise.
    - The sea-level nearer to the equator is projected to be higher than the global mean of 100 cm at the end of the century. In South East Asia for example, sea-level rise is projected to be 10–15 percent higher than the global mean. Coupled with storm surges and tropical cyclones, this increase is projected to have devastating impacts on coastal systems.

6. **Marine ecosystems:** The combined effects of warming and ocean acidification are projected to cause major damages to coral reef systems and lead to losses in fish production, at least regionally.
    - Substantial losses of coral reefs are projected by the time warming reaches 1.5–2°C from both heat and ocean

[3] In this report, "unusual" and "unprecedented" heat extremes are defined by using thresholds based on the historical variability of the current local climate. The absolute level of the threshold thus depends on the natural year-to-year variability in the base period (1951–1980), which is captured by the standard deviation (sigma). Unusual heat extremes are defined as 3-sigma events. For a normal distribution, 3-sigma events have a return time of 740 years. The 2012 US heat wave and the 2010 Russian heat wave classify as 3-sigma events. Unprecedented heat extremes are defined as 5-sigma events. They have a return time of several million years. These events which have almost certainly never occurred to date are projected for the coming decades. See also Chapter 2 (Box 2.2).

acidification effects, with a majority of coral systems no longer viable at current locations. Most coral reefs appear unlikely to survive by the time 4°C warming is reached.

- Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units. Since the pH scale, like the Richter scale, is logarithmic, this change represents approximately a 30 percent increase in acidity. Future predictions indicate that ocean acidity will further increase as oceans continue to absorb carbon dioxide. Estimates of future carbon dioxide levels, based on business as usual emission scenarios, indicate that by the end of this century the surface waters of the ocean could be nearly 150 percent more acidic, resulting in pH levels that the oceans have not experienced for more than 20 million years.

Sub-Saharan Africa: Food Production at Risk

Sub-Saharan Africa is a rapidly developing region of over 800 million people, with 49 countries, and great ecological, climatic and cultural diversity. Its population for 2050 is projected to approach 1.5 billion people.

The region is confronted with a range of climate risks that could have far-reaching repercussions for Sub-Saharan Africa´s societies and economies in future. Even if warming is limited below 2°C, there are very substantial risks and projected damages, and as warming increases these are only expected to grow further. Sub-Saharan Africa is particularly dependent on agriculture for food, income, and employment, almost all of it rain-fed. Under 2°C warming, large regional risks to food production emerge; these risks would become stronger if adaptation measures are inadequate and the CO_2 fertilization effect is weak. Unprecedented heat extremes are projected over an increasing percentage of land area as warming goes from 2 to 4°C, resulting in significant changes in vegetative cover and species at risk of extinction. Heat and drought would also result in severe losses of livestock and associated impacts on rural communities.

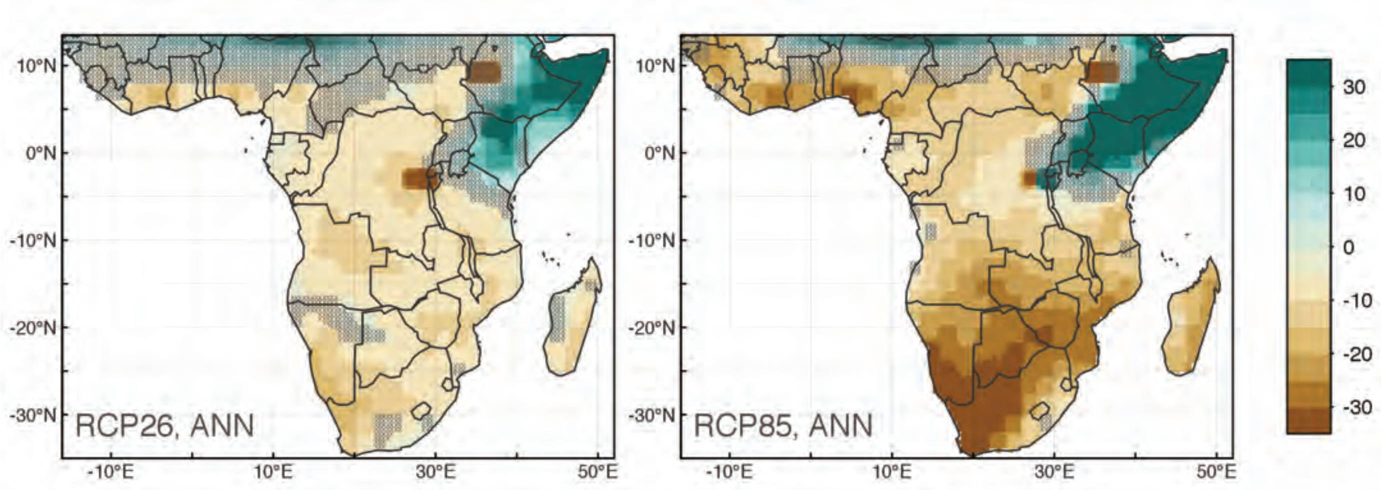
Likely Physical and Biophysical Impacts as a Function of Projected Climate Change

- **Water availability:** Under 2°C warming the existing differences in water availability across the region could become more pronounced.
  - In southern Africa, annual precipitation is projected to decrease by up to 30 percent under 4°C warming, and parts of southern and west Africa may see decreases in groundwater recharge rates of 50–70 percent. This is projected to lead to an overall increase in the risk of drought in southern Africa.
  - Strong warming and an ambiguous precipitation signal over central Africa is projected to increase drought risk there.
  - In the Horn of Africa and northern part of east Africa substantial disagreements exists between high-resolution regional and global climate models. Rainfall is projected by many global climate models to increase in the Horn of Africa and the northern part of east Africa, making these areas somewhat less dry. The increases are projected to occur during higher intensity rainfall periods, rather than evenly during the year, which increases the risk of floods. In contrast, high-resolution regional climate models project an increasing tendency towards drier conditions. Recent research showed that the 2011 Horn of Africa drought, particularly severe in Kenya and Somalia, is consistent with an increased probability of long-rains failure under the influence of anthropogenic climate change.
- **Projected aridity trends:** Aridity is projected to spread due to changes in temperature and precipitation, most notably in southern Africa (Figure 2). In a 4°C world, total hyper-arid and arid areas are projected to expand by 10 percent compared to the 1986–2005 period. Where aridity increases, crop yields are likely to decline as the growing season shortens.

Sector Based and Thematic Impacts

- **Agricultural production is expected to be affected in the near-term,** as warming shifts the climatic conditions that are conducive to current agricultural production. The annual average temperature is already above optimal values for wheat during the growing season over much of the Sub-Saharan Africa region and non-linear reductions in maize yield above certain temperature thresholds have been reported. Significant impacts are expected well before mid-century even for relatively low levels of warming. For example, a 1.5°C warming by the 2030s could lead to about 40 percent of present maize cropping areas being no longer suitable for current cultivars. In addition, under 1.5°C warming, significant negative impacts on sorghum suitability in the western Sahel and southern Africa are projected. Under warming of less than 2°C by the 2050s, total crop production could be reduced by 10 percent. For higher levels of warming there are indications that yields may decrease by around 15–20 percent across all crops and regions.
- **Crop diversification strategies will be increasingly important:** The study indicates that sequential cropping is the preferable option over single cropping systems under changing climatic conditions. Such crop diversification strategies have long been

Figure 2 Projected impact of climate change on the annual Aridity Index in Sub-Saharan Africa



Multi-model mean of the percentage change in the annual Aridity Index in a 2°C world (left) and a 4°C world (right) for Sub-Saharan Africa by 2071–2099 relative to 1951–1980. In non-hatched areas, at least 4/5 (80 percent) of models agree. In hatched areas, 2/5 (40 percent) of the models disagree. Note that a negative change corresponds to a shift to more arid conditions. Particular uncertainty remains for east Africa, where regional climate model projections tend to show an increase in precipitation, which would be associated with a decrease in the Aridity Index. A decrease in aridity does not necessarily imply more favorable conditions for agriculture or livestock, as it may be associated with increased flood risks.

practiced in Africa, providing a robust knowledge base and opportunity for scaled up approaches in this area.

- **Diversification options for agro-pastoral systems are likely to decline** (e.g. switching to silvopastoral systems, irrigated forage production, and mixed crop-livestock systems) as climate change reduces the carrying capacity of the land and livestock productivity. For example, pastoralists in southern Ethiopia lost nearly 50 percent of their cattle and about 40 percent of their sheep and goats to droughts between 1995 and 1997.
- **Regime shifts in African ecosystems are projected** and could result in the extent of savanna grasslands being reduced. By the time 3°C global warming is reached, savannas are projected to decrease to approximately one-seventh of total current land area, reducing the availability of forage for grazing animals. Projections indicate that species composition of local ecosystems might shift, and negatively impact the livelihood strategies of communities dependent on them.
- **Health is expected to be significantly affected by climate change.** Rates of undernourishment are already high, ranging between 15–65 percent, depending on sub-region. With warming of 1.2–1.9°C by 2050, the proportion of the population undernourished is projected to increase by 25–90 percent compared to the present. Other impacts expected to accompany climate change include mortality and morbidity due to extreme events such as extreme heat and flooding.
- **Climate change could exacerbate the existing development challenge of ensuring that the educational needs of all children are met.** Several factors that are expected to worsen with climate change, including undernourishment, childhood stunting, malaria and other diseases, can undermine childhood educational performance. The projected increase in extreme monthly temperatures within the next few decades may also have an adverse effect on learning conditions.

South East Asia: Coastal Zones and Productivity at Risk

South East Asia has seen strong economic growth and urbanization trends, but poverty and inequality remain significant challenges in the region. Its population for 2050 is projected to approach 759 million people with 65 percent of the population living in urban areas. In 2010, the population was 593 million people with 44 percent of the population living in urban areas.

South East Asia has a high and increasing exposure to slow onset impacts associated with rising sea-level, ocean warming and increasing acidification combined with sudden-onset impacts associated with tropical cyclones and rapidly increasingly heat extremes. When these impacts combine they are likely to have adverse effects on several sectors simultaneously, ultimately undermining coastal livelihoods in the region. The deltaic areas of South East Asia that have relatively high coastal population densities are particularly vulnerable to sea-level rise and the projected increase in tropical cyclones intensity.

Likely Physical and Biophysical Impacts as a Function of Projected Climate Change

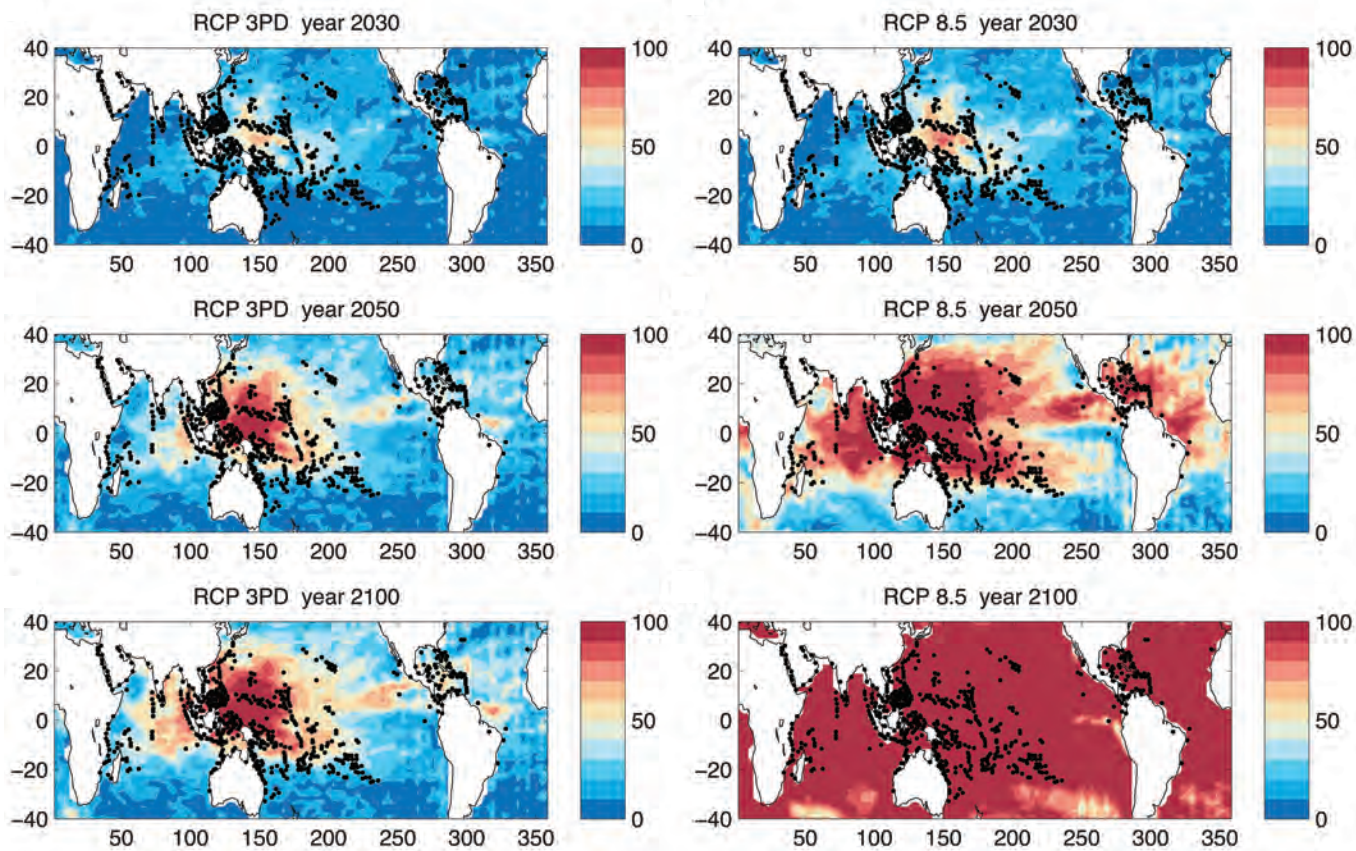
- **Heat extremes:** The South East Asian region is projected to see a strong increase in the near term in monthly heat extremes. Under 2°C global warming, heat extremes that are virtually absent at present will cover nearly 60–70 percent of total land area in summer, and unprecedented heat extremes up to 30–40 percent of land area in northern-hemisphere summer. With 4°C global warming, summer months that in today´s climate would be termed unprecedented, would be the new normal, affecting nearly 90 percent of the land area during the northern-hemisphere summer months.
- **Sea-level rise:** For the South East Asian coastlines, projections of sea-level rise by the end of the 21st century relative to 1986–2005 are generally 10–15 percent higher than the global mean. The analysis for Manila, Jakarta, Ho Chi Minh City, and Bangkok indicates that regional sea-level rise is likely to exceed 50 cm above current levels by about 2060, and 100 cm by 2090.
- **Tropical cyclones:** The intensity and maximum wind speed of tropical cyclones making landfall is projected to increase significantly for South East Asia; however, the total number of land-falling cyclones may reduce significantly. Damages may still rise as the greatest impacts are caused by the most intense storms. Extreme rainfall associated with tropical cyclones is expected to increase by up to a third reaching 50–80 mm per hour, indicating a higher level of flood risk in susceptible regions.
- **Saltwater intrusion:** A considerable increase of salinity intrusion is projected in coastal areas. For example, in the case of the Mahaka River region in Indonesia for a 100 cm sea-level rise by 2100, the land area affected by saltwater intrusion is expected to increase by 7–12 percent under 4°C warming.

Sector Based and Thematic Impacts

- **River deltas are expected to be impacted by projected sea-level rise and increases in tropical cyclone intensity,** along with land subsidence caused by human activities. These factors will increase the vulnerability of both rural and urban populations to risks including flooding, saltwater intrusion and coastal erosion. The three river deltas of the Mekong, Irrawaddy and Chao Phraya, all with significant land areas less than 2 m above sea-level, are particularly at risk. Aquaculture, agriculture, marine capture fisheries and tourism are the most exposed sectors to climate change impacts in these deltas.
- **Fisheries would be affected** as primary productivity in the world´s oceans is projected to decrease by up to 20 percent by 2100 relative to pre-industrial conditions. Fish in the Java Sea and the Gulf of Thailand are projected to be severely affected by increased water temperature and decreased oxygen levels, with very large reductions in average maximum body size by 2050. It is also projected that maximum catch potential in the southern Philippines could decrease by about 50 percent.
- **Aquaculture farms may be affected by several climate change stressors.** Increasing tropical cyclone intensity, salinity intrusion and rising temperatures may exceed the tolerance thresholds of regionally important farmed species. Aquaculture is a rapidly growing sector in South East Asia, which accounts for about 5 percent of Vietnam's GDP. As nearly 40 percent of dietary animal protein intake in South East Asia comes from fish, this sector also significantly contributes to food security in the region.
- **Coral reef loss and degradation would have severe impacts for marine fisheries and tourism.** Increasing sea surface temperatures have already led to major, damaging coral bleaching events in the last few decades.[4] Under 1.5°C warming and increasing ocean acidification, there is a high risk (50 percent probability) of annual bleaching events occurring as early as 2030 in the region (Figure 3). Projections indicate that all coral reefs in the South East Asia region are very likely to experience severe thermal stress by the year 2050, as well as chemical stress due to ocean acidification.

[4] Coral bleaching can be expected when a regional warm season maximum temperature is exceeded by 1°C for more than four weeks and bleaching becomes progressively worse at higher temperatures and/or longer periods over which the regional threshold temperature is exceeded. Whilst corals can survive a bleaching event they are subject to high mortality and take several years to recover. When bleaching events become too frequent or extreme coral reefs can fail to recover.

Figure 3 Projected impact of climate change on coral systems in South East Asia



Probability of a severe bleaching event (DHW>8) occurring during a given year under scenario RCP2.6 (approximately 2°C, left) and RCP8.5 (approximately 4°C, right). Source: Meissner et al. (2012).

- **Agricultural production, particularly for rice in the Mekong Delta, is vulnerable to sea-level rise.** The Mekong Delta produces around 50 percent of Vietnam's total agricultural production and contributes significantly to the country's rice exports. It has been estimated that a sea-level rise of 30 cm, which could occur as early as 2040, could result in the loss of about 12 percent of crop production due to inundation and salinity intrusion relative to current levels.
- **Coastal cities concentrate increasingly large populations and assets exposed to climate change risks** including increased tropical storm intensity, long-term sea-level rise and sudden-onset coastal flooding. Without adaptation, the area of Bangkok projected to be inundated due to flooding linked to extreme rainfall events and sea-level rise increases from around 40 percent under 15 cm sea-level rise above present (which could occur by the 2030s), to about 70 percent under an 88cm sea-level rise scenario (which could occur by the 2080s under 4°C warming). Further, the effects of heat extremes are particularly pronounced in urban areas due to the urban heat island effect and could result in high human mortality and morbidity rates in cities. High levels of growth of both urban populations and GDP further increase financial exposure to climate change impacts in these areas. The urban poor are particularly vulnerable to excessive heat and humidity stresses. In 2005, 41 percent of the urban population of Vietnam and 44 percent of that of the Philippines lived in informal settlements. Floods associated with sea-level rise and storm surges carry significant risks in informal settlements, where lack of drainage and damages to sanitation and water facilities are accompanied by health threats.

South Asia: Extremes of Water Scarcity and Excess

South Asia is home to a growing population of about 1.6 billion people, which is projected to rise to over 2.2 billion people by 2050. It has seen robust economic growth in recent years, yet poverty remains widespread, with the world's largest concentration of poor people residing in the region. The timely arrival of the summer monsoon, and its regularity, are critical for the rural economy and agriculture in South Asia.

In South Asia, climate change shocks to food production and seasonal water availability appear likely to confront populations with ongoing and multiple challenges to secure access to safe drinking water, sufficient water for irrigation and hydropower production, and adequate cooling capacity for thermal power production. Potential impact hotspots such as Bangladesh are projected to be confronted by increasing challenges from extreme river floods, more intense tropical cyclones, rising sea-level and very high temperatures. While the vulnerability of South Asia's large and poor populations can be expected to be reduced in the future by economic development and growth, climate projections indicate that high levels of local vulnerability are likely to remain and persist.

Many of the climate change impacts in the region, which appear quite severe with relatively modest warming of 1.5–2°C, pose a significant challenge to development. Major investments in infrastructure, flood defense, development of high temperature and drought resistant crop cultivars, and major improvements in sustainability practices, for example in relation to groundwater extraction would be needed to cope with the projected impacts under this level of warming.

Likely Physical and Biophysical Impacts as a Function of Projected Climate Change

- **Heat extremes:** Irrespective of future emission paths, in the next twenty years a several-fold increase in the frequency of unusually hot and extreme summer months is projected. A substantial increase in mortality is expected to be associated with such heat extremes and has been observed in the past.
- **Precipitation:** Climate change will impact precipitation with variations across spatial and temporal scales. Annual precipitation is projected to increase by up to 30 percent in a 4°C world, however projections also indicate that dry areas such as in the north west, a major food producing region, would get drier and presently wet areas, get wetter. The seasonal distribution of precipitation is expected to become amplified, with a decrease of up to 30 percent during the dry season and a 30 percent increase during the wet season under a 4°C world (Figure 4). The projections show large sub-regional variations, with precipitation increasing during the monsoon season for currently wet areas (south, northeast) and precipitation decreasing for currently dry months and areas (north, northwest), with larger uncertainties for those regions in other seasons.
- **Monsoon:** Significant increases in inter-annual and intra-seasonal variability of monsoon rainfall are to be expected. With global mean warming approaching 4°C, an increase in intra-seasonal variability in the Indian summer monsoon precipitation of approximately 10 percent is projected. Large uncertainty, however, remains about the fundamental behavior of the Indian summer monsoon under global warming.
- **Drought:** The projected increase in the seasonality of precipitation is associated with an increase in the number of dry days, leading to droughts that are amplified by continued warming, with adverse consequences for human lives. Droughts are expected to pose an increasing risk in parts of the region. Although drought projections are made difficult by uncertain precipitation projections and differing drought indicators, some regions emerge to be at particularly high risk. These include north-western India, Pakistan and Afghanistan. Over southern India, increasing wetness is projected with broad agreement between climate models.
- **Glacial loss, snow cover reductions and river flow:** Over the past century, most of the Himalayan glaciers have been retreating. Melting glaciers and loss of snow cover pose a significant risk to stable and reliable water resources. Major rivers, such as the Ganges, Indus and Brahmaputra, depend significantly on snow and glacial melt water, which makes them highly susceptible to climate change-induced glacier melt and reductions in snowfall. Well before 2°C warming, a rapid increase in the frequency of low snow years is projected with a consequent shift towards high winter and spring runoff with increased flooding risks, and substantial reductions in dry season flow, threatening agriculture. These risks are projected to become extreme by the time 4°C warming is reached.
- **Sea-level rise:** With South Asian coastlines located close to the equator, projections of local sea-level rise show a stronger increase compared to higher latitudes. Sea-level rise is projected to be approximately 100–115 cm in a 4°C world and 60–80 cm in a 2°C world by the end of the 21st century relative to 1986–2005, with the highest values expected for the Maldives.

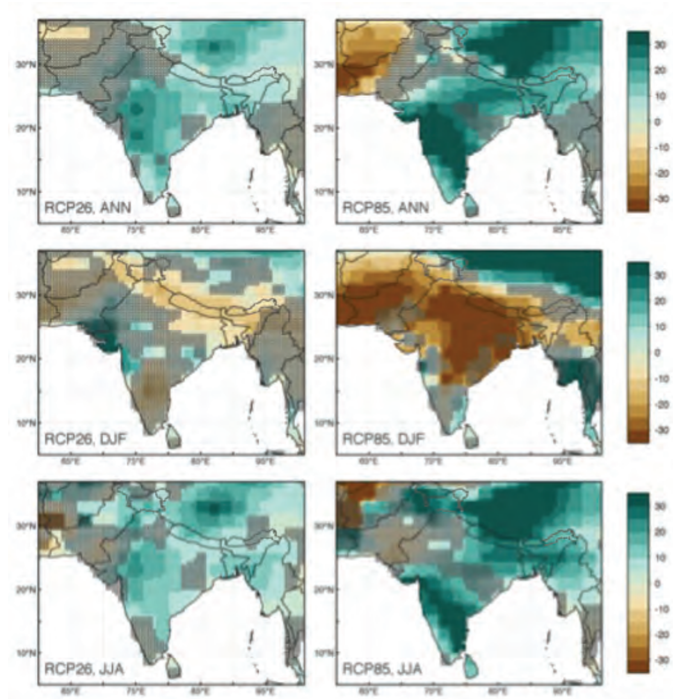
Sector Based and Thematic Impacts

- **Crop yields are vulnerable to a host of climate-related factors in the region,** including seasonal water scarcity, rising temperatures and salinity intrusion due to sea-level rise. Projections indicate an increasingly large and likely negative impact on crop yields with rising temperatures. The projected

CO_2 fertilization effect could help to offset some of the yield reduction due to temperature effects, but recent data shows that the protein content of grains may be reduced. For warming greater than 2°C, yield levels are projected to drop even with CO_2 fertilization.

- **Total crop production and per-capita calorie availability is projected to decrease significantly** with climate change. Without climate change, total crop production is projected to increase significantly by 60 percent in the region. Under a 2°C warming, by the 2050s, more than twice the imports might be required to meet per capita calorie demand when compared to a case without climate change. Decreasing food availability is related to significant health problems for affected populations, including childhood stunting, which is projected to increase by 35 percent compared to a scenario without climate change by 2050, with likely long-term consequences for populations in the region.
- **Water resources are already at risk in the densely populated countries of South Asia,** according to most methods for assessing this risk. For global mean warming approaching 4°C, a 10 percent increase in annual-mean monsoon intensity and a 15 percent increase in year-to-year variability of Indian summer monsoon precipitation is projected compared to normal levels during the first half of the 20th century. Taken together, these changes imply that an extreme wet monsoon that currently has a chance of occurring only once in 100 years is projected to occur every 10 years by the end of the century.
- **Deltaic regions and coastal cities are particularly exposed to compounding climate risks** resulting from the interacting effects of increased temperature, growing risks of river flooding, rising sea-level and increasingly intense tropical cyclones, posing a high risk to areas with the largest shares of poor populations. Under 2°C warming, Bangladesh emerges as an impact hotspot with sea-level rise causing threats to food production, livelihoods, urban areas and infrastructure. Increased river flooding combined with tropical cyclone surges also present significant risks. Human activity (building of irrigation dams, barrages, river embankments and diversions in the inland basins of rivers) can seriously exacerbate the risk of flooding downstream from extreme rainfall events higher up in river catchments.
- **Energy security is expected to come under increasing pressure from climate-related impacts to water resources.** The two dominant forms of power generation in the region are hydropower and thermal power generation (e.g., fossil fuel, nuclear and concentrated solar power), both of which can be undermined by inadequate water supply. Thermal power generation may also be affected through pressure placed on cooling systems due to increases in air and water temperatures.

Figure 4 Projected impact of climate change on annual, wet and dry season rainfall in South Asia



Multi-model mean of the percentage change in annual (top), dry-season (DJF, middle) and wet-season (JJA, bottom) precipitation for RCP2.6 (left) and RCP8.5 (right) for South Asia by 2071–2099 relative to 1951–1980. Hatched areas indicate uncertainty regions, with 2 out of 5 models disagreeing on the direction of change compared to the remaining 3 models.

Tipping Points, Cascading Impacts and Consequences for Human Development

This report shows that the three highly diverse regions of Sub-Saharan Africa, South East Asia, and South Asia that were analyzed are exposed to the adverse effects of climate change (Tables 1-3). Most of the impacts materialize at relatively low levels of warming, well before warming of 4°C above pre-industrial levels is reached.

Each of the regions is projected to experience a rising incidence of unprecedented heat extremes in the summer months by the mid-2020s, well before a warming of even 1.5°C. In fact, with temperatures at 0.8°C above pre-industrial levels, the last decade has seen extreme events taking high death tolls across all regions and causing wide-ranging damage to assets and agricultural production. As warming approaches 4°C, the severity of impacts is expected to grow with regions being affected differently (see Box 1).

Box 1: Regional Tipping Points, Cascading Impacts, and Development Implications

- **Sub-Saharan Africa's** food production systems are increasingly at risk from the impacts of climate change. Significant yield reductions already evident under 2°C warming are expected to have strong repercussions on food security and may negatively influence economic growth and poverty reduction in the region. Significant shifts in species composition and existing ecosystem boundaries could negatively impact pastoral livelihoods and the productivity of cropping systems and food security.
- **South East Asian** rural livelihoods are faced with mounting pressures as sea-level rises and important marine ecosystem services are expected to be lost as warming approaches 4°C. Coral systems are threatened with extinction and their loss would increase the vulnerability of coastlines to sea-level rise and storms. The displacement of impacted rural and coastal communities resulting from the loss of livelihood into urban areas could lead to ever higher numbers of people in informal settlements being exposed to multiple climate impacts, including heat waves, flooding, and disease.
- **South Asian** populations in large parts depend on the stability of the monsoon, which provides water resources for most of the agricultural production in the region. Disturbances to the monsoon system and rising peak temperatures put water and food resources at severe risk. Particularly in deltaic areas, populations are exposed to the multiple threats of increasing tropical cyclone intensity, sea-level rise, heat extremes and extreme precipitation. Such multiple impacts can have severe negative implications for poverty eradication in the region.

Tipping Points and Cascading Impacts

As temperatures continue to rise, there is an increased risk of critical thresholds being breached. At such "tipping points", elements of human or natural systems—such as crop yields, dry season irrigation systems, coral reefs, and savanna grasslands—are pushed beyond critical thresholds, leading to abrupt system changes and negative impacts on the goods and services they provide. Within the agricultural sector, observed high temperature sensitivity in some crops (e.g., maize), where substantial yield reductions occur when critical temperatures are exceeded, points to a plausible threshold risk in food production regionally. In a global context, warming induced pressure on food supplies could have far-reaching consequences.

Some major risks cannot yet be quantified adequately: For example, while large uncertainty remains, the monsoon has been identified as a potential tipping element of the Earth system. Physically plausible mechanisms for an abrupt change in the Indian monsoon towards a drier, lower rainfall state could precipitate a major crisis in the South Asian region.

Climate impacts can create a domino-effect and thereby ultimately affect human development. For example, decreased yields and lower nutritional value of crops could cascade throughout society by increasing the level of malnutrition and childhood stunting, causing adverse impacts on educational performance. These effects can persist into adulthood with long-term consequences for human capital that could substantially increase future development challenges. Most of the impacts presented in the regional analyses are not unique to these regions. For example, global warming impacts on coral reefs worldwide could have cascading impacts on local livelihoods, and tourism.

Multi-Sectoral Hotspots

Under 4°C warming, most of the world's population is likely to be affected by impacts occurring simultaneously in multiple sectors. Furthermore, these cascading impacts will likely not be confined to one region only; rather they are expected to have far-reaching repercussions across the globe. For example, impacts in the agricultural sector are expected to affect the global trade of food commodities, so that production shocks in one region can have wide-ranging consequences for populations in others. Thus, vulnerability could be greater than suggested by the sectoral analysis of the assessed regions due to the global interdependence, and impacts on populations are by no means limited to those that form the focus of this report. Many of the climatic risk factors are concentrated in the tropics. However, no region is immune to the impacts of climate change. In fact, under 4°C warming, most of the world´s population is likely to be affected by impacts occurring simultaneously in multiple sectors.

Results from the recent Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) were used to assess 'hotspots' where considerable impacts in one location occur concurrently in more than one sector (agriculture, water resources, ecosystems and health (malaria)). The proportion of the global population affected contemporaneously by multiple impacts increases significantly under higher levels of warming. Assuming fixed year-2000 population levels and distribution, the proportion of people exposed to multiple stressors across these sectors would increase by 20 percent under 2°C warming to more than 80 percent under 4°C warming above pre-industrial levels. This novel analysis[5] finds exposure hotspots to be the southern Amazon Basin, southern Europe, east Africa and the north of South Asia. The Amazon and

[5] Based on the first inter-sectoral climate model intercomparison, the first round of which was concluded in early 2013. Papers are in revision at the time of writing this report.

the East African highlands are particularly notable due to their exposure to three overlapping sectors. Small regions in Central America and West Africa are also affected.

Consequences for Development

Climate change is already undermining progress and prospects for development and threatens to deepen vulnerabilities and erode hard-won gains. Consequences are already being felt on every continent and in every sector. Species are being lost, lands are being inundated, and livelihoods are being threatened. More droughts, more floods, more strong storms, and more forest fires are taxing individuals, businesses and governments. Climate-related extreme events can push households below the poverty trap threshold, which could lead to greater rural-urban migration (see Box 2). Promoting economic growth and the eradication of poverty and inequality will thus be an increasingly challenging task under future climate change.

Actions must be taken to mitigate the pace of climate change and to adapt to the impacts already felt today. It will be impossible to lift the poorest on the planet out of poverty if climate change proceeds unchecked. Strong and decisive action must be taken to avoid a 4°C world—one that is unmanageable and laden with unprecedented heat waves and increased human suffering. It is not too late to hold warming near 2°C, and build resilience to temperatures and other climate impacts that are expected to still pose significant risks to agriculture, water resources, coastal infrastructure, and human health. A new momentum is needed. Dramatic technological change, steadfast and visionary political will, and international cooperation are required to change the trajectory of climate change and to protect people and ecosystems. The window for holding warming below 2°C and avoiding a 4°C world is closing rapidly, and the time to act is now.

Box 2: New Clusters of Vulnerability—Urban Areas

One of the common features that emerge from the regional analyses is of new clusters of vulnerability appearing in urban areas.

Urbanization rates are high in developing regions. For example, by 2050, it is projected that up to 56 percent of Sub-Saharan Africa's population will live in urban areas compared to 36 percent in 2010. Although the urbanization trend is driven by a host of factors, climate change is becoming an increasingly significant driver as it places rural and coastal livelihoods under mounting pressure.

While rural residents are expected to be exposed to a variety of climatic risk factors in each region, a number of factors define the particular vulnerability of urban dwellers, especially the urban poor, to climate change impacts. For example:

- Extreme heat is felt more acutely in cities where the built-up environments amplify temperatures.
- As many cities are located in coastal areas, they are often exposed to flooding and storm surges.
- Informal settlements concentrate large populations and often lack basic services, such as electricity, sanitation, health, infrastructure and durable housing. In such areas, people are highly exposed to extreme weather events, such as storms and flooding. For example, this situation is the case in Metro Manila in the Philippines, or Kolkata in India, where poor households are located in low-lying areas or wetlands that are particularly vulnerable to tidal and storm surges.
- Informal settlements often provide conditions particularly conducive to the transmission of vector and water borne diseases, such as cholera and malaria that are projected to become more prevalent with climate change.
- The urban poor have been identified as the group most vulnerable to increases in food prices following production shocks and declines that are projected under future climate change.

Climate change poses a particular threat to urban residents and at the same time is expected to further drive urbanization, ultimately placing more people at risk to the clusters of impacts outlined above. Urban planning and enhanced social protection measures, however, provide the opportunity to build more resilient communities in the face of climate change.

Table 1: Climate Impacts in Sub-Saharan Africa

RISK/IMPACT		0.8°C WARMING (Observed)	2°C WARMING (2040s)[1]	4°C WARMING (2080s)
Heat extremes	Unusual heat extremes	Virtually absent	About 45 percent of land in austral summer months (DJF)	>85 percent of land in austral summer months (DJF)
	Unprecedented heat extremes	Absent	About 15 percent of land in austral summer months (DJF)	>55 percent of land in austral summer months (DJF)
Drought		Increasing drought trends observed since 1950	Likely risk of severe drought in southern and central Africa, increased risk in west Africa, possible decrease in east Africa but west and east African projections are uncertain[2]	Likely risk of extreme drought in southern Africa and severe drought in central Africa, increased risk in west Africa, possible decrease in east Africa, but west and east African projections are uncertain[3]
Aridity		Increased drying[4]	Area of hyper-arid and arid regions grows by 3 percent	Area of hyper-arid and arid regions grows by 10 percent
Sea-level rise			70cm (60–80cm) by 2080–2100	105 (85–125cm) by 2080–2100
Ecosystem shifts			10–15 percent Sub-Saharan species at risk of extinction (assuming warming too rapid to allow migration of species) [5]	
Water availability (Run-off / Groundwater recharge)			50–70 percent decrease in recharge rates in western southern Africa and southern west Africa; 30 percent increase in recharge rate in some parts of eastern southern Africa and east Africa[6]	Increase in blue water availability in east Africa and parts of west Africa[7]; decrease in green water availability in most of Africa, except parts of east Africa
Crop yields, areas and food production	Crop growing areas		Projected climate over less than 15 percent of maize, millet and sorghum areas overlaps with present-day climate of crop-growing areas	Reduced length of growing period by more than 20 percent
	Crop production	Baseline of approximately 81 million tonnes in 2000, about 121 kg/capita	Without climate change, a large projected increase of total production to 192 million tonnes that fails to keep up with population growth, hence decrease to 111 kg/capita. With climate change smaller increase to 176 million tonnes and further decrease to 101 kg/capita[8]	
Yields	All crops		Increased crop losses and damages (maize, sorghum, wheat, millet, groundnut, cassava)[9]	
Livestock		Severe drought impacts on livestock[10]		10 percent increase in yields of *B. decumbens* (pasture species) in east and southern Africa; 4 percent and 6 percent decrease in central and west Africa[11]
Marine fisheries			Significant reduction in available protein; economic and job losses projected[12]	
Coastal areas				Approximately 18 million people flooded per year without adaptation[13]
Health and poverty			Undernourishment is expected to increase significantly, and those affected by moderate and severe stunting is expected to increase[14]	

Table 2: Climate Impacts in South East Asia

RISK/IMPACT		0.8°C WARMING (Observed)	2°C WARMING (2040s)[1]	4°C WARMING (2080s)
Heat extremes	Unusual heat extremes	Virtually absent	About 60–70 percent of land in boreal summer months (JJA)	>90 percent of land in boreal summer months (JJA)
	Unprecedented heat extremes	Absent	30–40 percent of land area during boreal summer months (JJA)[15]	>80 percent of land area during boreal summer months (JJA)
Tropical cyclones			Overall decrease in tropical cyclone frequency [16,17]; global increase in tropical cyclone rainfall; increasing frequency of category 5 storms[18]	Decreased number of tropical cyclones making landfall, but maximum wind velocity at the coast is projected to increase by about 6 percent for mainland South East Asia and about 9 percent for the Philippines
Sea-level rise			75cm (65–85cm) by 2080–2100	110 cm (85–130cm) by 2080–2100, lower around Bangkok by 5 cm
Sea-level rise impacts	Coastal erosion (loss of land)	For the south Hai Thinh commune in the Vietnamese Red River delta, about 34 percent (12 percent) of the increase of erosion rate between 1965 and 1995 (1995 and 2005) has been attributed to the direct effect of sea-level rise[19]		Mekong delta significant increase in coastal erosion[20]
	Population exposure	20 million people in South East Asian cities exposed to coastal flooding in 2005[21]		8.5 million people more than at present are projected to be exposed to coastal flooding by 2100 for global sea-level rise of 1 m[22]
	City exposure			Ho Chi Minh City—up to 60 percent of the built-up area projected to be exposed[23] to 1 m sea-level rise
Salinity intrusion		Mekong River delta (2005): Long An province's sugar cane production diminished by 5–10 percent; and significant rice in Duc Hoa district was destroyed[24]		Mahakam river region in Indonesia, increase in land area affected by 7–12 percent[25]
Ecosystem impacts (Coral reefs / coastal wetlands)			Nearly all coral reefs experience severe thermal stress under warming levels of 1.5–2°C	Coral reefs subject to severe bleaching events annually and coastal wetland area decrease[26]
Aquaculture			Estimations of the costs of adapting[27] aquaculture in South East Asia range from US$130–190 million per year from 2010–2050	
Marine fisheries			Decrease in maximum catch potential around the Philippines and Vietnam[28]	Markedly negative trend in bigeye tuna[29]
Health and poverty			The relative risk of diarrhoea is expected to increase[30]	
Tourism			Thailand, Indonesia, the Philippines, Myanmar and Cambodia among the most vulnerable tourism destinations[31]	

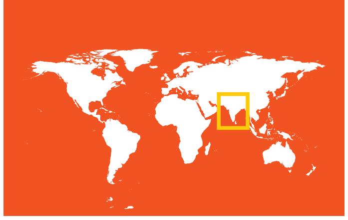


Table 3: Climate Impacts in South Asia

RISK/IMPACT		0.8°C WARMING (Observed)	2°C WARMING (2040s)[1]	4°C WARMING (2080s)
Heat extremes	Unusual heat extremes	Virtually absent	About 20 percent of land in boreal summer months (JJA)	>70 percent of land in boreal summer months (DJF)
	Unprecedented heat extremes	Absent	<5 percent of land in boreal summer months (JJA), except for the southernmost tip of India and Sri Lanka with 20-30 percent of summer months experiencing unprecedented heat	>40 percent of land in boreal summer months (DJF)
Drought				Increased drought over northwestern India, Pakistan, and Afghanistan[32]. Increased length of dry spells in eastern India and Bangladesh[33]
Sea-level rise			70cm (60–80cm) by 2080–2100[34]	105 cm (85–125cm) by 2080–2100, higher by 5–10 cm around Maldives, Kolkata
Tropical cyclones			Increasingly severe tropical cyclone impacts[35]	
Flooding			Increasingly severe flooding[36]	By 2070 approximately 1.5 million people are projected to be affected by coastal floods in the coastal cities of Bangladesh[37]
River run-off	Indus		Mean flow increase of about 65 percent[38]	
	Ganges		20 percent increase in run-off[39]	50 percent increase in run-off
	Brahmaputra		Very substantial reductions in late spring and summer flow[40]	
Water availability	Overall	In India, gross per capita water availability is projected to decline due to population growth[41]	Food water requirements in India projected to exceed green water availability[42, 43]. Around 3°C, it is very likely that per capita water availability in South Asia will decrease by more than 10 percent[44]	
	Groundwater recharge	Groundwater resources already under stress[45]	Climate change is projected to further aggravate groundwater stress	
Crop production			Overall crop production is projected to increase by only 12 percent above 2000 levels (instead of a 60 percent increase without climate change), leading to a one third decline in per capita crop production[46]	
Yields	All crops	Reduced rice yields, especially in rain-fed areas	Crop yield decreases regardless of potentially positive effects	
Health and poverty	Malnutrition and childhood stunting		With climate change percentages increase to 14.6 percent and about 5 percent respectively[47]	
	Malaria		Relative risk of malaria projected to increase by 5 percent in 2050[48]	
	Diarrheal disease		Relative risk of diarrheal disease increase by 1.4 percent compared to 2010 baseline by 2050	
	Heat waves vulnerability	New Delhi exhibits a 4 percent increase in heat-related mortality per 1°C above the local heat threshold of 20°C[49]	Most South Asian countries are likely to experience a very substantial increase in excess mortality due to heat stress by the 2090s[50]	

Endnotes

1 Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario, not in mitigation scenarios limiting warming to these levels, or below, since in that case the year of exceeding would always be 2100, or not at all.

2 This is the general picture from CMIP5 global climate models; however, significant uncertainty appears to remain. Observed drought trends (Lyon and DeWitt 2012) and attribution of the 2011 drought in part to human influence (Lott et al. 2013) leaves significant uncertainty as to whether the projected increased precipitation and reduced drought are robust (Tierney, Smerdon, Anchukaitis, and Seager 2013).

3 Dai (2012). CMIP5 models under RCP4.5 for drought changes 2050–99, warming of about 2.6°C above pre-industrial levels.

4 see Endnote 2.

5 Parry et al. (2007).

6 Temperature increase of 2.3°C and 2.1°C for the period 2041–2079 under SRES A2 and B2 (Döll, 2009).

7 Gerten et al. (2011).

8 Nelson et al. (2010).

9 Schlenker and Lobell (2010).

10 FAO (2008).

11 Thornton et al. (2011).

12 Lam, Cheung, Swartz, & Sumaila (2012). Applying the same method and scenario as (Cheung et al., 2010).

13 Hinkel et al. (2011) high SLR scenario 126 cm by 2100. In the no sea-level rise scenario, only accounting for delta subsidence and increased population, up to 9 million people would be affected.

14 Lloyd, Kovats, and Chalabi (2011) estimate the impact of climate-change-induced changes to crop productivity on undernourished and stunted children under five years of age by 2050 and find that the proportion of undernourished children is projected to increase by 52 percent, 116 percent, 82 percent, and 142 percent in central, east, south, and west Sub-Saharan Africa, respectively. The proportion of stunting among children is projected to increase by 1 percent (for moderate stunting) or 30 percent (for severe stunting); 9 percent or 55 percent; 23 percent or 55 percent; and 9 percent or 36 percent for central, east, south, and west Sub-Saharan Africa.

15 Beyond 5-sigma under 2°C warming by 2071–2099.

16 Held and Zhao (2011).

17 Murakami, Wang, et al. (2012).

18 Murakami, Wang, et al. (2012). Future (2075–99) projections SRES A1B scenario.

19 Duc, Nhuan, & Ngoi (2012).

20 1m sea-level rise by 2100 (Mackay and Russell, 2011).

21 Hanson et al. (2011).

22 Brecht et al. (2012). In this study, urban population fraction is held constant over the 21st century.

23 Storch & Downes (2011). In the absence of adaptation, the planned urban development for the year 2025 contributes to increase Ho Chi Minh City exposure to sea-level rise by 17 percent.

24 MoNRE (2010) states "Sea-level rise, impacts of high tide and low discharge in dry season contribute to deeper salinity intrusion. In 2005, deep intrusion (and more early than normal), high salinity and long-lasting salinization occurred frequently in Mekong Delta provinces."

25 Under 4°C warming and 1 m sea-level rise by 2100 (Mcleod, Hinkel et al., 2010).

26 Meissner, Lippmann, & Sen Gupta (2012).

27 US$190.7 million per year for the period 2010–2020 (Kam, Badjeck, Teh, Teh, & Tran, 2012); US$130 million per year for the period 2010–2050 (World Bank, 2010).

28 Maximum catch potential (Cheung et al., 2010).

29 Lehodey et al. (2010). In a 4°C world, conditions for larval spawning in the western Pacific are projected to have deteriorated due to increasing temperatures. Overall adult mortality is projected to increase, leading to a markedly negative trend in biomass by 2100.

30 Kolstad & Johansson (2011) derived a relationship between diarrhoea and warming based on earlier studies. (Scenario A1B).

31 Perch-Nielsen (2009). Assessment allows for adaptive capacity, exposure and sensitivity in a 2°C warming and 50cm SLR scenario for the period 2041–2070.

32 Dai (2012).

33 Sillmann & Kharin (2013).

34 For a scenario in which warming peaks above 1.5°C around the 2050s and drops below 1.5°C by 2100. Due to slow response of oceans and ice sheets the sea-level response is similar to a 2°C scenario during the 21st century, but deviates from it after 2100.

35 World Bank (2010a). Based on the assumption that landfall occurs during high-tide and that wind speed increases by 10 percent compared to cyclone Sidr.

36 Mirza (2010).

37 Brecht et al. (2012). In this study, urban population fraction is held constant over the 21st century.

38 Van Vliet et al. (2013), for warming of 2.3°C and of 3.2°C.

39 Fung, Lopez, & New (2011) SRES A1B warming of about 2.7°C above pre-industrial levels.

40 For the 2045 to 2065 period (global-mean warming of 2.3°C above pre-industrial) (Immerzeel, Van Beek, & Bierkens, 2010).

41 Bates, Kundzewicz, Wu, & Palutikof (2008); Gupta & Deshpande (2004).

42 When taking a total availability of water below 1300m^3 per capita per year as a benchmark for water amount required for a balanced diet.

43 Gornall et al. (2010). Consistent with increased precipitation during the wet season for the 2050s, with significantly higher flows in July, August and September than in 2000. Increase in overall mean annual soil moisture content is expected for 2050 with respect to 1970–2000, but the soil is also subject to drought conditions for an increased length of time.

44 Gerten et al. (2011). For a global warming of approximately 3°C above pre-industrial and the SRES A2 population scenario for 2080.

45 Rodell, Velicogna, & Famiglietti (2009). (Döll, 2009; Green et al., 2011).

46 Nelson et al. (2010).

47 Lloyd et al. (2011). South Asia by 2050 for a warming of approximately 2°C above pre-industrial (SRES A2).

48 Pandey (2010). 116,000 additional incidents, 1.8°C increase in SRES A2 scenario.

49 McMichael et al. (2008).

50 Takahashi, Honda, & Emori (2007), global mean warming for the 2090s of about 3.3°C above pre-industrial under the SRES A1B scenario and estimated an increase in the daily maximum temperature change over South Asia in the range of 2 to 3°C.

Abbreviations

°C	degrees Celsius
3-sigma events	Events that are three standard deviations outside the historical mean
5-sigma events	Events that are five standard deviations outside the historical mean
AI	Aridity Index
ANN	Annual
AOGCM	Atmosphere-Ocean General Circulation Model
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
CAT	Climate Action Tracker
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon Dioxide
DIVA	Dynamic Interactive Vulnerability Assessment
DJF	December January February
ECS	Equilibrium Climate Sensitivity
GCM	General Circulation Model
GDP	Gross Domestic Product
FPU	Food Productivity Units
GFDRR	Global Facility for Disaster Reduction and Recovery
IAM	Integrated Assessment Model
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISI-MIP	Inter-Sectoral Impact Model Intercomparison Project
JJA	June July August
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MGIC	Mountain Glaciers and Ice Caps
NH	Northern Hemisphere
OECD	Organisation for Economic Cooperation and Development
PDSI	Palmer Drought Severity Index
ppm	parts per million
RCP	Representative Concentration Pathway
SCM	Simple Climate Model
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
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNRCO	United Nations Resident Coordinator's Office
USAID	United States Agency for International Development
WBG	World Bank Group

Glossary

Aridity Index The Aridity Index (AI) is an indicator designed for identifying structurally "arid" regions, that is, regions with a long-term average precipitation deficit. AI is defined as total annual precipitation divided by potential evapotranspiration, with the latter a measure of the amount of water a representative crop type would need as a function of local conditions such as temperature, incoming radiation and wind speed, over a year to grow, which is a standardized measure of water demand.

Biome A biome is a large geographical area of distinct plant and animal groups, one of a limited set of major habitats, classified by climatic and predominant vegetative types. Biomes include, for example, grasslands, deserts, evergreen or deciduous forests, and tundra. Many different ecosystems exist within each broadly defined biome, which all share the limited range of climatic and environmental conditions within that biome.

C3/C4 plants refers to two types of photosynthetic biochemical "pathways". C3 plants include more than 85 percent of plants on Earth (e.g. most trees, wheat, rice, yams and potatoes) and respond well to moist conditions and to additional carbon dioxide in the atmosphere. C4 plants (for example savanna grasses, maize, sorghum, millet, sugarcane) are more efficient in water and energy use and outperform C3 plants in hot and dry conditions.

CAT The Climate Action Tracker (CAT) is an independent science-based assessment, which tracks the emission commitments and actions by individual countries. The estimates of future emissions deducted from this assessment serve to analyse warming scenarios that would result from current policy: (a) *CAT Reference BAU*: a lower reference 'business-as-usual' (BAU) scenario that includes existing climate policies, but not pledged emission reductions; and (b) CAT Current Pledges: a scenario additionally incorporating reductions currently pledged internationally by countries.

CMIP5 The Coupled Model Intercomparison Project Phase 5 (CMIP5) brought together 20 state-of-the-art GCM groups, which generated a large set of comparable climate-projections data. The project provided a framework for coordinated climate change experiments and includes simulations for assessment in the IPCC´s AR5.

CO_2 fertilization The CO_2 fertilization effect may increase the rate of photosynthesis mainly in C3 plants and increase water use efficiency, thereby producing increases in agricultural C3 crops in grain mass and/or number. This effect may to some extent offset the negative impacts of climate change, although grain protein content may decline. Long-term effects are uncertain as they heavily depend on a potential physiological long-term acclimation to elevated CO_2, as well as on other limiting factors including soil nutrients, water and light.

GCM A General Circulation Model is the most advanced type of climate model used for projecting changes in climate due to increasing greenhouse-gas concentrations, aerosols and external forcings like changes in solar activity and volcanic eruptions. These models contain numerical representations of physical processes in the atmosphere, ocean, cryosphere and land surface on a global three-dimensional grid, with the current generation of GCMs having a typical horizontal resolution of 100 to 300 km.

GDP (Gross Domestic Product) is the sum of the gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without deductions for depreciation of fabricated assets or for depletion and degradation of natural resources.

GDP (PPP) per capita is GDP on a purchasing power parity basis divided by population. Please note: Whereas PPP estimates for OECD countries are quite reliable, PPP estimates for developing countries are often rough approximations.

Hyper-aridity Land areas with very low Aridity Index (AI), generally coinciding with the great deserts. There is no universally standardized value for hyper-aridity, and values between 0 and 0.05 are classified in this report as hyper-arid.

IPCC AR4, AR5 The Intergovernmental Panel on Climate Change (IPCC) is the leading body of global climate change assessments. It comprises hundreds of leading scientists worldwide and on a regular basis publishes assessment reports which give a comprehensive overview over the most recent scientific, technical and socio-economic information on climate change and its implications. The Fourth Assessment Report (AR4) was published in 2007. The upcoming Fifth Assessment Report (AR5) will be completed in 2013/2014.

ISI-MIP The first Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) is a community-driven modeling effort which provides cross-sectoral global impact assessments, based on the newly developed climate [Representative Concentration Pathways (RCPs)] and socio-economic scenarios. More than 30 models across five sectors (agriculture, water resources, biomes, health and infrastructure) participated in this modeling exercise.

MAGICC Carbon-cycle/climate model of "reduced complexity," here applied in a probabilistic set-up to provide "best-guess" global-mean warming projections, with uncertainty ranges related to the uncertainties in carbon-cycle, climate system and climate sensitivity. The model is constrained by historical observations of hemispheric land/ocean temperatures and historical estimates for ocean heat-uptake, reliably determines the atmospheric burden of CO_2 concentrations compared to high-complexity carbon-cycle models and is also able to project global-mean near-surface warming in line with estimates made by GCMs.

Pre-industrial levels (what it means to have present 0.8°C warming) The instrumental temperature records show that the 20-year average of global-mean near-surface air temperature in 1986–2005 was about 0.6°C higher than the average over 1851–1879. There are, however, considerable year-to-year variations and uncertainties in data. In addition the 20-year average warming over 1986–2005 is not necessarily representative of present-day warming. Fitting a linear trend over the period 1901 to 2010 gives a warming of 0.8°C since "early industrialization." Global-mean near-surface air temperatures in the instrumental records of surface-air temperature have been assembled dating back to about 1850. The number of measurement stations in the early years is small and increases rapidly with time. Industrialization was well on its way by 1850 and 1900, which implies using 1851–1879 as a base period, or 1901 as a start for linear trend analysis might lead to an underestimate of current and future warming, but global greenhouse-gas emissions at the end of the 19^{th} century were still small and uncertainties in temperature reconstructions before this time are considerably larger.

RCP Representative Concentration Pathways (RCPs) are based on carefully selected scenarios for 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 socioeconomic or emissions scenarios, and instead can result from different combinations of economic, technological, demographic, policy, and institutional futures.

RCP2.6 RCP2.6 refers to a scenario which is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2°C above the pre-industrial period. This emissions path is used by many studies that are being assessed for the IPCC´s Fifth Assessment Report and is the underlying low emissions scenario for impacts assessed in other parts of this report. In this report we refer to the RCP2.6 as a 2°C World.

RCP8.5 RCP8.5 refers to a scenario with no-climate-policy baseline with comparatively high greenhouse gas emissions which is used by many studies that are being assessed for the upcoming IPCC Fifth Assessment Report (AR5). This scenario is also the underlying high emissions scenario for impacts assessed in other parts of this report. In this report we refer to the RCP8.5 as a 4°C World above the pre-industrial period.

Severe & extreme Indicating uncommon (negative) consequences. These terms are often associated with an additional qualifier like "unusual" or "unprecedented" that has a specific quantified meaning (see "Unusual & unprecedented").

SRES 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. The SRES study includes consideration of 40 different scenarios, each making different assumptions about the driving forces determining future greenhouse gas emissions. Scenarios are grouped into four families, corresponding to a wide range of high and low emission scenarios.

SREX In 2012 the IPCC published a special report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). The report provides an assessment of the physical as well as social factors shaping vulnerability to climate-related disasters and gives an overview of the potential for effective disaster risk management.

Unusual & unprecedented In this report, unusual and unprecedented heat extremes are defined using thresholds based on the historical variability of the current local climate. The absolute level of the threshold thus depends on the natural year-to-year variability in the base period (1951–1980), which is captured by the standard deviation (sigma). Unusual heat extremes are defined as 3-sigma events. For a normal distribution, 3-sigma events have a return time of 740 years. The 2012 U.S. heat wave and the 2010 Russian heat wave classify as 3-sigma and thus unusual events. Unprecedented heat extremes are defined as 5-sigma events. They 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 from the ones expected in a normal distribution. Nevertheless, 3-sigma events are extremely unlikely and 5-sigma events have almost certainly never occurred.

Chapter 1

Introduction

A 4°C world by the end of the century remains a real risk. The updated United Nations Environment Programme (UNEP) Emissions Gap Report, released at the Climate Convention Conference in Doha in December 2012, found that present emission trends and pledges are consistent with emission pathways that reach warming in the range of 3.5°C to 5°C by 2100 (UNEP 2012) (Box 1.1). This outlook is higher than that of *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided,*[6] which estimated that current pledges, if fully implemented, would likely lead to warming exceeding 3°C before 2100. Several lines of evidence indicate that emissions are likely to be higher than those that would result from present pledges, as estimated in *Turn Down the Heat* in 2012. Apart from the 2012 UNEP Gap report, the Turn Down The Heat report includes recent estimates derived from a large set of energy sector economic models. Estimates of present trends and policies come from the International Energy Agency (IEA) *World Energy Outlook 2012* report. Based on the IEA current policy scenario, in the absence of further mitigation action, a 4°C warming above pre-industrial levels within this century is a real possibility with a 40 percent chance of warming exceeding 4°C by 2100 and a 10 percent chance of it exceeding 5°C (International Energy Agency 2012).[7]

One of the key conclusions of *Turn Down the Heat* was that the impacts of climate change would not be evenly distributed (Box 1.2). In a 4°C world, climate change is expected to affect societies across the globe. As is illustrated in Figure 1.1, temperatures do not increase uniformly relative to present-day conditions and sea levels do not rise evenly. Impacts are both distributed and felt disproportionately toward the tropics and among the poor.

This report provides a better understanding of the distribution of impacts in a 4°C world by looking at how different regions—Sub-Saharan Africa, South East Asia, and South Asia—are projected to experience climate change. While such climate events as heat waves are expected to occur across the globe, geographic and socioeconomic conditions produce particular vulnerabilities in different regions. Vulnerability here is broadly understood as a function of exposure to climate change and its impacts and the extent to which populations are able to cope with these impacts.[8]

Specific climate impacts form the basis of each regional assessment:

- Sub-Saharan Africa heavily relies on agriculture as a source of food and income. Ninety-seven percent of agricultural production is currently rainfed. This leaves the region highly vulnerable to the consequences of changes in precipitation patterns, temperature, and atmospheric CO_2 concentration for agricultural production.
- South East Asia, with its archipelagic landscape and a large proportion of the population living in low-lying deltaic and coastal regions (where a number of large cities are located), is particularly vulnerable to the impacts of sea-level rise. South East Asia is also home to highly bio-diverse marine wildlife and many coastal livelihoods depend on the goods

6 Hereafter referred to as *Turn Down the Heat*.

7 This report analyzes a range of scenarios that includes a recent IEA analysis, as well as current and planned national climate policies, and makes projections of warming that are quantified in Chapter 2. In contrast, the previous report (World Bank 2012) used an illustrative "policy" scenario that has relatively ambitious proposed reductions by individual countries for 2020, as well as for 2050, and thus suggests that there is only a 20 percent likelihood of exceeding 4°C by 2100.

8 IPCC (2007) defines vulnerability as "the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change".

Box 1.1 Definition of Warming Levels and Base Period in this Report

This report and the previous *Turn Down the Heat* report referenced future global-warming levels against the pre-industrial period. A "2°C World" and a "4°C World" is defined as the increase in global-mean near-surface air temperature above pre-industrial climate by the end of the 21st century. This approach is customary in the international policy debate, including the UNFCCC, as well as in scientific assessments closely related to this debate, such as those produced by the IEA (World Energy Outlooks) and UNEP (UNEP Emissions Gap Reports). By contrast, IPCC's Fourth Assessment Report expressed warming projections relative to an increase in the mean over the period 1980–1999, while the upcoming Fifth Assessment Report (AR5) uses 1986–2005 as a base period. Given observed warming from pre-industrial levels to 1986–2005 of about 0.7°C, all projections in AR5 would thus be around 0.7°C "lower" than those shown in this report for the same emission scenarios and impact levels. In other words a "4°C world" scenario in 2100 in this report would be a world 3.3°C warmer than 1986–2005 in the AR5. See further details in Appendix 1.

In addition, while projections in this report often refer to projections around the year 2100, it is also common to refer to averages for the 20 years around 2090, as is often done in many impact assessments and in the IPCC. In this case a 4°C scenario in 2100 would be about a 3.5°C scenario above pre-industrial for the 2080–2099 period, given the projected rate of warming in such scenarios of 0.5°C/decade by the end of the century. This scenario would thus be only 2.8°C warmer than the 1986–2005 base period by the 2080–2099 period yet it would be identical with the "4°C world" scenario in this report. While different base and averaging periods are used to describe the climate changes resulting from the same underlying emissions scenarios, it is important to realize that the concentration of carbon dioxide and other greenhouse gases and aerosols in a given year or period are not changed, nor is the nature of the impacts described.

Box 1.2 Extreme Events 2012–2013

During the last year, extreme events have been witnessed across the globe. A particular high-temperature event at a particular place cannot be attributed one-on-one to anthropogenic climate change, but the likelihood of such events is projected to increase, in particular in the tropics where local year-to-year variations are smaller. Although below-average temperatures were recorded over Alaska and northern and eastern Australia, high temperatures occurred over North America, southern Europe, most of Asia, and parts of northern Africa. Across the United States, the number of broken temperature records in 2012 doubled compared to the August 2011 heat wave. Extremes in other climate variables can occur in tandem with heat events, such as the extreme drought accompanying this year's heat wave in the US, which extended into northern Mexico. The drought in northern Brazil was the worst in 50 years.

By contrast, countries in Africa, including Tanzania, Nigeria, Niger, and Chad, experienced severe flooding because of an unusually active African monsoon season. Devastating floods impacted Pakistan as well, with more than 5 million people and 400,000 hectares of crops estimated to have been affected. Even in some areas of above-average warming, early in the year several unusually cold spells were accompanied by heavy snowfall, including in northeast China and Mongolia. 2012 saw a record loss of Arctic sea ice.

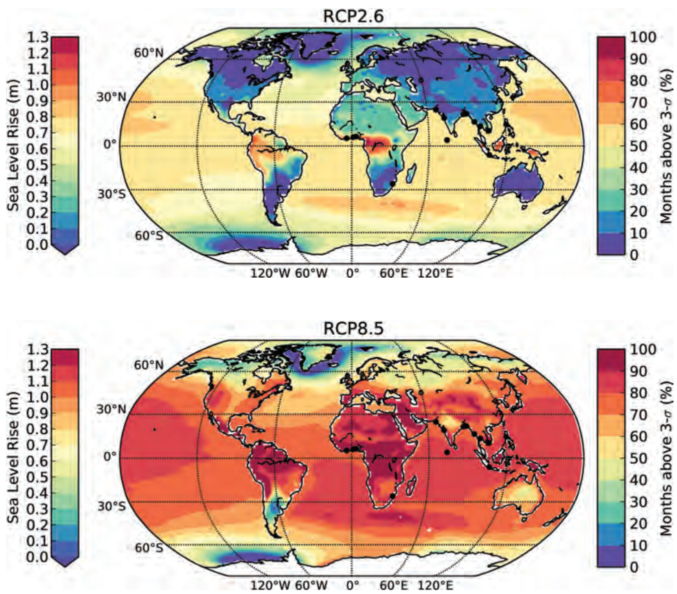
The year 2012 was also an active year for tropical cyclones, with Hurricane Sandy the most noteworthy because of the high number of lives lost and infrastructure damaged in the Caribbean and in the United States. Typhoon Sanba in East Asia was the strongest cyclone globally in 2012; it affected thousands of people in the Philippines, Japan, and the korean Peninsula.

Australia saw a severe heat wave during the Australian summer, with record temperatures and associated severe bush fires followed by extreme rainfall and flooding. Records were continuously broken, with the hottest summer on record and the hottest seven consecutive days ever recorded in Australia. A recent report by the Australian Climate Commission (Australian Climate Comission 2013) attributes the severity and intensity of recorded temperatures and extreme events to anthropogenic climate change. However, no studies have been published attributing the other extreme events listed above to anthropogenic climate change.

and services offered by these ecosystems. The impacts of sea-level rise and changes in marine conditions, therefore, are the focus for South East Asia, with the Philippines and Vietnam serving as examples for maritime and mainland regions respectively.

- In South Asia, populations rely on seasonal monsoon rainfall to meet a variety of needs, including human consumption and irrigation. Agricultural production, an income source for approximately 70 percent of the population, in most part depends on groundwater resources being replenished by monsoon rains. Snow and glacial melt in the mountain ranges are the primary source of upstream freshwater for many river basins and play an important role in providing freshwater for the region. The variability of monsoon rainfall is expected to increase and the supply of water from melting mountain glaciers is expected to decline in the long term. South Asia is, therefore, particularly vulnerable to impacts on freshwater resources and their consequences.

Figure 1.1: Projected sea-level rise and northern-hemisphere summer heat events over land in a 2°C World (upper panel) and a 4°C World (lower panel)[a]



Unusual heat extremes (3-σ, or sigma) refer to temperatures exceeding the historical ("normal") mean recorded in the respective area by 3 standard deviations. Such heat extremes are highly unlikely in a stable climate: In a normal distribution based on climate conditions from 1951–80, events warmer than 3-sigma from the mean occur on average once in 740 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 from the ones expected in a normal distribution. Nevertheless, 3-sigma heat extremes are extremely unlikely without climate change. The US heat wave 2012 and the Russian heat wave 2010 classify as unusual heat extremes, that is, 3-sigma events. However, extreme heat events are more likely in future under climate change as the normal distribution shifts: for example, a value of 50 percent in Figure 1.1 indicates that heat extremes of 3-sigma or greater have a probability of occurring once every two months.

[a] Following (Hansen, Sato, & Ruedy, 2012), the period 1951–80 is defined as a baseline for changes in heat extremes. This baseline has the advantage of having been a period of relatively stable global temperature, prior to rapid global warming, and of providing sufficient observational measurements such that the climatology is well defined. The baseline for sea-level rise projections is the period 1986–2005.

This new report builds on the scientific background of the earlier report and zooms in on the three focus regions to examine how they are impacted by warming up to and including an increase in global mean temperature of 4°C above pre-industrial levels in the 21st century. The projections on changes in temperature, heat extremes, precipitation, and aridity are based on original analysis of Coupled Model Intercomparison Project Phase 5 (CMIP5) Global Circulation Model (GCM) output and those of sea-level rise on CMIP5 GCMs, semi-empirical modeling, and the "simple climate model," the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC; see also Appendix 1 for details) (Box 1.3). The sectoral analysis for the three regions is based on existing literature.

The report is structured as follows. Chapter 2 explores the probability of warming reaching 4°C above pre-industrial levels and discusses the possibility of significantly limiting global mean warming to below 2°C. It further provides an update on global climate impact projections for different levels of global warming. The updated analysis of the risks at the global level further complements the 2012 report and provides a framework for the regional case studies. Chapters 3 to 5 present analysis of climate impacts for the three regions: Sub-Saharan Africa, South East Asia, and South Asia.

The focus of the regional chapters is the nature of the impacts and the associated risks posed to the populations of the regions. The possibility of adaptation and its capacity to minimize the vulnerability to the risks accompanying climate change is not assessed in this report. Rather, this report sets out to provide an overview of the challenges that human populations are expected to face under future projected climate change due to impacts in selected sectors. Some dimensions of vulnerability of populations are not covered here, such as gender and the ways in which climate change impacts may be felt differently by men and women. Finally, while many of the findings presented in this report may prove relevant to development policy in these regions, this report is not intended to be prescriptive; rather, it is intended to paint a picture of some of the challenges looming in a 4°C world.

In this report, as in the previous one, "a 4°C world" is used as shorthand for warming reaching 4°C above pre-industrial levels by the end of the century. It is important to note that this does not imply a stabilization of temperatures nor that the magnitude of impacts is expected to peak at this level. 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 and associated higher risk of thresholds in the climate system being crossed, 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; International Energy Agency 2012; Schaeffer and van Vuuren 2012). For a 2°C warming above pre-industrial levels, stabilization at this level by 2100 and beyond is assumed in the projections, although climate impacts would persist for decades, if not centuries to come: sea-level rise, for example, would likely reach 2.7 meters above 2000 levels by 2300 (Schaeffer, Hare, Rahmstorf, and Vermeer 2012).

Populations across the world are already experiencing the first of these challenges at the present level of warming of 0.8°C above pre-industrial levels. As this report shows, further major challenges are expected long before the end of the century in both 2°C and a 4°C warming scenarios. Urgent action is thus needed to prevent those impacts that are still avoidable and to adapt to those that are already being felt and will continue to be felt for decades to come. For many systems, climate change exacerbates other non-climatic stressors such as land degradation or marine pollution. Even without climate change, human support systems are likely to be placed under further pressure as populations grow.

Box 1.3 Climate Change Projections, Impacts, and Uncertainty

In this report the projections of future climate change and its plausible consequences are based, necessarily, on modeling exercises. The results discussed take into account the inherent uncertainties of model projections. The analysis of temperature and precipitation changes, as well as heat extremes and aridity, is based on state-of-the-art Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models. Precipitation data was bias-corrected, such that it reproduces the historical mean and variation in precipitation. Results are reported as the mean of the CMIP5 models and where relevant a measure of agreement/disagreement of models on the sign of changes is indicated. The projections might therefore provide more robust and consistent trends than a random selection of model results, even at regional scales. Results reported from the literature are, in most cases, based on climate impact models and are likewise faced with issues about uncertainty. As with the case for climate projections, there are limitations on the precision with which conclusions can be drawn. For this reason, conclusions are drawn where possible, from multiple lines of evidence across a range of methods, models and data sources including the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC AR4) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX).

Chapter 2

The Global Picture

Global projections of temperature, heat extremes, and precipitation changes, as well as projections of sea-level rise, are presented in this chapter. Drawing on the latest data from the first inter-sectoral impact model intercomparison project (ISI-MIP), a number of sectoral impacts are updated. These include the risk of biome shifts and diminished water availability. The final section of this chapter presents an initial evaluation of hotspots where impacts in multiple sectors occur and places this evaluation in the context of the most recent literature for each sector.

In this report, the low-emissions scenario RCP2.6, a scenario which is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2°C (Van Vuuren et al. 2011), is used as a proxy for a 2°C world. The high-emissions scenario RCP8.5 is used as proxy for a 4°C world. These emissions paths are used by many studies that are being assessed for the Fifth Assessment Report (AR5) of the IPCC. These are the underlying projections of temperature and precipitation changes, as well as those on heat extremes and sea-level rise in this chapter and the regional parts of this report.

Observed Changes and Climate Sensitivity

Observations show that warming during the last decade has been slower than earlier decades (Figure 2.1). This is likely the result of a temporary slowdown or "hiatus" in global warming and a natural phenomenon (Easterling and Wehner 2009; Meehl et al. 2011). Slower and faster decades of warming occur regularly superimposed on an overall warming trend (Foster and Rahmstorf 2011). Evaluating all major influences that determine global mean temperature changes, Foster and Rahmstorf (2011) show that over the past decade the underlying trend in warming continued unabated, if one filters out the effects of ENSO, solar variations, and volcanic activity.[9]

One of the basic tests of a model is whether it is able to reproduce observed changes: recent analysis shows clearly that in both the IPCC's Third and Fourth Assessment Reports climate model warming projections match observations very well. (Figure 2.2) (Foster and Rahmstorf (2011).

The recent slower warming has led to media attention that suggests the sensitivity of the climate system to anthropogenic emissions might be smaller than estimated previously.[10] However, an overall review of climate sensitivity that takes into account multiple lines of evidence, including methodologies that result in low climate sensitivity estimates and other studies that show instead a larger estimate of sensitivity (Knutti and Hegerl 2008), results in values for climate sensitivity consistent with IPCC's AR4: "most likely" around 3°C, a 90 percent probability of larger than 1.5°C, "very likely" in the range of 2–4.5°C; values substantially higher than 4.5°C cannot be ruled out.

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9 This can be explained by natural external forcings, like those of solar and volcanic origin, and physical mechanisms within the climate system itself, with a large role played by the El Niño/La Niña-Southern-Oscillation (ENSO), a pattern of natural fluctuations in heat transfer between the ocean's surface and deeper layers. If such fluctuations are filtered out of the observations, a robust continued warming signal emerges over the past three decades. It is this signal that should be compared to the average warming of climate models, because the latter exhibit the same upswings and downswings of warming as the observational signal, but at different times, due to the natural chaotic nature of the climate system. Taking an average from many models filters out these random variations; hence, this must also be done with observational data sets before comparing with model results.

10 Recently, one such study that resulted in a value around 2°C, much like other studies using comparable methods and included in IPCC's meta-analysis, received media attention (see Box 2.1). http://www.forskningsradet.no/en/Newsarticle/Global_warming_less_extreme_than_feared/1253983344535/p1177315753918.

Box 2.1 Climate Sensitivity

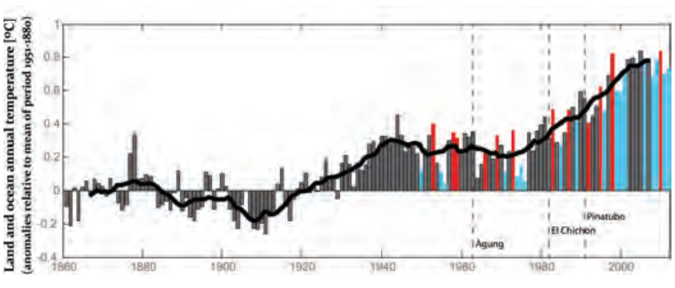
Climate sensitivity (more specifically equilibrium climate sensitivity [ECS]) is defined as the change in global mean surface temperature at equilibrium following a doubling of atmospheric carbon dioxide (CO_2) concentrations. It is a measure of the long-term response of the climate system to a sustained increase in radiative[a] forcing.

Research efforts are continuing to better constrain ECS. Recent studies indicate that both the high end (Fasullo and Trenberth 2012) and the low end (Amundsen and Lie 2012) cannot be excluded, while the current range of results for the most advanced climate models (Andrews et al. 2012) and reconstructions of climatic records over the last 65 million years (E. J. Rohling et al. 2012) confirm the "likely" range given in the AR4 assessment.

The probabilistic global mean climate projections in this section consider the AR4 assessment as still being representative of our current understanding of the ECS and use an intermediate (that is, neither the most optimistic nor the most conservative) interpretation of it (Rogelj et al. 2012b). Note that in projections from more complex models (such as the CMIP5 models analyzed for temperature, precipitation, and aridity projections in this report), climate sensitivity is not a predefined model parameter but is emerging from all the feedback processes included in the model.

[a] In the context of climate change, the IPCC AR4 defines this as "a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism."

Figure 2.1: Time series from the instrumental measurement record of global-mean annual-mean surface-air temperature anomalies relative to a 1851–80 reference period



Solid black lines represent the 11-year running mean. Vertical dashed lines indicate three of the largest recent volcanic eruptions. Coloring of annual-mean temperature bars from 1950 onward indicate "neutral years" (grey), as opposed to warming El Niño (red) and cooling La Niña ENSO events (blue).

Sources: Jones et al. (2012); Morice et al. (2012) for temperature record, ENSO years from NOAA (adapted from NOAA - http://www.ncdc.noaa.gov/sotc/global/2012/13).

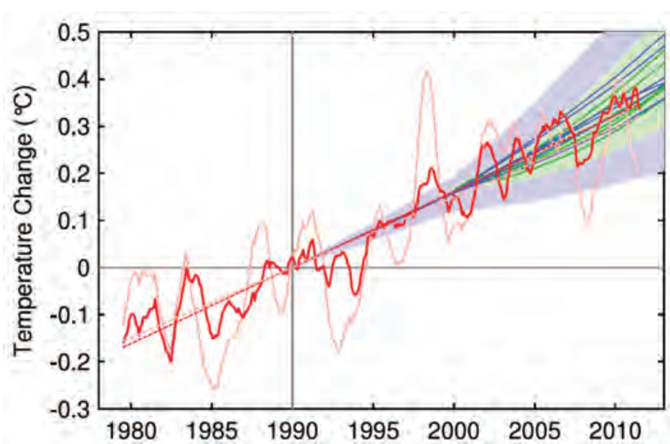
Unlike global warming, for sea-level rise, the models consistently underestimate the accelerating rise in sea levels compared to observations (Figure 2.3). Along with observations, Figure 2.3 shows projections for sea-level rise by ice-sheet and ocean models reported in the IPCC's Third and Fourth Assessment Reports. Remarkably, the models are not able to keep pace with observed sea-level rise, which rises 60-percent faster compared to the best estimates from models. This mismatch initiated the development of "semi-empirical" models (e.g., Rahmstorf 2007; Kemp et al. 2011) that constrain model parameters by centuries to millennia of observations.[11] Based on these parameters, such models project changes that by 2100 are generally higher than the process-based models by around 30–50 percent (see World Bank 2012 for more background).

How Likely is a 4°C World?

The previous *Turn Down the Heat* report estimated that current emission reductions pledges by countries worldwide, if fully implemented, would likely lead to warming exceeding 3°C before 2100.

New assessments of business-as-usual emissions in the absence of strong climate mitigation policies (Riahi et al. 2013; Kriegler et al. 2013; Schaeffer et al. 2013), as well as recent reevaluations of the likely emission consequences of pledges and targets adopted

Figure 2.2: Global-mean surface-air temperature time series unadjusted (thin pink line) and adjusted for short-term variability (red line)

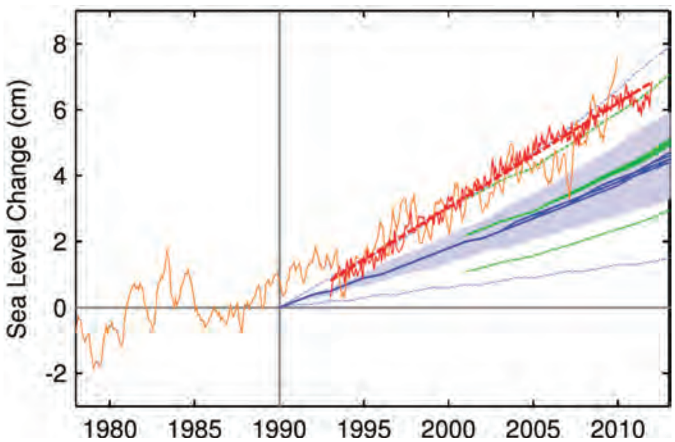


The blue range represents model results from IPCC Third Assessment Report and the green range from IPCC AR4.

Source: Adapted from Rahmstorf et al. (2012).

[11] Data dating back more than about 150 years is generally from reconstructions of past climatic circumstance obtained by proxy data, i.e. observational evidence from which past climate changes can be derived.

Figure 2.3: Sea-level rise from observations (orange: tide gauges, red: satellites) and models (blue: projections from IPCC TAR starting in 1990, green: projections from IPCC AR4 starting in 2000)



Models do not include a sea-level decline due to dam building estimated for 1961–2003 that is part of the observed time series. Including this in the models would widen the gap with observations further, although this is likely fully compensated by increased groundwater extraction during the last 2 decades

Source: Adapted from Rahmstorf et al. (2012).

by countries, point to a considerable likelihood of warming reaching 4°C above pre-industrial levels within this century. The latest research supports both of these findings (see Appendix 1):

The most recent generation of energy-economic models estimates emissions in the absence of further substantial policy action (business as usual), with the median projections reaching a warming of 4.7°C above pre-industrial levels by 2100, with a 40 percent chance of exceeding 5°C (Schaeffer et al. 2013). Newly published assessments of the recent trends in the world's energy system by the International Energy Agency in its World Energy Outlook 2012 indicate global-mean warming above pre-industrial levels would approach 3.8°C by 2100. In this assessment, there is a 40 percent chance of warming exceeding 4°C by 2100 and a 10 percent chance of it exceeding 5°C.

In relation to the effects of pledges, the updated UNEP Emissions Gap Assessment 2012, found that present emission trends and pledges are consistent with emission pathways that reach warming in the range of 3 to 5°C by 2100, with global emissions estimated for 2020 closest to levels consistent with a pathway leading to 3.5–4°C warming by 2100.[12]

The high emissions scenario underlying novel assessments, RCP8.5, reaches a global-mean warming level of about 4°C above pre-industrial levels by the 2080s and gives a median warming of about 5°C by 2100.[13]

According to new analysis (see Appendix 1), there is a 66-percent likelihood that emissions consistent with RCP8.5 will lead to a warming of 4.2 to 6.5°C, and a remaining 33-percent chance that warming would be either lower than 4.2°C or higher than 6.5°C by 2100.[14] On average, the most recent business-as-usual scenarios lead to warming projections close to those of RCP8.5 and there is a medium chance that end-of-century temperature rise exceeds 4°C. Approximately 30 percent of the most recent business-as-usual scenarios reach a warming higher than that associated with RCP8.5 by 2100 (see Figure 2.4, right-hand panel).

Can Warming be Held Below 2°C?

State-of-the-art climate models show that, if emissions are reduced substantially, there is a high probability that global mean temperatures can be held to below 2°C relative to pre-industrial levels. Climate policy has to date not succeeded in curbing global greenhouse gas emissions, and emissions are steadily rising (Peters et al. 2013). However, recent high emission trends do not imply high emissions forever (van Vuuren and Riahi 2008). Several studies show that effective climate policies can substantially influence the trend and bring emissions onto a feasible path in line with a high probability of limiting warming to below 2°C, even with limited emissions reductions in the short term (for example, OECD 2012; Rogelj et al. 2012a; UNEP 2012; van Vliet et al. 2012; Rogelj et al. 2013). The available scientific literature makes a strong case that achieving deep emissions reductions over the long term is feasible; reducing total global emissions to below 50 percent of 2000 levels by 2050 (Clarke et al. 2009; Fischedick et al. 2011; Riahi et al. 2012). Recent studies also show the possibility, together with the consequences of delaying action (den Elzen et al. 2010; OECD 2012; Rogelj et al. 2012a, 2013; van Vliet et al. 2012).

Patterns of Climate Change

This report presents projections of global and regional temperature and precipitation conditions, as well as expected changes in aridity and in the frequency of severe heat extremes. These analyses are based on the ISI-MIP database (Warszawski et al., in preparation), consisting of a subset of the state-of-the-art climate model projections of the Coupled Model Intercomparison Project phase 5 (CMIP5; K. E. Taylor, Stouffer, and Meehl, 2011) that were bias-corrected against late twentieth century meteorological observations (Hempel, Frieler,

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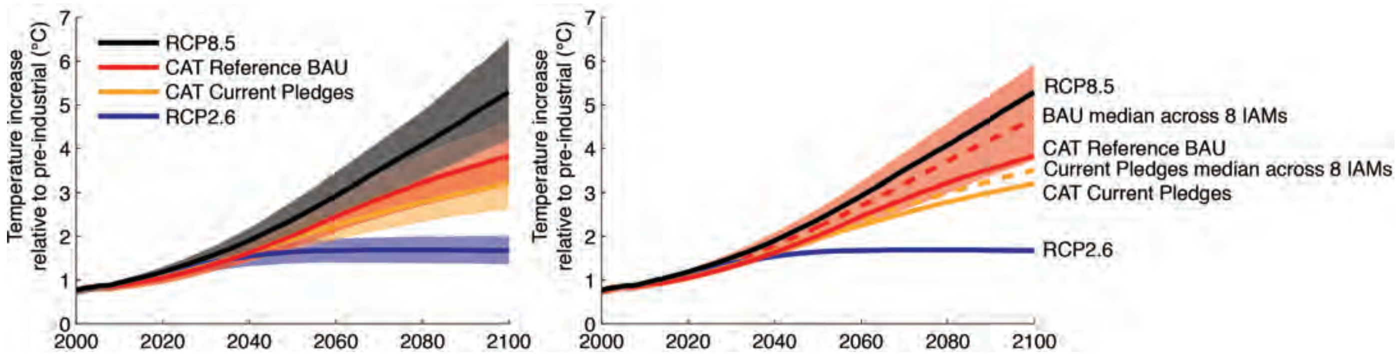
12 This applies for the "unconditional pledges, strict rules" case.

13 RCP refers to "Representative Concentrations Pathway," which underlies the IPCC´s Fifth Assessment Report. RCPs are consistent sets of projections for 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 inputs for climate modeling. See also Box 1, "What are Emission Scenarios?" on page 22 of the previous report.

14 A probability of >66 percent is labeled "likely" in IPCC's uncertainty guidelines adopted here.

Figure 2.4: Projections for surface-air temperature increase

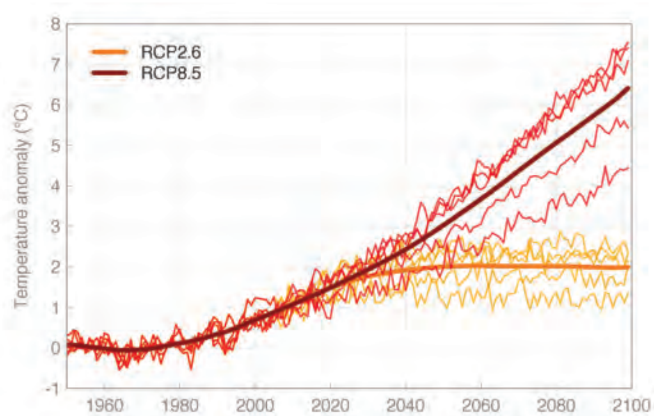


The left-hand panel shows probabilistic projections by the Simple Climate Model (SCM; see Appendix 1). Lines show "best-estimate" (median) projections for each emission scenario, while shaded areas indicate the 66 percent uncertainty range. The shaded ranges represent the uncertainties in how emissions are translated into atmospheric concentrations (carbon cycle uncertainty) and how the climate system responds to these increased concentrations (climate system uncertainty). The right-hand panel shows projections of temperature increase for the scenarios assessed in this report in the context of business-as-usual (BAU) projections from the recent Integrated Assessment Model (IAM) literature discussed in the Appendix. The light-red shaded area indicates the 66 percent uncertainty range around the median (red dashed line) of BAU projections from 10 IAMs.

Warszawski, Schewe and Piontek 2013; see also Appendix 2). The latter refers to a method of letting the models provide more accurate future projections on a global, as well as on a regional (subcontinental) scale. The patterns of change in this subset of models are shown to be consistent with published CMIP5 multi-model mean changes for temperature, precipitation, and heat extremes. Following Hansen, Sato, and Ruedy (2012), the period 1951–80 is defined as a baseline for changes in heat extremes. This baseline has the advantage of having been a period of relatively stable global temperature, prior to rapid global warming, and of providing sufficient observational measurements such that the climatology is well defined. The baseline for sea-level rise projections is the period 1986–2005.

This chapter discusses the results from a global perspective; the following three chapters look at three selected regions: Sub-Saharan Africa, South East Asia, and South Asia. The focus is on changes expected during the summer, as this is the season when climate change is expected to have the greatest impact on human populations in many regions (Hansen, Sato, and Ruedy 2012).

Figure 2.5: Temperature projections for global land area



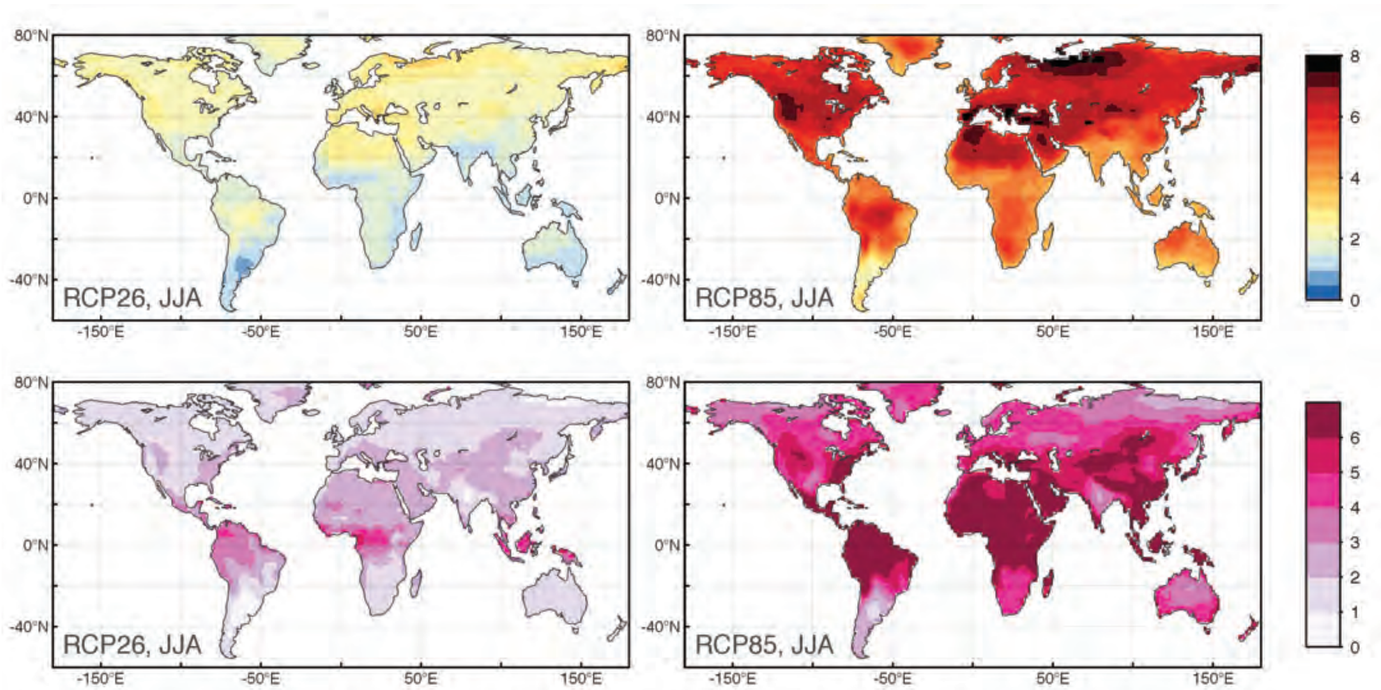
Temperature projections for global land area, for the multi-model mean (thick lines), and individual models (thin lines), under scenarios RCP2.6 and RCP8.5 for the months of June, July, and August (JJA). The multi-model mean has been smoothed to give the climatological trend.

Projected Temperature Changes

Under scenario RCP2.6, global average land surface temperatures for the months June, July, August peak at approximately 2°C above the 1951–80 baseline by 2050 and remain at this level until the end of the century (Figure 2.5). The high emissions scenario RCP8.5 follows a temperature trajectory similar to that of RCP2.6 until 2020, but starts to deviate upwards strongly after 2030. Warming continues to increase until the end of the century with global-mean land surface temperature for the northern hemisphere summer reaching nearly 6.5°C above the 1951–80 baseline by 2100. Note that these values are higher than the associated global mean temperature anomalies since warming is more pronounced over land than ocean.

Warming is generally stronger in the Northern Hemisphere, a pattern which is found for both emissions scenarios and for both the summer and winter seasons (see Figure 2.6 for JJA). This is a well-documented feature of global warming. Thus, Northern Hemisphere summers are expected to typically warm by 2–3°C under RCP2.6 and by 6.5–8°C under RCP8.5. As shown in the previous report, regions that see especially strong absolute warming include the Mediterranean, the western United States, and northern Russia.

Figure 2.6: Multi-model mean temperature anomaly for RCP2.6 (left) and RCP8.5 (right) for the months of JJA



Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–99 relative to 1951–80, and normalized by the local standard deviation (bottom row).

A good way to gain appreciation of the warming is to compare it to the historically observed natural year-to-year temperature variability (Hansen et al. 2012). The absolute warming is thus divided (normalized) by the local standard deviation (sigma), which represents the normal year-to-year changes in monthly temperature because of natural variability (see the box 2.2). A normalized warming of 5-sigma, therefore, means that the average change in the climate is five times larger than the current normal year-to-year variability. In the tropics, natural variability is small (with typical standard deviations of less than 1°C), so the normalized warming peaks in the tropics (Figure 2.6), although the absolute warming is generally larger in the Northern Hemisphere extra-tropics. Under a high-emissions scenario (RCP8.5), the expected 21st century warming in tropical regions in Africa, South America, and Asia shifts the temperature distribution by more than six standard deviations (Fig. 2.2.1.2). A similarly large shift is projected for some localized extra-tropical regions, including the eastern Mediterranean, the eastern United States, Mexico, and parts of central Asia. Such a large normalized warming implies a totally new climatic regime in these regions by the end of the 21st century, with the coldest months substantially warmer than the hottest months experienced during 1951–80. The extent of the land area projected to shift into a new climatic regime (that is, a warming by six standard deviations or more) is dramatically reduced when emissions are limited to the RCP2.6 scenario. Under such a low-emissions scenario, only localized regions in eastern tropical Africa and South East Asia are projected to see substantial normalized warming up to about four standard deviations. In some regions, non-linear climate feedbacks seem to play a role in causing warming under RCP8.5 to be much larger than under RCP2.6. The eastern Mediterranean region illustrates this situation. It warms by ~3°C (or ~2 sigma) under the low-emissions scenario compared to ~8°C (or ~6 sigma) under the high-emissions scenario.

Projected Changes in Heat Extremes

A thorough assessment of extreme events by the IPCC (2012) concludes that it is very likely that the length, frequency, and intensity of heat waves will increase over most land areas under future climate warming, with more warming resulting in more extremes. The following quantifies how much a low emission scenario (RCP2.6) would limit the increase in frequency and intensity of future heat waves as compared to RCP8.5.

Several studies have documented the expected increase in heat extremes under a business-as-usual (BAU) emissions scenario or in simulations with a doubling of CO_2 (typically resulting in ~3°C global mean warming). Without exception, these show that heat extremes, whether on daily or seasonal time scales, greatly increase under high-emissions scenarios. The intensity of extremely hot days, with a return time of 20 years,[15] is expected to increase 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 there (Zwiers and Kharin 1998). The frequency of days exceeding the present-day 99th percentile could increase by a factor of 20 (D. N. Barnett, Brown, Murphy, Sexton, and Webb 2005). Moreover, the intensity, duration, and frequency of three-day heat events is projected to significantly increase—by up to 3°C in the Mediterranean and the western and southern United States (G. A. Meehl and Tebaldi 2004). Studying the 2003 European heat wave, Schär et al. (2004) project that toward the end of the century approximately every second European summer is likely to be warmer than the 2003 event. On a global scale, extremely hot summers are also robustly predicted to become much more common (D. N. Barnett, Brown, Murphy, Sexton, and Webb 2005b). Therefore, 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 (Clark, Brown, and Murphy 2006).

In this and in the previous report, threshold-exceeding heat extremes are analyzed with the threshold defined by the historical observed variability (see Box 2.2). For this definition of extremes, regions that are characterized by high levels of warming combined with low levels of historical variability tend to see the strongest increase in extremes (Sillmann and Kharin 2013a). The approach is useful because ecosystems and humans are adapted to local climatic conditions and infrastructure is designed with local climatic conditions and its historic variations in mind. Thus even a relatively small change in temperature in the tropics can have relatively large impacts, for example if coral reefs experience temperatures exceeding their sensitivity thresholds (see, for example, Chapter 4 on "Projected Impacts on Coral Reefs").

An alternative approach would be to study extremes exceeding an absolute threshold, independent of the past variability. This is mostly relevant when studying impacts on specific sectors where the exceedance of some specific threshold is known to cause severe impacts. For example, wheat growth in India has been shown to be very sensitive to temperatures greater than 34°C (Lobell, Sibley, & Ortiz-Monasterio, 2012). As this report is concerned with impacts across multiple sectors, thresholds defined by the local climate variability are considered to be the most relevant index.

This report analyzes the timing of the increase in monthly heat extremes and their patterns by the end of the 21st century for both the low-emission (RCP2.6 or a 2°C world) and high-emission (RCP8.5 or a 4°C world) scenarios. In a 2°C world, the bulk of

15 This means that there is a 0.5 probability of this event occurring in any given year.

Box 2.2 Heat Extremes

In sections assessing extremes, this report defines two types of extremes using thresholds based on the historical variability of the current local climate (similar to Hansen et al. 2012). The absolute level of the threshold thus depends on the natural year-to-year variability in the base period (1951–1980), which is captured by the standard deviation (sigma).

3-sigma Events – Three Standard Deviations Outside the Normal

- Highly unusual at present
- Extreme monthly heat
- Projected to become the norm over most continental areas by the end of the 21st century

5-sigma Events – Five Standard Deviations Outside the Normal

- Essentially absent at present
- Unprecedented monthly heat: new class of monthly heat extremes
- Projected to become common, especially in the tropics and in the Northern Hemisphere (NH) mid-latitudes during summertime

For a normal distribution, 3-sigma events have a return time of 740 years. The 2012 U.S. heat wave and the 2010 Russian heat wave classify as 3-sigma events (Coumou & Robinson, submitted). 5-sigma events 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 from the ones expected in a normal distribution. Nevertheless, 3-sigma events are extremely unlikely and 5-sigma events have almost certainly never occurred over the lifetime of key ecosystems and human infrastructure.[a]

[a] Note that the analysis performed here does not make assumptions about the underlying probability distribution.

the increase in monthly extremes, as projected for a 4°C world by the end of the century, would be avoided. Although unusual heat extremes (beyond 3-sigma) would still become substantially more common over extended regions, unprecedented extremes (beyond the 5-sigma threshold) would remain essentially absent over most continents. The patterns of change are similar to those described for a 4°C world, but the frequency of threshold-exceeding extremes is strongly reduced. It is only in some localized tropical regions that a strong increase in frequency compared to the present day is expected (see the regional chapters). In these regions, specifically in western tropical Africa (see Chapter 3 on "Regional Patterns of Climate Change") and South East Asia (see Chapter 5 on "Regional Patterns of Climate Change"), summer months with unusual temperatures become dominant, occurring in about 60–80 percent of years, and extremes of unprecedented temperatures become regular (about 20–30 percent of years) by the end of the century.

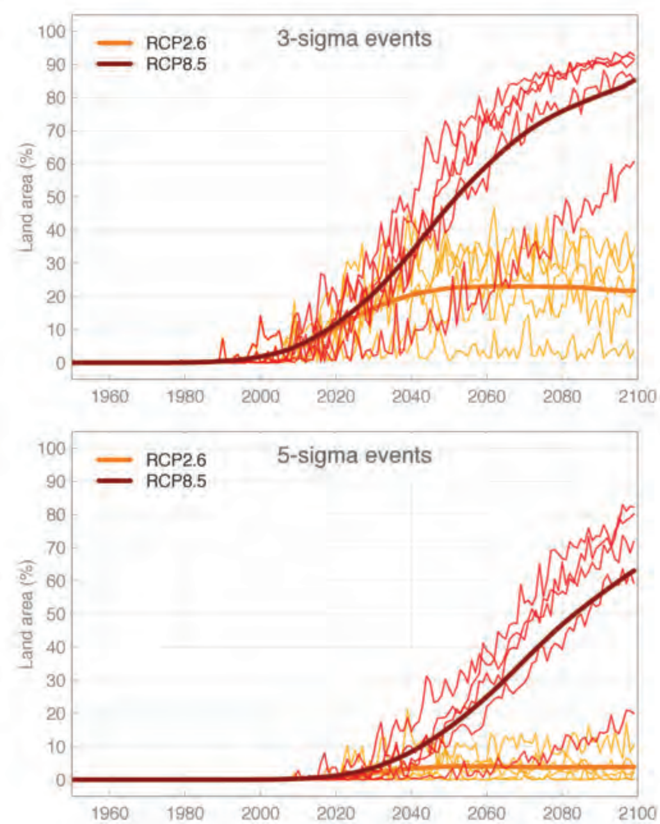
In parallel with the increase in global mean temperature, in a 2°C world the percentage of land area with unusual temperatures steadily increases until 2050; it then plateaus at around 20 percent, as shown in Figure 2.7. On a global scale, the land area affected by northern hemisphere summer months with unprecedented temperatures remains relatively small (at less than 5 percent). This implies that, in the near term, extremes would increase manifold compared to today even under the low-emissions scenario. In a 4°C world, the land area experiencing extreme heat would continue to increase until the end of the century. This results in unprecedented monthly heat covering approximately 60 percent of the global land area by 2100. Although these analyses are based on a new set of climate models (that is, those used in ISI-MIP—see Appendix 2), the projections for a 4°C world are quantitatively consistent with the results published in the previous report.

Under RCP8.5 (or a 4°C world), the annual frequency of warm nights beyond the 90th percentile increases to between 50–95 percent, depending on region, by the end of the century (Sillmann and Kharin 2013a). Under RCP2.6 (or a 2°C world), the frequency of warm nights remains limited to between 20–60 percent, with the highest increases in tropical South East Asia and the Amazon region (Sillmann and Kharin 2013a). Extremes, expressed as an exceedance of a particular percentile threshold derived from natural variability in the base period, show the highest increase in tropical regions, where interannual temperature variability is relatively small. Under RCP8.5, the duration of warm spells, defined as the number of consecutive days beyond the 90th percentile (Sillmann and Kharin 2013b), increases in tropical regions to more than 300, occurring essentially year round (Sillmann and Kharin 2013a).

Precipitation Projections

On a global scale, warming of the lower atmosphere strengthens the hydrological cycle, mainly because warmer air can hold more water vapor (Coumou and Rahmstorf 2012). This strengthening causes dry regions to become drier and wet regions to become wetter (Trenberth 2010). There are other important mechanisms, however, such as changes in circulation patterns and aerosol forcing, which may lead to strong deviations from this general picture. Increased atmospheric water vapor can also amplify extreme precipitation (Sillmann and Kharin 2013a).

Figure 2.7: Multi-model mean (thick line) and individual models (thin lines) of the percentage of global land area warmer than 3-sigma (top) and 5-sigma (bottom) during boreal summer months (JJA) for scenarios RCP2.6 and RCP8.5



Although modest improvements have been reported in the precipitation patterns simulated by the state-of-the-art CMIP5 models (Kelley, Ting, Seager, and Kushnir 2012; Jia & DelSole 2012; Zhang and Jin 2012) as compared to the previous generation (CMIP3), substantial uncertainty remains. This report therefore only provides changes in precipitation patterns on annual and seasonal timescales. The ISI-MIP models used were bias-corrected such that they reproduce the observed historical mean and variation in precipitation. The projections might therefore also provide more robust and consistent trends on regional scales.

The expected change in annual mean precipitation by 2071–99 relative to 1951–80 is shown in Figure 2.8 for RCP2.6 (a 2°C world) and RCP8.5 (a 4°C world). Across the globe, most dry areas get drier and most wet areas get wetter. The patterns of change in precipitation are geographically similar under the low and high emissions scenarios, but the magnitude is much larger in the latter. Under the weak climatic forcing in a 2°C world, precipitation changes are relatively small compared to natural variability, and the models disagree in the direction of change over extended regions. As the climatic signal in a 4°C world becomes stronger, the models converge in their predictions showing much less inter-model disagreement in the direction of change. Uncertainty remains mostly in those regions at the boundary between areas getting wetter and areas getting drier in the multi-model mean.

There are important exceptions to the dry-get-drier and wet-get-wetter patterns. Firstly, arid regions in the southern Sahara and in eastern China are expected to see more rainfall. Although the percentage change can be greater than 50 percent, absolute changes are still very small because of the current exceptionally dry conditions in these regions. Secondly, in the eastern part of the Amazon tropical rainforest, annual rainfall is likely to decrease. A clearly highly impacted region is the Mediterranean/North African region, which is expected to see up to 50 percent less annual rainfall under the high-emission scenario associated with a 4°C world.

In some regions, changes in extreme precipitation are expected to be more relevant from the point of view of impact than changes in the annual mean. Inter-model disagreement, however, tends to be larger for more extreme precipitation events, limiting robust projections (Sillmann and Kharin 2013b). Still on a global scale, total wet day precipitation and maximum five-day precipitation are robustly projected to increase by 10 percent and 20 percent, respectively, under RCP8.5 (Sillmann and Kharin 2013a). Regionally, the number of consecutive dry days is expected to increase in subtropical regions and decrease in tropical and near-arctic regions (Sillmann and Kharin 2013a). In agreement with Figures 2.6 and 2.8, extreme indices for both temperature and precipitation (notably consecutive dry days) stand out in the Mediterranean, indicating a strong intensification of heat and water stress.

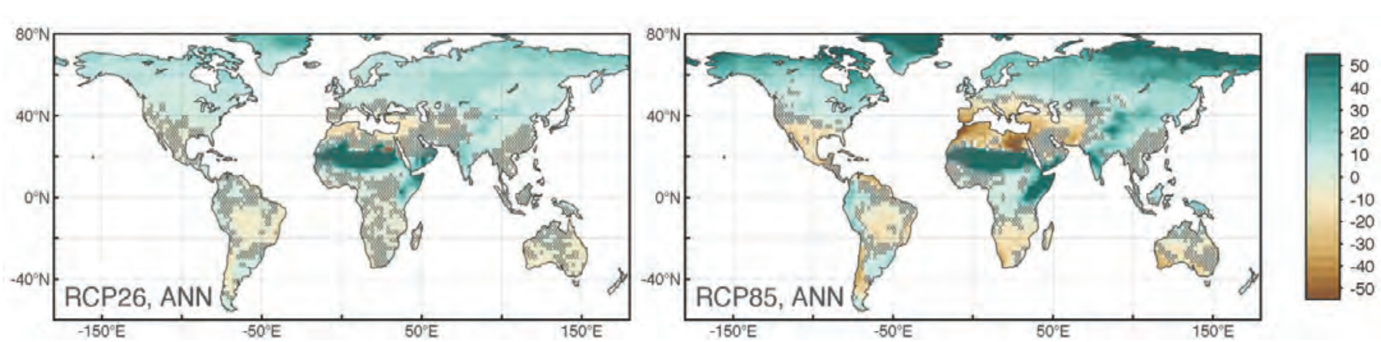
Sea-level Rise

Projecting sea-level rise as a consequence of climate change is a highly difficult, complex, and controversial scientific problem, as was discussed in the previous report. This section focuses on briefly recapping projections at a global level and providing an update on new findings, thus providing the global context for the regional sea-level rise projections in Chapters 3–5.

Process-based approaches dominate sea-level rise projections. They refer to the use of numeric models that represent the physical processes at play, such as the CMIP5 models discussed in Chapter 2 on "Patterns of Climate Change" that form the basis for much of the work on projected climate impacts presented in this report. Key contributions of observed and future sea-level rise are the thermal expansion of the ocean and the melting of mountain glaciers ice caps, and the large ice sheets of Greenland and Antarctica. In the case of the Greenland and Antarctic ice sheets, uncertainties in the scientific understanding of 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 (e.g., Rahmstorf 2007).

A second approach to projecting global sea-level rise is to take into account the observed relationship between past sea-level rise and global mean temperature over the past millennium to project future sea-level rise (Kemp et al. 2011; Schaeffer et al. 2012). This "semi-empirical" approach generally leads to higher projections, with median sea-level rise by 2081–2100 of 100 cm for RCP8.5, with a 66 percent uncertainty range of 81–118 cm and a 90 percent range of 70–130 cm. The low-carbon pathway RCP2.6 leads

Figure 2.8: Multi-model mean of the percentage change in annual mean precipitation for RCP2.6 (left) and RCP8.5 (right) by 2071–99 relative to 1951–80



Hatched areas indicate uncertainty regions with two out of five models disagreeing on the direction of change compared to the remaining three models.

to 67 cm of SLR by that time, with a 66 percent range of 57–77 cm and a 90 percent range of 54–98 cm. According to this analysis, a 50 cm sea-level rise by the 2050s may be locked in whatever action is taken now; limiting warming to 2°C may limit sea-level rise to about 70 cm by 2100, but in a 4°C world over 100cm can be expected, with the sea-level rise in the tropics 10–15 percent higher than the global average. All three regions studied here have extensive coastlines within the tropics with high concentrations of vulnerability.

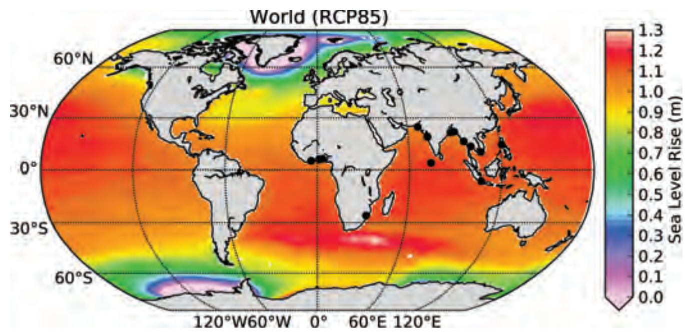
Although semi-empirical approaches have their own limitations and challenges (for example, Lowe and Gregory 2010; Rahmstorf et al. 2012), in this report these higher projections were adopted as the default, noting that uncertainties are large and this report primarily looks at the literature from a risk perspective.

Most impacts studies looking at sea-level rise focus on the level reached by a certain time. The *rate* of sea-level rise is another key indicator for risk, as well as for the long-term resilience of ecosystems and small-island developing states (Figure 2.9). The difference between high- and low-emissions scenarios is especially large for this indicator by 2100 compared to sea-level rise *per se*.[16]

As explained in the previous report, sea-level rises unevenly across the globe. A clear feature of regional projections (see Figure 2.10) is the relatively high sea-level rise at low latitudes (in the tropics) and below-average sea-level rise at higher latitudes (Perrette, Landerer, Riva, Frieler, and Meinshausen 2013). This is primarily because of the polar location of ice masses, the gravitational pull of which decreases because of the gradual melting process and accentuates the rise in the tropics, far away from the ice sheets. Close to the main ice-melt sources (Greenland, Arctic Canada, Alaska, Patagonia, and Antarctica), crustal uplift and reduced attraction cause a below-average rise, and even a sea-level fall in the very near-field of a mass source.

Ocean dynamics, such as ocean currents and wind patterns, shape the pattern of projected sea level. In particular, an above-average contribution from ocean dynamics is projected along the

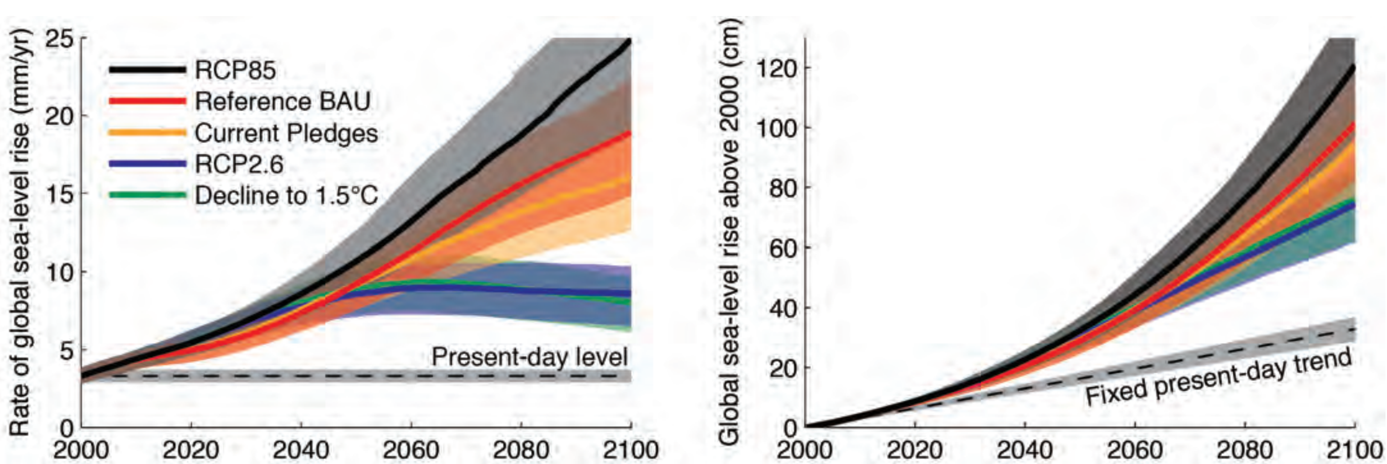
Figure 2.10: Sea-level rise in the period 2081–2100 relative to 1986–2005 for the high-emission scenario RCP8.5



Cities in the focus regions of this report are indicated in both this and Figure 2.11 and labeled in the lower panel of the latter.

[16] In addition, a high rate of sea-level rise by 2100 will set the stage for several centuries of further sea-level rise, given the slow response of oceans and ice sheets, amounting to multiple meters of SLR for the highest scenarios. Indeed, even in the low *Decline to 1.5°C* scenario extended model runs (not shown) analogous to those in Schaeffer et al. (2013) show that even with emissions fixed at year-2100 levels, the rate of SLR is projected to drop well below present-day observed rates by 2300, but not yet to zero.

Figure 2.9: Projections of the rate of global sea-level rise (left panel) and global sea-level rise (right panel)

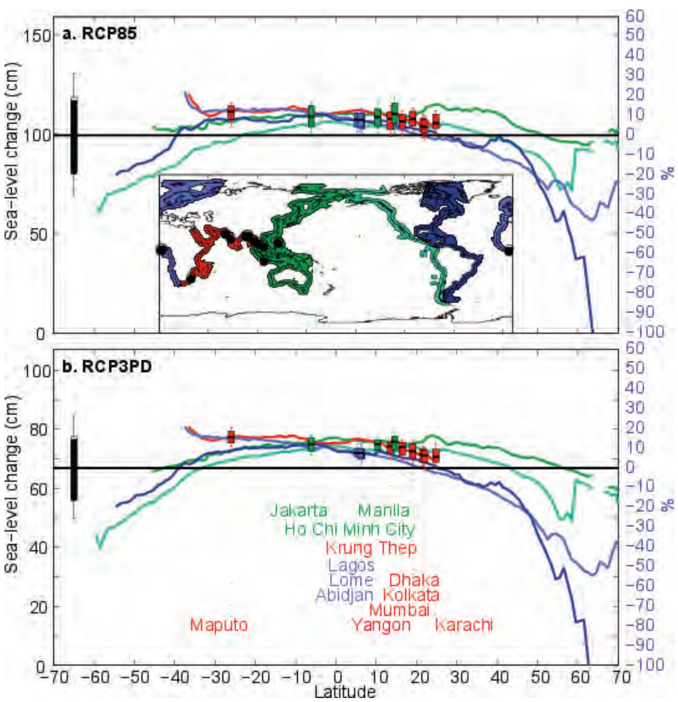


Lines show "best-estimate" (median) projections for each emission scenario, while shaded areas indicate the 66 percent uncertainty range.

Source: Present-day rate from Mayssignac and Cazenave (2012).

northeastern North American and eastern Asian coasts, as well as in the Indian Ocean. On 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, 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. Highlighting the coastlines, Figure 2.11 shows sea-level rise along a latitudinal gradient, with specified locations relevant for the regional climate impacts sections presented later.

Figure 2.11: Sea-level rise in the period 2081–2100 relative to 1986–2005 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 the uncertainty thereof, showing 50 percent, 68 percent, and 80 percent ranges. The top panel shows results for the RCP8.5 emission pathway, the lower panel the low emission pathway RCP2.6. Cities in the focus regions of this report are indicated in both panels and labeled in the lower panel.

Other local circumstances can modify the regional pattern significantly through local vertical movement of land caused by natural factors, such as the post-glacial rebound of land still underway at high latitudes; anthropogenic influences other than climate change, such as compaction of soil following extraction of natural resources or large-scale infrastructure development, can also modify the regional pattern It is beyond the scope of this report to explore such particular local circumstances.

Ocean Warming and Acidification

The world's oceans are expected to see further changes related to climate change. The previous report presented projections of ocean acidification, which occurs when the oceans absorb CO_2 as atmospheric concentrations: 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 pre-industrial levels. The degree and rate of observed ocean acidification due to anthropogenic CO_2 emissions appears to be greater than during any of the ocean acidification events identified in the geological past and is expected to have wide-ranging and adverse consequences for coral reefs and marine production. Some of the impacts of ocean acidification are presented in Chapter 4 under "Impacts on Agricultural and Aquaculture Production in Deltaic and Coastal Regions".

The world´s oceans have, in addition, been taking up approximately 93 percent of the additional heat caused by anthropogenic climate change (Levitus et al. 2012). This has been observed for depths up to 2,000 meters. Since the late 1990s, the contribution of waters below 700 meters increases and the overall heat uptake has been reported to have been higher during the last decade (1.19 ± 0.11 W m^{-2}) than the preceding record (Balmaseda, Trenberth, and Källén 2013). Ocean warming exerts a large influence on the continents: 80 to 90 percent of warming over land has been estimated to be indirectly driven by ocean warming (Dommenget 2009). This implies a time lag and commitment to further global warming following even large emission decreases. Furthermore, recent research suggests that warming further enhances the negative effect of acidification on growth, development, and survival across many different calcifying species (Kroeker et al. 2013).

Chapter 3

Sub-Saharan Africa: Food Production at Risk

REGIONAL SUMMARY

Sub-Saharan Africa is a rapidly developing region of over 800 million people, with 49 countries[17], and great ecological, climatic, and cultural diversity. By 2050, its population is projected to approach 1.5–1.9 billion people. With a 4°C global warming by the end of the century, sea level is projected to rise up to 100 cm, droughts are expected to become increasingly likely in central and southern Africa, and never-before-experienced heat extremes are projected to affect increasing proportions of the region. Projections also show an increased likelihood of increased annual precipitation in the Horn of Africa and parts of East Africa that is likely to be concentrated in bursts and, thereby, increase the risk of flooding. Increased atmospheric concentrations of CO_2 are likely to facilitate a shift from grass to woodland savanna and thereby negatively impact pastoral livelihoods if grass-based forage is reduced. Climate change is expected to have adverse impacts and pose severe risks, particularly on agricultural crop production, pastoral and livestock systems, and capture fisheries. It may also significantly increase the challenges of ensuring food security and eradicating poverty.

Sub-Saharan Africa is particularly vulnerable to impacts on agriculture. Most of the region´s agricultural crop production is rainfed and therefore highly susceptible to shifts in precipitation and temperature. A net expansion of the overall area classified as arid or hyper-arid is projected for the region as a whole, with likely adverse consequences for crop and livestock production. Since the 1950s, much of the region has experienced increased drought and the population´s vulnerability is high: The 2011 drought in the Horn of Africa, for example, affected 13 million people and led to extremely high rates of malnutrition, particularly among children. Under future climate change, droughts are projected to become increasingly likely in central and southern Africa, with a 40-percent decrease in precipitation in southern Africa if global temperatures reach 4°C above pre-industrial levels by the 2080s (2071–2099 relative to 1951–1980).

[17] This report defines Sub-Saharan Africa as the region south of the Sahara. For the projections on changes in temperature, precipitation, aridity, heat extremes, and sea-level rise, the area corresponds broadly to regions 15, 16, and 17 in the IPCC´s special report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX).

Pastoral systems are also at risk from climate impacts, as livestock is affected by extreme heat, water stress, an increased prevalence of diseases, and reduced fodder availability. Marine fish stocks migrate toward higher latitudes as waters warm and potential catches may be diminished locally, adding to the already large pressure placed on ecosystems by overfishing.

Heat extremes are projected to affect increasing proportions of the region, with adverse consequences for food production systems, ecosystems and human health. Direct and indirect impacts on human health are also expected, and an acceleration of the urbanization trend in response to additional pressures caused by climate change is likely to compound vulnerability.

Current Climate Trends and Projected Climate Change to 2100

Climate change exerts pressure on ecosystems and key sectors in Sub-Saharan Africa, with repercussions for the human populations dependent on them.

Rainfall

In terms of precipitation, the region is characterized by significant inter-annual and inter-decadal variability, and long-term trends are uncertain and inconsistent on the sub-regional scale: For example, while West Africa has experienced declines in mean annual precipitation over the past century, an increase in the Sahel has been observed over the last decade. In southern Africa and the tropical rainforest zone, no long-term trend has been observed. Inter-annual variability has increased, however, with more intense droughts and rainfall events reported in parts of southern Africa. Eastern Africa has seen increasing rainfall in some parts over the past decades, which is a reversal of a drying trend over most parts of the region during the past century.

Under 2°C warming, the existing differences in water availability across the region are likely to become more pronounced. For example, average annual rainfall is projected to increase mainly in the Horn of Africa (with both positive and negative impacts), while parts of Southern and West Africa may see decreases in rainfall and groundwater recharge rates of 50–70 percent. Under 4°C warming, annual precipitation in Southern Africa may decrease by up to 30 percent, while East Africa is projected by many models to be wetter than today, leading to an overall decrease in the risk of drought. Some important caveats are in order however, on precipitation projections. First, there is a significant degree of uncertainty, particularly for east and west Africa. Second, even if, on an annual average, precipitation does increase, it is likely to be concentrated in bursts rather than evenly distributed over the year.[18] In addition, droughts are projected to become increasingly likely over southern and central Africa. A "likely" event is defined as a >66 percent chance of occurring, using the modeling approaches adopted in this report.

Temperature

Since the 1960s, measurements show that there has been a warming trend that has continued to the present, with an increase in the number of warm spells over southern and western Africa. Recent work has found a detectable human-induced warming over Africa as a whole, with warm extremes in South Africa since 1961. A summer warming trend is projected to be mostly uniformly distributed throughout the region. In a 4°C world and relative to a 30-year baseline period (1951–80), monthly summer temperature increases over Sub-Saharan Africa are projected to reach 5°C above the baseline temperature by 2100. In a 2°C world, increases in African summer temperatures are projected to peak at about 1.5°C above the baseline temperature by 2050.

As global mean temperatures rise, unusual and unprecedented heat extremes[19] are projected to occur with greater frequency during summer months. By the time global warming reaches 1.5°C in the 2030s, heat extremes that are unusual or virtually absent today are projected to cover over one-fifth of land areas in the Southern Hemisphere summer months. Unprecedented monthly heat extremes, could cover up to 5 percent of land areas in this timeframe. Under 2°C warming, monthly heat extremes that are unusual or virtually absent in today´s regional climate are projected to cover nearly 45 percent of land areas by the 2050s, and unprecedented heat extremes are expected to cover up to 15 percent of land area in the summer. With global warming reaching about 4°C by the end of the century, unusual summertime heat extremes are projected to cover most of the land areas (85 percent), with unprecedented heat extremes covering more than 50 percent.

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18 Uncertainty is particularly large for East Africa due to concerns about whether the GCM models adequately capture the dynamics of the rainy seasons in that region and because higher resolution regional climate models do not seem to reproduce, but rather contradict, the increase in precipitation seen in the projections of most global models. Drought risk results from periods of anomalously low precipitation or high warming or both, but this risk is also influenced by other climate variables like wind speed and incoming radiation. Climate-model projections of warming generally have lower uncertainty, while uncertainties in precipitation projections differ between regions. Uncertainties in drought projections are smallest for Southern Africa (primarily driven by warming), somewhat larger for Central Africa (because of smaller signals of change), and largest for West Africa (for which there is large disagreement across models on precipitation changes, both in sign and in amplitude).

19 In this report, unusual and unprecedented heat extremes are defined using thresholds based on the historical variability of the current local climate. The absolute level of the threshold thus depends on the natural year-to-year variability in the base period (1951–1980), which is captured by the standard deviation (sigma). Unusual heat extremes are defined as 3-sigma events. For a normal distribution, 3-sigma events have a return time of 740 years. The 2012 U.S. heat wave and the 2010 Russian heat wave classify as 3-sigma events. Unprecedented heat extremes are defined as 5-sigma events. They 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 from the ones expected in a normal distribution. Nevertheless, 3-sigma events are extremely unlikely and 5-sigma events have almost certainly never occurred.

Likely Physical and Biophysical Impacts of Projected Climate Change

The projected changes in rainfall, temperature, and extreme event frequency and/or intensity will have both direct and indirect impacts on sea-level rise, aridity, crop yields, and agro-pastoral systems that would affect populations.

Projected Aridity Trends

Patterns of aridity[20] are projected to shift and expand within the total area classified as such due to changes in temperature and precipitation. Arid regions are projected to spread, most notably in Southern Africa but also in parts of West Africa. Total hyper-arid and arid areas are projected to expand by 10 percent compared to the 1986–2005 period. Where aridity increases, crop yields are likely to decline as the growing season shortens. Decreased aridity is projected in East Africa; the change in area, however, does not compensate for increases elsewhere.

Sea-level Rise

Sea level is projected to rise more than the global average in the tropics and sub-tropics. Under a warming of 1.5°C, sea-level is projected to rise by 50 cm along Sub-Saharan Africa's tropical coasts by 2060, with further rises possible under high-end projections. In the 2°C warming scenario, sea-level rise is projected to reach 70 cm by the 2080s, with levels higher toward the south. The 4°C warming scenario is projected to result in a rise of 100 cm of sea-level by the 2090s. The difference in rate and magnitude of sea-level rise between the 4°C warming scenario and the 2°C warming scenario by 2100 becomes pronounced due to the continuing rate of sea-level rise in the higher warming scenario relative to the stabilized level under 2°C. The projected sea-level under 4°C would increase the share of the population at risk of flooding in Guinea-Bissau and Mozambique to around 15 percent by 2100, compared to around 10 percent in projections without sea-level rise; in The Gambia, the share of the population at risk of flooding would increase many fold to 10 percent of the population by 2070.

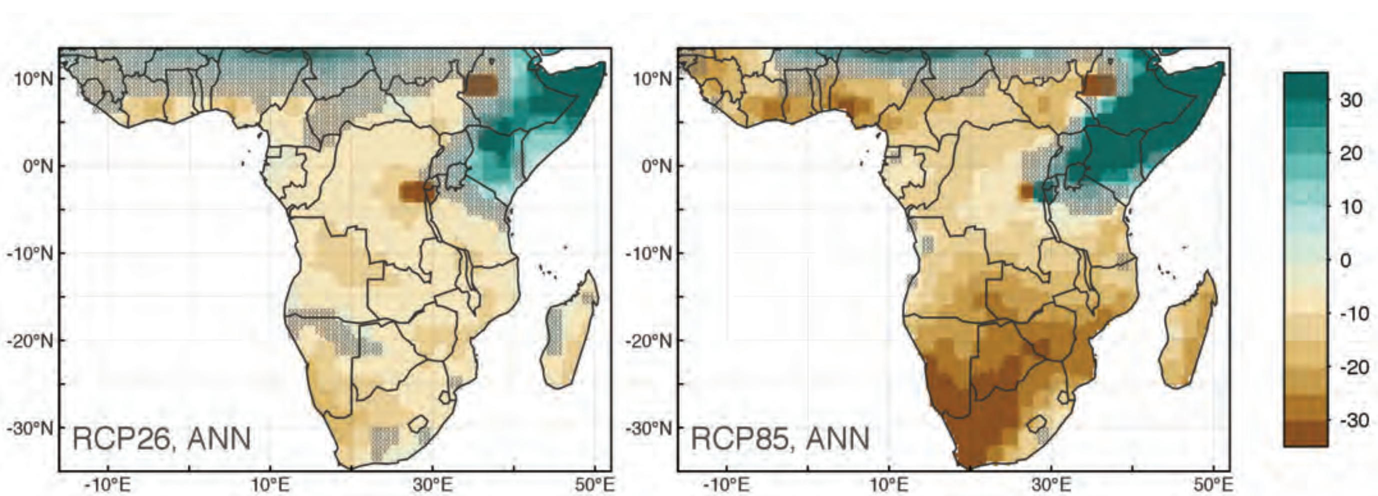
Sector-based and Thematic Impacts

Ecosystems

Savanna grasslands may be reduced in area, with potential impacts on livelihoods and pastoral systems. By the time 3°C global warming is reached, savannas are projected to decrease from about a quarter at present to approximately one-seventh of total land area, reducing the availability of food for grazing animals. Both changes in climatic conditions and increasing atmospheric CO_2 concentration are projected to play a role in bringing about regime shifts in African ecosystems, thereby altering the composition of species. Due to

20 Aridity is characterized by a structural precipitation deficit-meaning a lack of necessary rainfall amounts for vegetation and/or crop growth-and is potentially driven by a positive feedback mechanism. In regions where the soil dries out due to a lack of precipitation, no more heat can be converted into latent heat and all heat results in increased surface temperatures. This additional heating of the land increases evaporative demand of crops and amplifies the precipitation deficit.

Figure 3.1: Sub-Saharan Africa – Multi-model mean of the percentage change in the Aridity Index in a 2°C world (left) and a 4°C world (right) for Sub-Saharan Africa by 2071–2099 relative to 1951–1980



In non-hatched areas, at least 4/5 (80 percent) of models agree. In hatched areas, 2/5 of the models disagree. Note that a negative change corresponds to a shift to more arid conditions. Particular uncertainty remains for East Africa, where regional climate model projections tend to show an increase in precipitation, which would be associated with a decrease in the Aridity Index (see also footnote 2). A decrease in aridity does not necessarily imply more favorable conditions for agriculture or livestock, as it may be associated with increased flood risks.

Table 3.1: Summary of climate impacts and risks in Sub-Saharan Africa[a]

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C[b,c] (≈2030s[d])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C (≈2080s)
Heat extreme[e] (in the Southern Hemisphere summer)	Unusual heat extremes	Virtually absent	20–25 percent of land	45 percent of land	70 percent of land	>85 percent of land
	Unprecedented heat extremes	Absent	<5 percent of land	15 percent of land	35 percent of land	>55 percent of land
Drought		Increasing drought trends observed since 1950	Increasing drought risk in southern, central, and West Africa, decrease in East Africa, but West and East African projections are uncertain	Likely risk of severe drought in southern and central Africa, increased risk in West Africa, decrease in east Africa but west and East African projections are uncertain	Likely risk of extreme drought in southern Africa and severe drought in central Africa, increased risk in West Africa, decrease in East Africa, but West and East African projections are uncertain	Likely risk of extreme drought in southern Africa and severe drought in central Africa, increased risk in West Africa, decrease in East Africa, but West and East African projections are uncertain
Aridity		Increased drying	Little change expected	Area of hyper-arid and arid regions grows by 3 percent		Area of hyper-arid and arid regions grows by 10 percent. Total arid and semi-arid area increases by 5 percent
Sea-level rise above present (1985–2005)		About 21 cm to 2009[f]	30cm[g]-2040s 50cm-2070 70cm by 2080–2100	30cm-2040s 50cm-2070 70cm by 2080–2100	30cm-2040s 50cm-2060 90cm by 2080–2100	30cm-2040s 50cm-2060 105cm by 2080–2100

[a] A more comprehensive table of impacts and risks for SSA is presented at the end of Chapter 3.
[b] Refers to the global mean increase above pre-industrial temperatures.
[c] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario exceeding 4°C by the 2080s.
[d] Years indicate the decade during which warming levels are exceeded with a 50 percent or greater change (generally at the start of the decade) in a business-as-usual scenario (RCP8.5 scenario). Exceedance with a likely chance (>66 percent) generally occurs in the second half of the decade cited.
[e] Mean heat extremes across climate model projections are given. Illustrative uncertainty range across the models (minimum to maximum) for 4°C warming are 70–100 percent for unusual extremes, and 30–100 percent for unprecedented extremes. The maximum frequency of heat extreme occurrence in both cases is close to 100 percent, as indicator values saturate at this level.
[f] Above 1880 estimated global mean sea level.
[g] Add 20 cm to get an approximate estimate above the pre-industrial sea level.

CO_2 fertilization, trees may be able to outcompete shade-intolerant grasses in savannas, leading to a reduction in grassland area and declines in food availability for livestock and other animals. It is not yet clear if the negative effects of increased drought on trees in the region would limit such forest expansion. In response to changes in temperature and rainfall variability, a 20-percent decline in tree density in the western Sahel has been observed since the 1950s.

Agricultural Production

Several lines of evidence indicate a likely substantial risk to crop yields and food production adversely affecting food security by 1.5–2°C warming, with growing risks at higher levels of warming.

- **High temperature sensitivity** thresholds for some important crops, such as maize, wheat, and sorghum, have been observed, with large yield reductions once the threshold is exceeded. For example, the photosynthesis rate (key factor in growth and yield) of crops such as wheat and rice is at a maximum for temperatures from about 20–32°C. The IPCC AR4 report (IPCC 2007) stated that even moderate increases (1–2°C) are likely to have a negative effect on yields for major cereals like wheat, maize, and rice; further warming will have increasingly negative effects, showing decreases in wheat yield in low latitude regions of approximately 50 percent for an increase in mean local temperature of about 5°C. As these temperature thresholds are exceeded more frequently with 2°C and 4°C warming, significant production shocks are likely.
- **Loss or change of suitable areas.** A 1.5°–2°C warming by the 2030s–2040s could lead to about 40–80 percent reductions in present maize, millet, and sorghum cropping areas for current cultivars. By 3°C warming, this reduction could grow to more than 90 percent.
- **Significant yield decreases** are expected in the near term under relatively modest levels of warming. Under 1.5–2°C warming, median yield losses of around 5 percent are projected, increasing to median estimates of around –15 percent (range –5 percent to –27 percent for 2–2.5°C warming).[21] Under 3–4°C warming there are indications that yields may

21 The range is given across the following crops: millet, sorghum, wheat, cassava, and groundnuts.

decrease by around 15–20 percent across all crops and regions, although the availability of studies estimating potential yield impacts is limited.

- **Per capita crop production** at warming of about 1.8°C (by the 2050s) is projected to be reduced by 10 percent compared to a case without climate change. With larger yield reductions projected for higher levels of warming, this risk could grow; however, this has yet to be quantified. **Livestock production** is also expected to suffer due to climate impacts on forage availability and heat stress.
- **Diversification options for agro-pastoral systems** (e.g., switching to silvopastoral systems, irrigated forage production, and mixed crop-livestock systems) are likely to dwindle as climate change reduces the carrying capacity of the land and livestock productivity. The livestock sector has been vulnerable to drought in the past. For example, pastoralists in southern Ethiopia lost nearly 50 percent of their cattle and about 40 percent of their sheep and goats to droughts between 1995–97.
- **The CO_2 fertilization** effect remains uncertain. A strong positive response of crops to increasing atmospheric CO_2 concentrations would help to dampen the impacts related to changes in temperature and precipitation. However, important crops, including maize, sorghum, and pearl millet—among the dominant crops in Africa—are not very sensitive to atmospheric CO_2 concentrations. Furthermore, the magnitude of these effects remains uncertain when compared with the results from the free-air CO_2 enrichment (FACE)[22] experiments, because the fertilization effects used in various models appear to be overestimated. Under sustained CO_2 fertilization, the nutritional value of grain per unit of mass has been observed to decrease.

Fisheries

Livelihoods dependent on fisheries and other ecosystem services are projected to be threatened in some regions, with critical species possibly ceasing to be locally available. Potential fish catches off the coast of West Africa, where fish accounts for as much as 50 percent of the animal protein consumed, is likely to be reduced by as much as 50 percent by the 2050s (compared to 2000 levels). In other regions, such as the eastern and southeastern coasts of Sub-Saharan Africa, yield potential has been projected to increase.

Health

Malnutrition can have major secondary health implications by causing childhood stunting or by increasing susceptibility to other diseases. Under warming of 1.2–1.9°C, undernourishment levels are expected to be in the range of 15–65 percent, depending on the sub-region, due to crop yield and nutritional quality declines. Moderate stunting of children under age five is expected to occur at a rate of 16–22 percent, and severe stunting at a rate of 12–20 percent. Without climate change, however, moderate stunting rates are projected to remain close to present levels (21–30 percent across the region), and severe stunting is projected to decrease by 40 percent.

Integrated Synthesis of Climate Change Impacts in Sub-Saharan Africa

Sub-Saharan Africa is confronted with a range of climate risks that could have far-reaching repercussions for the region´s societies and economies. Even in a situation in which warming is limited below 2°C, there are very substantial risks that would continue to grow as warming approaches 4°C.

Climate Change Projected to Increase Poverty and Risks from Disease

Poverty in the region may grow even further due to climate impacts, as poor households with climate sensitive sources of income are often disproportionately affected by climate change and large parts of the population still depend on the agricultural sector as their primary source of food security and income. Below 2°C warming, large regional risks to food production and security emerge; these risks would become stronger if adaptation measures were inadequate and the CO_2 fertilization effect is weak. Poverty has been estimated to increase by up to one percent following severe food production shocks in Malawi, Uganda, and Zambia. As warming approaches 4°C, the impacts across sectors increase.

Malnutrition as a consequence of impacts on food production further increases susceptibility to diseases, compounding the overall health risks in the region. Childhood stunting resulting from malnutrition is associated with reductions in both cognitive ability and school performance. Projected crop yield losses and adverse effects on food production that result in lower real incomes would exacerbate poor health conditions and malnutrition; with malaria and other diseases expected to worsen under climate change, adverse effects on childhood educational performance may be expected.

The **diseases** that pose a threat in Sub-Saharan Africa as a consequence of climate change include vector- and water-borne diseases such as malaria, Rift Valley fever, and cholera. The risk of these diseases is expected to rise as changes in temperature and precipitation patterns increase the extent of areas with conditions conducive to vectors and pathogens. Other impacts expected to accompany climate change include mortality and morbidity due to such extreme events as flooding and more intense and hotter heat waves.

[22] FACE experiments measure the effect of elevated CO_2 concentrations in the open air, thereby excluding factors in a traditional laboratory setting that may influence experimental results.

Climate Change Expected to Challenge Urban Development, Infrastructure, and Education

The existing **urbanization** trend in Sub-Saharan Africa could be accelerated by the stresses that climate change is expected to place on rural populations. These pressures are expected to arise partly through impacts on agricultural production, which currently provides livelihoods to 60 percent of the labor force in the region. Migration to urban areas may provide new livelihood opportunities, but it also exposes migrants to new risks. Conditions that characterize poor urban areas, including overcrowding and inadequate access to water, drainage, and sanitation facilities, aid the transmission of vector- and water-borne diseases. As many cities are located in coastal areas, they are exposed to coastal flooding because of sea-level rise. The poorest urban dwellers tend to be located in vulnerable areas, such as floodplains and steep slopes, further placing them at risk of extreme weather events. Impacts occurring even far-removed from urban areas can be felt in these communities. For example, food price increases following agricultural production shocks have the most damaging consequences within cities.

Impacts on infrastructure caused by sea-level rise can have effects on human and economic development, including impacts on human health, port infrastructure, and tourism. For example, floods in 2009 in the Tana Delta in Kenya cut off medical services to approximately 100,000 residents; sea-level rise of 70cm by 2070 would cause damages to port infrastructure in Dar es Salaam, Tanzania—a hub for international trade—exposing assets of US$10 billion, or more than 10 percent of the city's GDP (Kebede and Nicholls 2011). Such damage to the Dar es Salaam port would have would have larger economic consequences since it serves as the seaport for several of its landlocked neighbours.

There are indications that climate change could impact the ability to meet the educational needs of children in particularly vulnerable regions. Projected crop yield losses and adverse effects on food production would exacerbate poor health conditions and malnutrition; with malaria and other diseases expected to worsen under climate change, adverse effects on childhood educational performance may be expected. Childhood stunting resulting from malnutrition is associated with reduced cognitive ability and school performance. The projected increase in extreme monthly temperatures within the next few decades may also have an adverse effect on learning conditions for students and teachers.

Overall, populations in Sub-Saharan Africa are expected to face mounting pressures on food production systems and risks associated with rising temperature and heat extremes, drought, changing precipitation patterns, sea-level rise, and other extreme events. Health impacts are likely to increase and be exacerbated by high rates of malnutrition, with possible far-reaching and long-term consequences for human development. Significant crop yield reductions at warming levels as low as 2°C warming are expected to have strong repercussions on food security for vulnerable populations, including in many growing urban areas. These and other impacts on infrastructure, in combination, may negatively impact economic growth and poverty reduction in the region. A warming of 4°C is projected to bring large reductions in crop yield, with highly adverse effects on food security, major increases in drought severity and heat extremes, reductions in water availability, and disruption and transformation of important ecosystems. These impacts may cause large adverse consequences for human populations and livelihoods and are likely to be highly deleterious to the development of the region.

Introduction

This report defines Sub-Saharan Africa as the region south of the Sahara. For the projections on changes in temperature, precipitation, aridity, heat extremes, and sea-level rise, the area corresponds broadly to regions 15, 16, and 17 in the IPCC´s special report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX).

The region´s development prospects have been improving as it has experienced above-average growth. The picture that emerges from the scientific evidence of climate impacts, however, is that global warming poses escalating risks which could undermine promising trends, even at relatively low levels of warming.

The most prominent physical risk factors identified for the region are:

- Increases in temperatures and extremes of heat
- Adverse changes to precipitation patterns in some regions
- Increased incidences of extreme weather events
- Sea-level rise
- Increased aridity

This analysis reviews these physical impacts[23] and their effects on specific sectors, including agriculture, water resources, and human health.[24]

Sub-Saharan Africa is characterized by a large diversity of cultural, social, and economic conditions. This diversity shapes

23 Not all physical risks are covered in this section; tropical cyclones, for example, are dealt with in the South East Asia section.

24 This section does not cover all sectors affected by climate change. Risks to the energy sector, for example, are dealt with in the South Asian section.

the vulnerability of populations to these physical impacts. A number of geographic factors also influence the nature and extent of the physical impacts of climate change. For example, more than one in five people in Sub-Saharan Africa live on degraded land, which is more prone to losses in agricultural production and water availability.

The focus of this regional analysis is on food production systems. The IPCC AR4 in 2007 found that Africa is particularly vulnerable to the impacts of climate change, with a substantial risk that agricultural production and access to food in many African countries could be severely compromised—which could adversely affect food security and malnutrition. Recent literature on agriculture and ecosystems confirms this finding, and is presented in Chapter 3, under "Projected Ecosystem Changes" and "Human Impacts."

Regional Patterns of Climate Change

A warming trend since the 1960s to the present has been observed in Sub-Saharan Africa (Blunden & Arndt, 2012). Between 1961 and 2000, for example, there was an increase in the number of warm spells over southern and western Africa. More recent work finds a detectable human-induced warming over Africa as a whole, with warm extremes in South Africa since 1961(Knutson, Zeng, and Wittenberg 2013). In terms of precipitation, the region is characterized by significant inter-annual and inter-decadal variability, but trends are inconsistent on the sub-regional scale: West Africa and the tropical rainforest zone have experienced declines in mean annual precipitation while no long-term trend has been observed in southern Africa even though inter-annual variability has increased with more intense droughts and rainfall events have been reported. Eastern Africa, meanwhile, has seen increasing rainfall in the northern part of the region and decreasing rainfall in the southern part.

In the IPCC AR4, Giannini, Biasutti, Held, and Sobel (2008) analyze temperature and precipitation changes in the CMIP3 climate model ensemble under the SRES AIB scenario relative to pre-industrial levels. Two continental-scale patterns dominate African climate variability: (1) a drying pattern related to ocean warming and enhanced warming of the southern tropics compared to the northern tropics, and (2) the effects of the El Niño Southern Oscillation (ENSO), which is more dominant in East Africa and South Africa (Giannini, Biasutti, Held, and Sobel 2008).

The CMIP3 model-spread is considerable, however, with uncertainty even in the direction of change for precipitation in some regions. For eastern tropical Africa and southern Africa, there is generally stronger consensus between models than for western Africa. A clear percentage-increase in rainfall is projected in eastern tropical Africa and a smaller percentage-decrease is projected in southern Africa.

Box 3.1 Observed Vulnerability

Sub-Saharan African populations are vulnerable to extreme weather events. A number of natural disasters have severely affected populations across the region in the past. Although no studies attributing these events to climate change were found in the course of this research, these events show the region's existing vulnerability. Throughout Sub-Saharan Africa, droughts have increased over the past half century. The consistency across this region between analyses, as well as model projections, suggest the observed trend toward more severe drying would continue under further global warming (Aiguo Dai 2011; Sheffield, Wood, and Roderick 2012; Van der Schrier, Barichivich, Briffa, and Jone 2013). An example of regional vulnerability is the 2011 drought in the Horn of Africa, which affected large numbers of people across Somalia, Ethiopia, Djibouti, and Kenya. As a result, more than 13 million people across the region required life-saving assistance (Karumba 2013). The situation led to extremely high rates of malnutrition, particularly among children (leading to the famine being described as a "children's famine"), accompanied by high rates of infectious diseases, such as cholera, measles, malaria, and meningitis (Zaracostas 2011). The drought particularly exacerbated an existing complex emergency characterized by conflict and insecurity in Somalia (USAID 2012) and caused large numbers of Somalis to become internally displaced or to flee to Ethiopia and Kenya, where they entered overcrowded refugee camps and were faced with further health risks because of inadequate facilities (McMichael, Barnett, and McMichael 2012).

Flooding in early 2013 in river valleys in southern Africa, which most severely affected Mozambique, is another recent example of significant exposure to extreme weather events. The flooding caused over 100 direct flood-caused deaths, such as drowning and electrocution from damaged power lines. Furthermore, indirect mortalities are likely to far exceed those of direct flood caused deaths, for instance through steep increases in the prevalence of diaroheal disease and malaria. The flooding also caused livestock and crop losses, and widespread temporary displacement with a total of 240,827 people affected in Mozambique (UNRCO 2013). A subsequent cholera epidemic with 1,352 reported cases in the northern province of Cabo Delgado has been linked to the disaster. Floodwaters also damaged health clinics (UNRCO 2013). The country has also seen other flooding and cyclones in recent years, notably in 2000, when one-third of crops were destroyed and hundreds of people lost their lives (Fleshman 2007).

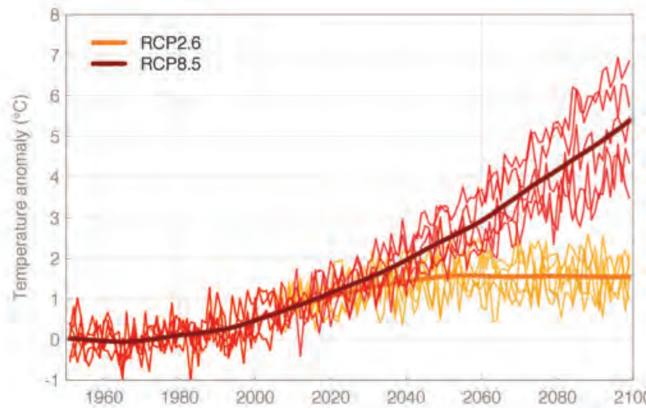
These examples from the Horn of Africa and Mozambique highlight the ramifications for exposed populations arising from the extreme events that may become more frequent and intense with climate change.

Some modest improvements in representing precipitation patterns by CMIP5 models have been reported, though not specifically for Sub-Saharan Africa (Kelley et al. 2012; Li, Waliser, Chen, and Guan 2012; Zhang and Jin 2012). Uncertainty in future precipitation projections remains large. Moreover, recent decadal fluctuations in Africa´s climate, especially droughts in the Sahel region, have been notoriously hard to reproduce in coupled climate models (Giannini, Biasutti, Held, and Sobel 2008; Mohino, Janicot, and Bader 2010). The analyses presented here are based on ISI-MIP models, which are bias-corrected to reproduce the observed historical mean and variation in both temperature and precipitation. This way, future projections might provide more robust and consistent trends. Nevertheless, given the uncertainty in the underlying climate models, only large-scale changes in precipitation patterns over those regions where the models agree can be considered robust. Warming patterns, however, are much more robust.

Projected Temperature Changes

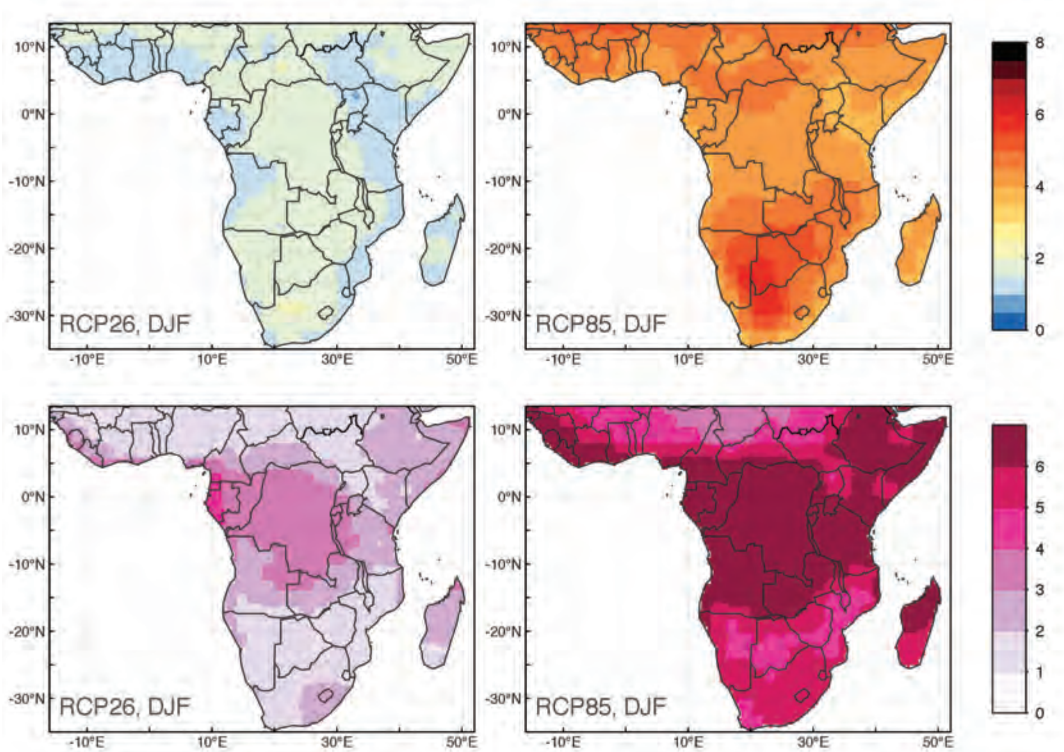
The projected austral summer (December, January, and February, or DJF) warming of the Sub-Saharan land mass for low- and high-emission scenarios is shown in Figure 3.2. Warming is slightly less strong than for that of the global land area, which is a general feature of the Southern Hemisphere (see Figure 2.7). In a 2°C

Figure 3.2: Temperature projections for Sub-Saharan land area



Multi-model mean (thick line) and individual models (thin lines) under RCP2.6 (2°C world) and RCP8.5 (4°C world) for the months of DJF. The multi-model mean has been smoothed to give the climatological trend.

Figure 3.3: Multi-model mean temperature anomaly for RCP2.6 (left) and RCP8.5 (right) for the months of DJF for Sub-Saharan Africa



Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–99 relative to 1951–80, and normalized by the local standard deviation (bottom row).

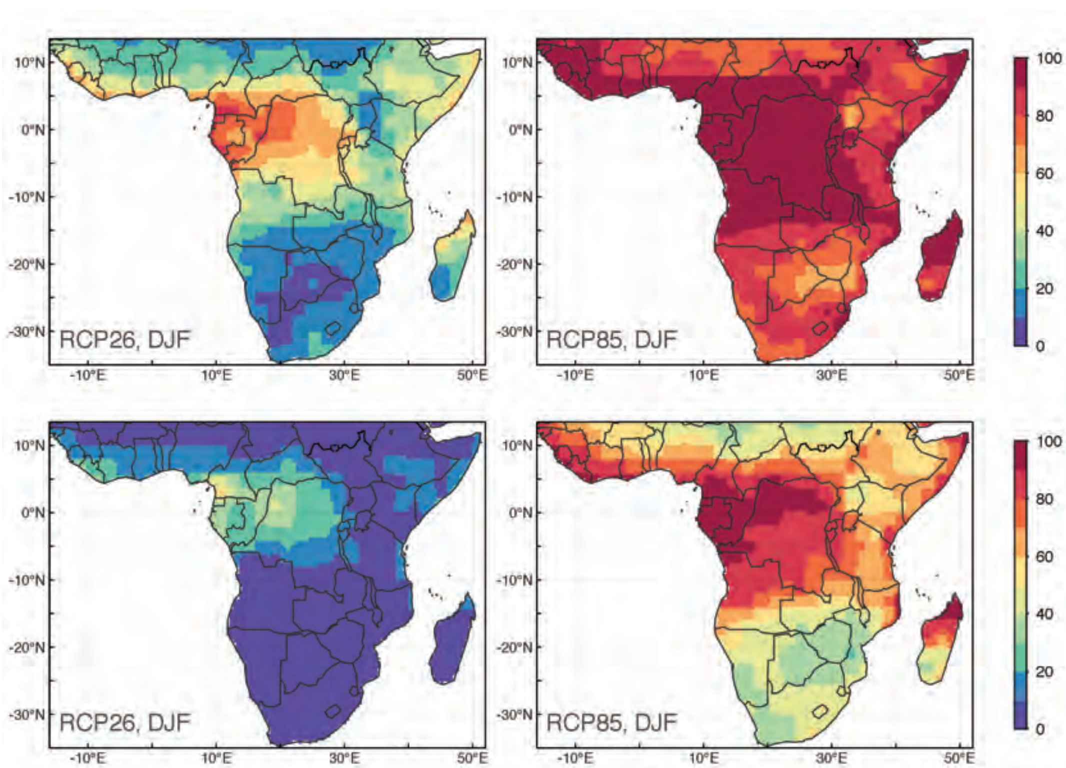
world, African summer temperatures peak by 2050 at about 1.5°C above the 1951–80 baseline and remain at this level until the end of the century. In a 4°C world, warming continues to increase until the end of the century, with monthly summer temperatures over Sub-Saharan Africa reaching 5°C above the 1951–80 baseline by 2100. Geographically, this warming is rather uniformly distributed, although in-land regions in the subtropics warm the most (see Figure 3.3). In subtropical southern Africa, the difference in warming between RCP2.6 and RCP8.5 is especially large. This is likely because of a positive feedback with precipitation: the models project a large decrease in precipitation here (see Figure 3.6), limiting the effectiveness of evaporative cooling of the soil.

The normalized warming (that is, the warming expressed in terms of the local year-to-year natural variability) shows a particularly strong trend in the tropics (Figure 3.3). The normalized warming is a useful diagnostic as it indicates how unusual the warming is compared to fluctuations experienced in the past. The monthly temperature distribution in tropical Africa shifts by more than six standard deviations under a high-emission scenario (RCP8.5), moving this region to a new climatic regime by the end of the 21st century. Under a low-emission scenario (RCP2.6), only localized regions in eastern tropical Africa will witness substantial normalized warming up to about four standard deviations.

Projected Changes in Heat Extremes

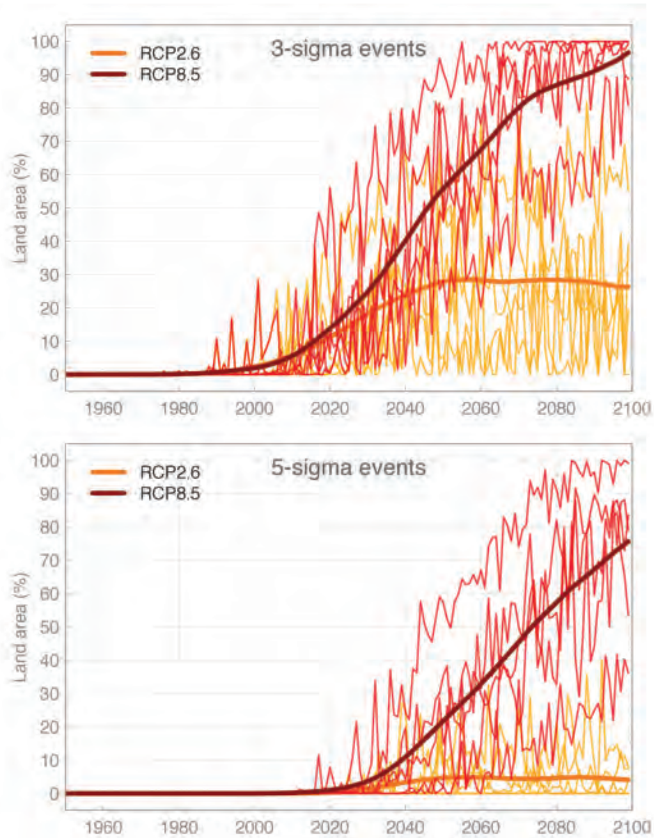
The frequency of austral summer months (DJF) hotter than 5-sigma, characterized by unprecedented temperatures (see the Chapter 2 on "Projected Temperature Changes"), increases over Sub-Saharan Africa under the high-emission scenario (Figure 3.4 and 3.5). By 2100, the multi-model mean of RCP8.5 projects that 75 percent of summer months would be hotter than 5-sigma (Figure 3.5) and substantially higher than the global average (see Chapter 2 on "Projected Changes in Heat Extremes"). The model uncertainty in the exact timing of the increase in frequency of extremely hot months is larger for Sub-Saharan Africa compared to the global mean uncertainty as averaging is performed over a smaller surface area. During the 2071–99 period, more than half (~60 percent) of Sub-Saharan African summer months are projected to be hotter than 5-sigma, with tropical West Africa in particular being highly impacted (~90 percent). Over this period, almost all summer months across Sub-Saharan Africa will be hotter than 3-sigma, with temperatures considered unusual or virtually absent in today's

Figure 3.4: Multi-model mean of the percentage of austral summer months in the time period 2071–99



Temperatures greater than 3-sigma (top row) and 5-sigma (bottom row) for scenario RCP2.6 (left) and RCP8.5 (right) over Sub-Saharan Africa.

Figure 3.5: Multi-model mean (thick line) and individual models (thin lines) of the percentage of Sub-Saharan African land area warmer than 3-sigma (top) and 5-sigma (bottom) during austral summer months (DJF) for scenarios RCP2.6 and RCP8.5



Multi-model mean (thick line) and individual models (thin lines) under RCP2.6 (2°C world) and RCP8.5 (4°C world) for the months of DJF. The multi-model mean has been smoothed to give the climatological trend.

climate (Figure 3.4). Under RCP8.5, all African regions, especially the tropics, would migrate to a new climatic regime. The precise timing of this shift depends on the exact regional definition and the model used.

Under the low-emission scenario, the bulk of the high-impact heat extremes expected in Sub-Saharan Africa under RCP8.5 would be avoided. Extremes beyond 5-sigma are projected to cover a minor, although non-negligible, share of the surface land area (~5 percent), concentrated over western tropical Africa (Figure 3.4). Over most subtropical regions, 5-sigma events would still be rare. In contrast, the less extreme months, beyond 3-sigma, would increase substantially to about 30 percent of the Sub-Saharan land area (Figure 3.5). Thus, even under a low-emission scenario, a substantial increase in heat extremes in the near term is anticipated.

Consistent with these findings, CMIP5 models project that the frequency of warm nights (beyond the 90th percentile) and the duration of warm spells increases most in tropical Africa (Sillmann and Kharin 2013a). Under RCP8.5, by the end of the century warm nights are expected to occur about 95 percent of the time in tropical west and east Africa and about 85 percent of the time in southern Africa, with only limited inter-model spread. Limiting greenhouse gas emissions to a RCP2.6 scenario reduces these numbers to ~50 percent and ~30 percent respectively.

Precipitation Projections

Consistent with CMIP3 projections (Giannini, Biasutti, Held, and Sobel 2008a), the ISI-MIP models' projected change in annual mean precipitation shows a clear pattern of tropical East Africa (Horn of Africa) getting wetter and southern Africa getting drier. Note that for Somalia and eastern Ethiopia the projections show a large relative change over a region that is very dry. Western tropical Africa only shows a weak (<10 percent) increase in annual precipitation, although model uncertainty is large and there is limited agreement among models on the size of changes. The dipole pattern of wetting in tropical East Africa and drying in southern Africa is observed in both seasons and in both emission scenarios. Under the low-emission scenario, the magnitudes of change are smaller, and the models disagree on the direction of change over larger areas. Under the high-emission scenario, the magnitude of change becomes stronger everywhere and the models converge in the direction of change. For this stronger signal of change, model disagreement between areas getting wetter and areas getting drier (in the multi-model mean) is limited to regions at the boundary and some regions in tropical western Africa.

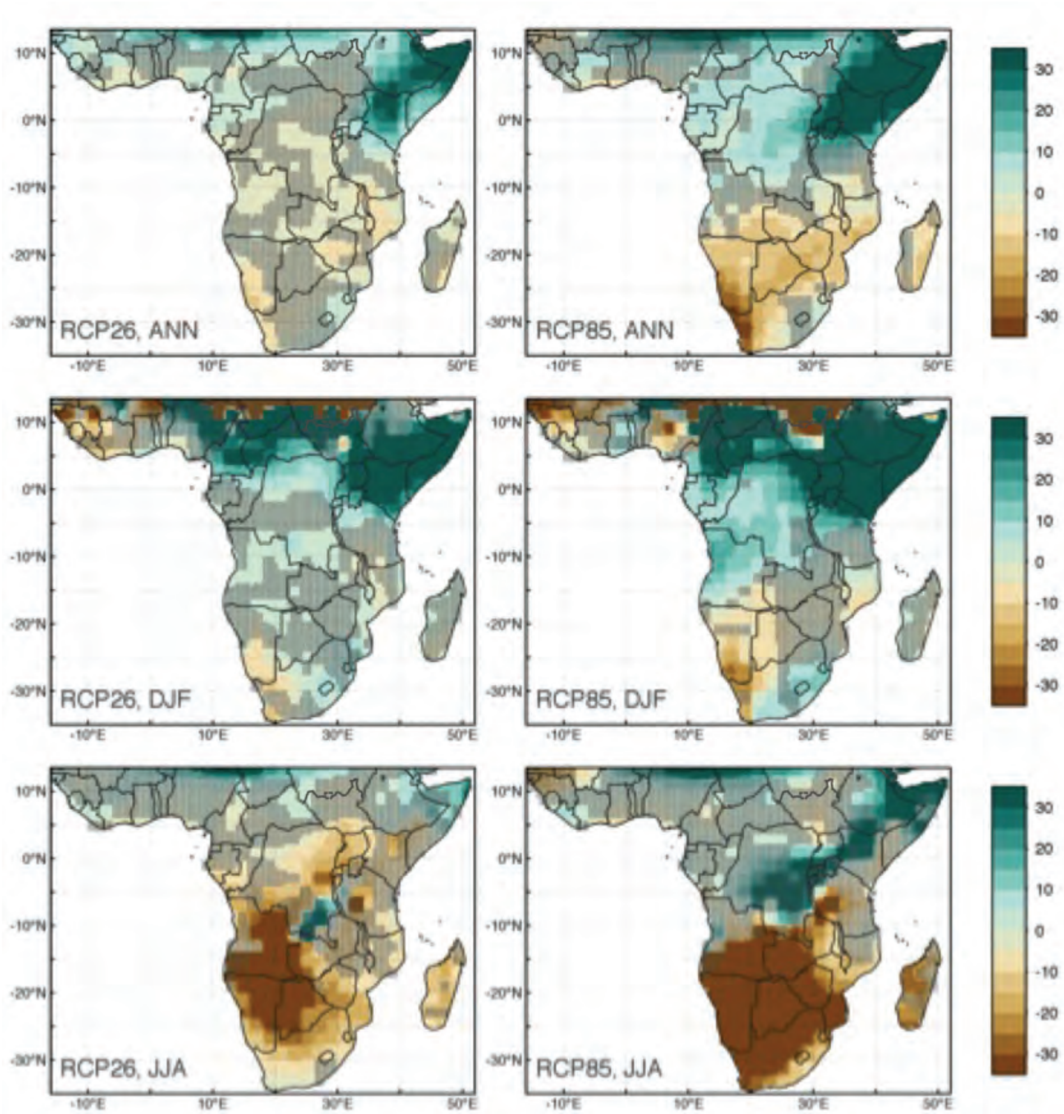
Subtropical southern Africa could see a decrease of annual precipitation by up to 30 percent, contributing to an increase in aridity in this region (see Chapter 3 on "Aridity"), although it must be noted that this is a large relative change in a region with very low rainfall.

The wetting of tropical East-Africa occurs predominantly during the austral summer (DJF), whereas the drying of southern Africa occurs predominantly during the austral winter (JJA), the driest season, so that the annual pattern is primarily determined by the smaller relative changes during the wetter season (DJF).

However, the agreement between global models on increased precipitation in East Africa and the Horn of Africa in particular does not necessarily imply high confidence in these results. Although global climate models are needed to project interactions between global circulation patterns of atmosphere and ocean, regional models offer a higher spatial resolution and provide a way to take into account complex regional geography and reproduce local climate generally better than global models. Regional models use boundary conditions prescribed by global models, so that their large-scale forcings, for example due to anthropogenic influences, are consistent with GCMs.

Regional climate models do not reproduce the increase in precipitation projected by global models for East Africa as a whole. On

Figure 3.6: Multi-model mean of the percentage change in annual (top), austral summer (DJF-middle) and austral winter (JJA-bottom) precipitation for RCP2.6 (left) and RCP8.5 (right) for Sub-Saharan Africa by 2071–99 relative to 1951–80



Hatched areas indicate uncertainty regions with two out of five models disagreeing on the direction of change compared to the remaining three models.

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a sub-regional scale, these models show areas of strongly reduced precipitation by mid-century for a roughly 2°C global warming, for example in Uganda and Ethiopia (Patricola and Cook 2010; Cook and Vizy 2013; Laprise et al. 2013). Cook and Vizy (2012) showed how the strong decrease of the long rains in regional climate models, combined with warming, would lead to a drastically shorter growing season in East Africa, partly compensated by a modest increase in short-rains season length.

Using global-model projections in precipitation, (Dai, 2012) estimated for a global-mean warming of 3°C by the end of the 21st century that drought risk expressed by the Palmer Drought Severity Index[25] (PDSI) reaches a permanent state of severe to extreme droughts in terms of present-day conditions over southern Africa, as well as increased drought risk over Central Africa. Dai (2012) showed that projected changes in soil-moisture content are generally consistent with the pattern of PDSI over Sub-Saharan Africa. Taylor et al. (2012) confirmed that the projected

[25] Drought indicators like PDSI include a time-dependent water balance calculation that includes monthly precipitation, temperature, wind speed, incoming radiation, and takes account of present-day local climate so that drought risk is presented relative to existing conditions.

increased drought risk over southern Africa is consistent across other drought indicators, but added West Africa as an area where projections consistently show an increased drought risk. However, Figure 3.6 shows that precipitation changes are highly uncertain in the latter region, which Taylor et al (2012) might not have been taken into account fully.

According to Giannini, Biasutti, Held, and Sobel (2008a), the uncertainties in western tropical Africa are mainly because of competing mechanisms affecting rainfall. On the one hand, the onset of convection and subsequent rainfall is mainly affected by temperature at the surface and higher levels in the atmosphere. On the other hand, the amount of moisture supply is primarily affected by changes in atmospheric circulation, which can be induced by the temperature contrast between land and ocean. The effect of El Niño events mainly act via the first mechanism, with warming of the whole tropical troposphere stabilizing the atmospheric column and thereby inhibiting strong convection (Giannini, Biasutti, Held, and Sobel 2008a).

Sillmann and Kharin (2013a) studied precipitation extremes for 2081–2100 in the CMIP5 climate model ensemble under the low emission high emission scenario. Under the high-emission scenario, the total amount of annual precipitation on days with at least 1 mm of precipitation (total wet-day precipitation) increases in tropical eastern Africa by 5 to 75 percent, with the highest increase in the Horn of Africa, although the latter represents a strong relative change over a very dry area. In contrast to global models, regional climate models project no change, or even a drying for East Africa, especially during the long rains. Consistently, one recent regional climate model study projects an increase in the number of dry days over East Africa (Vizy and Cook 2012b). Changes in extreme wet rainfall intensity were found to be highly regional and projected to increase over the Ethiopian highlands.

Sillmann and Kharin (2013a) further projected changes of +5 to –15 percent in total wet-day precipitation for tropical western Africa with large uncertainties, especially at the monsoon-dependent Guinea coast. Very wet days (that is, the top 5 percent) show even stronger increases: by 50 to 100 percent in eastern tropical Africa and by 30 to 70 percent in western tropical Africa. Finally in southern Africa, total wet day precipitation is projected to decrease by 15 to 45 percent, and very-wet day precipitation to increase by around 20 to 30 percent over parts of the region. However, some localized areas along the west coast of southern Africa are expected to see decreases in very wet days (up to 30 percent). Here, increases in consecutive dry days coincide with decreases in heavy precipitation days and maximum consecutive five-day precipitation, indicating an intensification of dry conditions. The percentile changes in total wet-day precipitation, as well as in very wet days, are much less pronounced in the low emission scenario RCP2.6.

Aridity

The availability of water for ecosystems and society is a function of both demand and supply. The long-term balance between demand and supply is a fundamental determinant of the ecosystems and agricultural systems able to thrive in a certain area. This section assesses projected changes in Aridity Index (AI), an indicator designed for identifying "arid" regions, that is regions with a structural precipitation deficit (UNEP 1997; Zomer 2008). AI is defined as total annual precipitation divided by potential evapotranspiration; the latter is a standardized measure of water demand representing the amount of water a representative crop type would need over a year to grow (see Appendix 2). Potential evapotranspiration is to a large extent governed by (changes in) temperature, although other meteorological variables play a role as well.

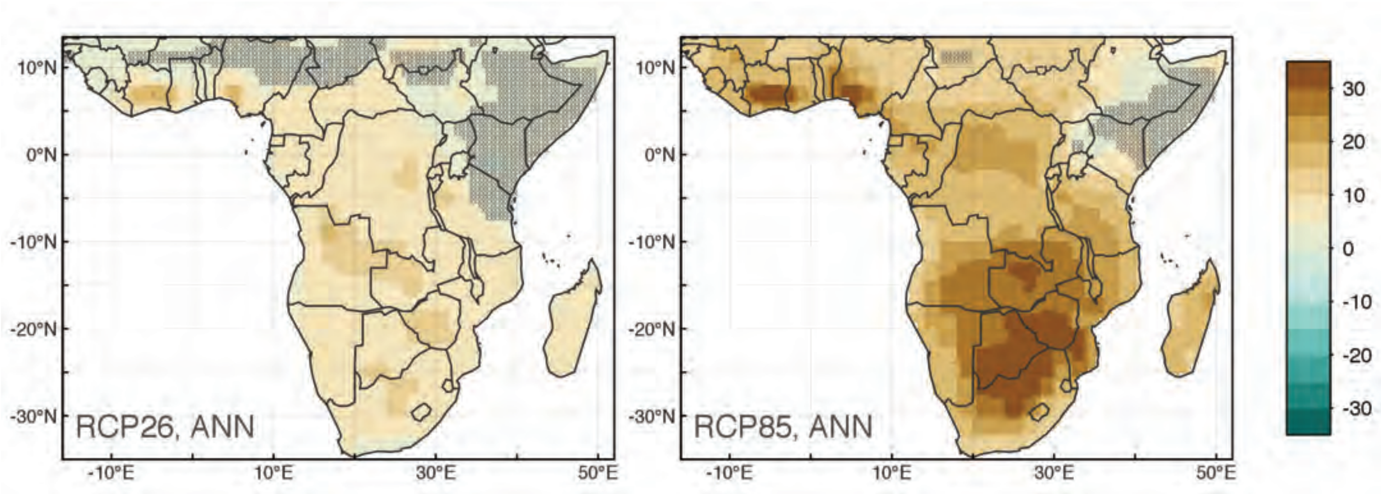
A smaller AI value indicates a larger water deficit (i.e., more arid condition), with areas classified as hyper-arid, arid, semi-arid, and sub-humid as specified in Table 3.2. In the absence of an increase in rainfall, an increase in potential evapotranspiration translates into a lower AI value and a shift toward more structurally arid conditions.

Analysis by the authors shows that, in general, the annual mean of monthly potential evapotranspiration increases under global warming (see Appendix 2). This is observed over all of Sub-Saharan Africa with strong model agreement, except for regions projected to see a strong increase in precipitation. In Eastern Africa and the Sahel region, the multi-model mean shows a small reduction in potential evapotranspiration—but the models disagree. Thus regions that are getting wetter in terms of increased rainfall see either only a limited increase or even a decrease in potential evapotranspiration. By contrast, a more unambiguous signal emerges for regions projected to get less rainfall (notably southern Africa), where the projections show an enhanced increase in potential evapotranspiration. This is likely because of the feedback between precipitation and evaporation via temperature. In regions receiving more rainfall there is enough water available for evaporative cooling; this limits the warming of the surface. In regions where the soil dries out because of a lack of precipitation, however, no more heat can be converted into latent heat and all heat results in increased surface temperatures.

Table 3.2: Climatic classification of regions according to Aridity Index (AI)

	Minimum AI Value	Maximum AI Value
Hyper-arid	0	0.05
Arid	0.05	0.2
Semi-arid	0.2	0.5
Sub-humid	0.5	0.65

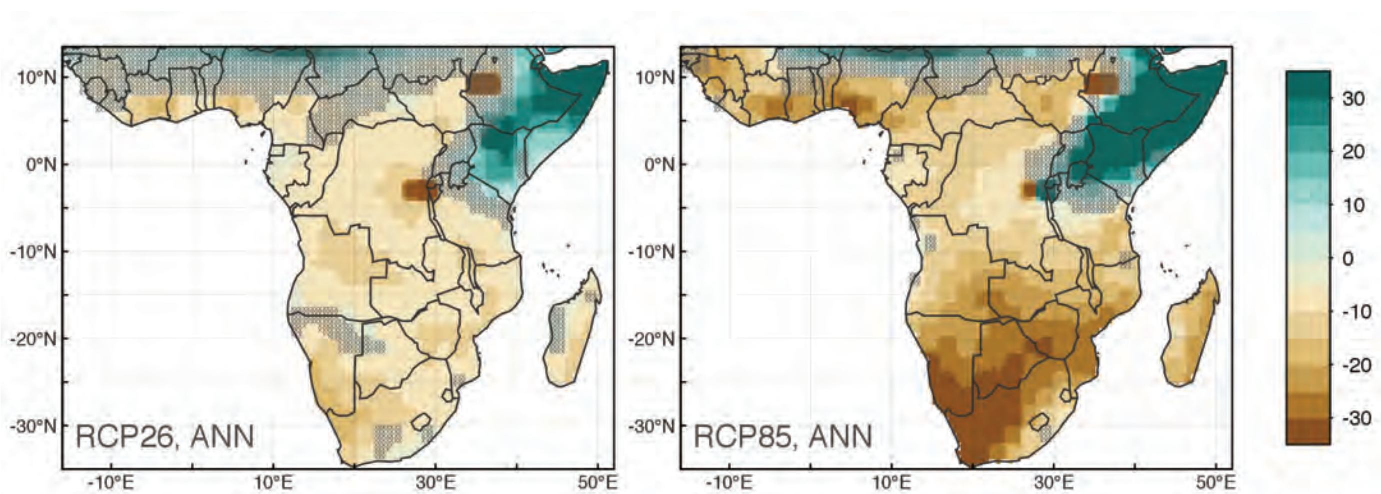
Figure 3.7: Multi-model mean of the percentage change in the annual-mean of monthly potential evapotranspiration for RCP2.6 (left) and RCP8.5 (right) for Sub-Saharan Africa by 2071–99 relative to 1951–80



In non-hatched areas, at least 4/5 (80 percent) of models agree. In hatched areas, at least 2/5 (20 percent) disagree.

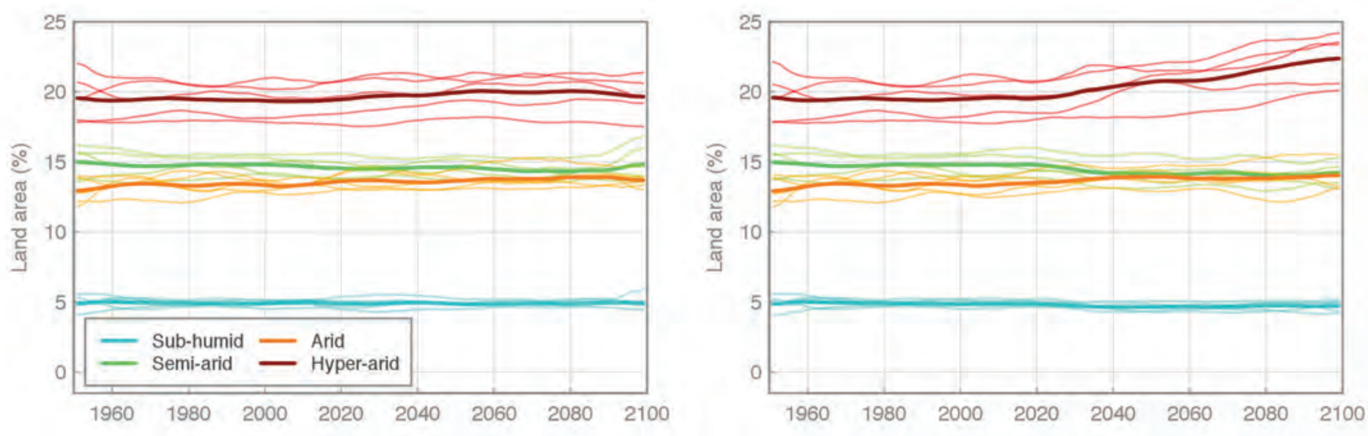
In general, a local warming, amplified by dry conditions, leads to an increase in potential evaporation. In other words, were a standard crop-type to grow there, it would need to release more heat in the form of evapotranspiration to survive the local conditions. This shortens the growing season, if moisture is the main factor constraining the length of the growing season, which is generally the case in sub-humid and drier regions. A shorter growing season implies lower crop yields, a higher risk of crop failure, or a need to shift to different crop types (adaptation). In the absence of an increase in rainfall (supply), an increase in potential evapotranspiration (demand) translates into a lower AI value and a shift toward more structurally arid conditions. There is a close match between the shift in potential evapotranspiration in Figure 3.7 and the shift in AI, which is shown in Figure 3.8, with the strongest deterioration toward more arid conditions in Southern Africa. A notable exception is southwestern Africa, where

Figure 3.8: Multi-model mean of the percentage change in the aridity index in a 2°C world (left) and a 4°C world (right) for Sub-Saharan Africa by 2071–99 relative to 1951–80



In non-hatched areas, at least 4/5 (80 percent) of models agree. In hatched areas, at least 2/5 (20 percent) disagree. Note that a negative change corresponds to a shift to more arid conditions and vice versa.

Figure 3.9: Multi-model mean (thick line) and individual models (thin lines) of the percentage of Sub-Saharan African land area under sub-humid, semi-arid, arid, and hyper-arid conditions for scenarios RCP2.6 (left) and RCP8.5 (right)



the evapotranspiration-driven shift in AI is amplified by a decline in rainfall (see Figure 3.6). By contrast, the improved (higher) aridity index in East Africa is correlated with higher rainfall projected by global climate models, a characteristic that is uncertain and not reproduced by higher-resolution regional climate models (see Chapter 3 on "Precipitation Projections"). In addition, note that for Somalia and eastern Ethiopia the shift implies a large relative shift imposed on a very low aridity index value, which results in AI values still classified as arid or semi-arid.

The shift in AI in Figure 3.8 translates into a shift of categorization of areas into aridity classes. Figure 3.9 shows that although there is little change in net dry areas in a 2°C world, a 4°C world leads to a shift of total area classification toward arid and hyper-arid. The overall area of hyper-arid and arid regions is projected to grow by 10 percent in a 4°C world (from about 20 percent to 23 percent of the total sub-Saharan land area), and by 3 percent in a 2°C world by 2080–2100 relative to 1986–2005. As semi-arid area shrinks, total arid area increases by 5 percent in a 4°C world and 1 percent in a 2°C world. The results for a 4°C world are consistent with Fischer et al. (2007), who used a previous generation of GCMs and a more sophisticated classification method based on growing period length to estimate a 5–8 percent increase in arid area in Africa by 2070–2100.

Regional Sea-level Rise

The difference in regional sea-level rise in Sub-Saharan Africa between a 2°C and a 4°C world is about 35 cm by 2100 using the semi-empirical model employed in this report. As explained in Chapter 2, current sea levels and projections of future sea-level rise are not uniform across the world. Sub-Saharan Africa as defined in this report stretches from 15° north to 35° south. Closer to the equator, but not necessarily symmetrically north and south, projections of local sea-level rise show a stronger increase compared to mid-latitudes. Sub-Saharan Africa experienced sea-level rise of 21 cm by 2010 (Church and White 2011). For the African coastlines, sea-level rise projected by the end of the 21st century relative to 1986–2005 is generally around 10-percent higher than the global mean, but higher than this for southern Africa (for example, Maputo) and lower for West Africa (for example, Lomé). Figure 3.10 shows the regional sea-level rise projections under the high emission scenario RCP8.5 for 2081–2100. Note that these projections include only the effects of human-induced global climate change, not those of local land subsidence resulting from natural or human influences.

Figure 3.10: Regional sea-level rise in 2081–2100 (relative to 1986–2005) for the Sub-Saharan coastline under RCP8.5

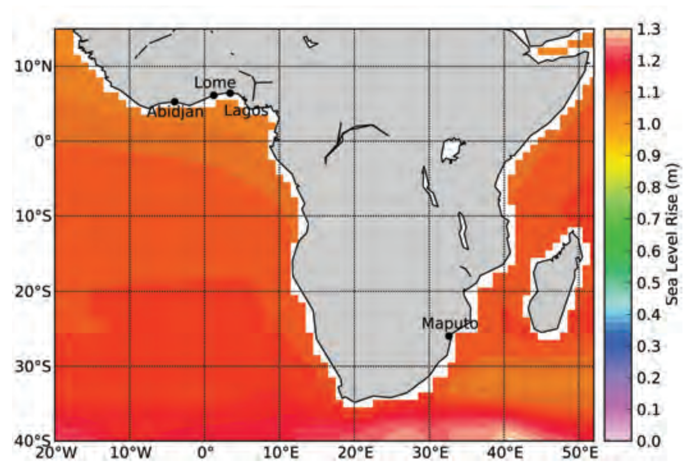
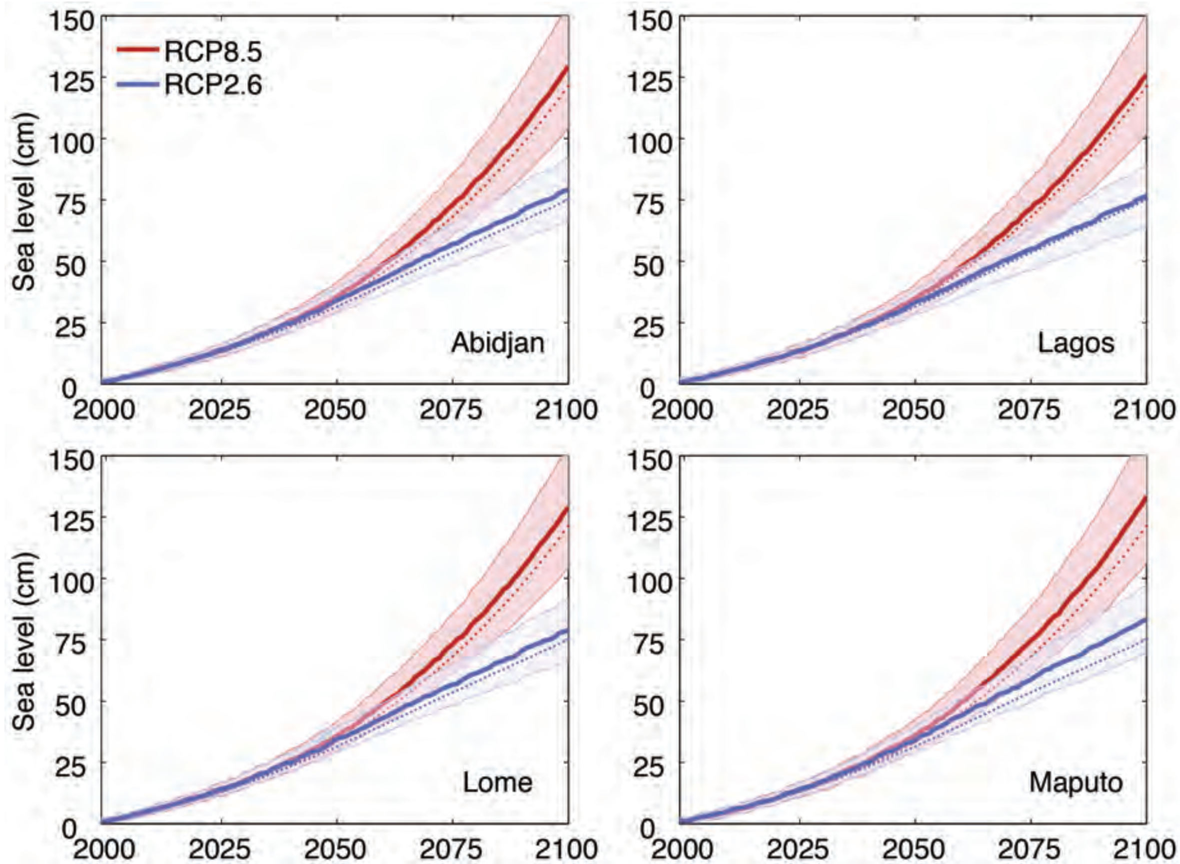


Figure 3.11: Local sea-level rise above 1986–2005 mean as a result of global climate change (excluding local change because of land subsidence by natural or human causes)



Shaded areas indicate 66 percent uncertainty range and dashed lines global-mean sea-level rise for comparison.

The time series of sea-level rise in a selection of locations in Sub-Saharan Africa is shown in Figure 3.11. Locations in West Africa are very close in terms of latitude and are projected to face comparable sea-level rise in a 4°C world, that is around 105 (85 to 125) cm by 2080–2100 (a common time period in impact studies assessed in the following sections). In a 2°C world, the rise is significantly lower but still considerable, at 70 (60 to 80) cm. Near Maputo in southern Africa, regional sea-level rise is some 5 cm higher by that time. For these locations, the likely regional sea-level rise (> 66 percent chance) exceeds 50 cm above 1986–2005 by the 2060s in a 4°C warming scenario and 100 cm by the 2090s, both about 10 years before the global mean exceeds these levels.

In a 2°C warming scenario, 0.5 m is likely exceeded by the 2070s, only 10 years after exceeding this level in a 4°C warming scenario. By the 2070s, the rate of sea-level rise in a 2°C warming scenario peaks and remains constant, while that in the 4°C warming scenario continues to increase. As a result, one meter of sea-level rise is reached in a 4°C warming scenario by 2090; this level is not likely to be exceeded until well into the 22nd century in a 2°C warming scenario.

The Vulnerability of Coastal Populations and Infrastructure

Sea-level rise would have repercussions for populations and infrastructure located in coastal areas. Using the DIVA model, Hinkel et al. (2011) investigate the future impacts of sea-level rise in Sub-Saharan Africa on population and assets in Sub-Saharan Africa, with and without adaptation measures, under four different sea-level rise scenarios[26] and a no sea-level rise scenario. The applied adaptation measures are dikes building, maintenance, and upgrades and beach nourishment.

[26] Forty-two cm, 64 cm, 104 cm, and 126 cm above 1995 sea level for a range of mitigation and non-mitigation scenarios.

Projected Number of People Flooded and Displaced

Hinkel et al. (2011) estimate the number of people flooded[27] every year and the number of people forced to migrate because of the impacts of coastal erosion induced by sea-level rise. Under the high sea-level rise scenario (126 cm by 2100), the authors estimate that there would be approximately 18 million[28] people flooded in Sub-Saharan Africa per year. Under a sea-level rise scenario (64 cm by 2100), there would be close to 11 million people flooded every year. In the no sea-level rise scenario, only accounting for delta subsidence and increased population, up to 9 million people would be affected.

Mozambique and Nigeria are projected to be the most affected African countries, with 5 and 3 million people respectively being flooded by 2100 under the high sea-level rise scenario. However, Guinea-Bissau, Mozambique, and The Gambia would suffer the highest percentage of population affected, with up to 10 percent of their total projected population affected by flooding.

As a consequence of land loss because of coastal erosion induced by sea-level rise, the authors project that by 2100 between 12,000[29] (low business-as-usual sea-level rise scenario) and 33,000 people[30] (high business-as-usual sea-level rise scenario) could be forced to migrate.

Projected Damage to Economic Assets

Infrastructure in coastal zones is particularly vulnerable to both sea-level rise and to such weather extremes as cyclones. Damage to port infrastructure in Dar es Salaam, Tanzania, for example, would have serious economic consequences. The seaport handles approximately 95 percent of Tanzania's international trade and serves landlocked countries further inland (Kebede and Nicholls 2011). Most of the tourism facilities of Mombasa, Kenya, are located in coastal zones, which are under threat of sea-level rise in addition to a higher frequency of flooding and other extreme weather events that already cause damage almost every year (Kebede, Nicholls, Hanson, and Mokrech 2012). Damage to seafront hotel infrastructure has also already been reported in Cotonou, Benin—with this also considered a risk with rising sea levels elsewhere (Hope 2009). While to date there are few projections of the effects on gross domestic product (GDP) from impacts on the tourism sector, the agglomeration of tourism infrastructure in coastal areas may place this sector at severe risk of the impacts of sea-level rise.

Hinkel et al. (2011) estimate the damage costs resulting from sea-level rise in Sub-Saharan Africa, defining damage costs as the projected cost of economic damage induced by coastal flooding, forced migration, salinity intrusion, and loss of dry land. The authors estimate damage costs using a 1995 dollar undiscounted value.[31] In a no-adaption scenario, the sea-level rise would incur approximately $3.3 billion[32] in damages in Sub-Saharan Africa under the 126 cm sea-level rise scenario. Under a lower emission scenario leading to a 2°C temperature increase by the end of the century, damages due to sea-level rise may be up to half a billion dollars lower. Mozambique and Guinea Bissau are expected to be the most affected African countries, with a loss of over 0.15 percent of their national GDPs.

Water Availability

The impact of climate change on temperature and precipitation is expected to bring about major changes in the terrestrial water cycle. This affects the availability of water resources and, consequently, the societies that rely on them (Bates, Kundzewicz, Wu, and Palutikof 2008).

Different forms of water availability are distinguishable. Blue water refers to water in rivers, streams, lakes, reservoirs, or aquifers that is available for irrigation, municipal, industrial, and other uses. Green water refers to the precipitation that infiltrates the soil, which rainfed agriculture and natural ecosystems depend on. Because of the different exposure to climate change, the fraction of blue water in aquifers will be discussed separately as groundwater. Blue water resulting from river runoff and surface water and green water are directly affected by temperature and precipitation changes; whereas, groundwater, a component of blue

27 This is the "expected number of people subject to annual flooding taking into account coastal topography, population and defenses" as well the effects of sea-level rise (Hinkel et al. 2011).

28 Hinkel, Vuuren, Nicholls, and Klein (2012)the number of people flooded reaches 168 million per year in 2100. Mitigation reduces this number by factor 1.4, adaptation by factor 461 and both options together by factor 540. The global annual flood cost (including dike upgrade cost, maintenance cost and residual damage cost project 27 million people flooded in 2100 under this sea-level rise scenario in Africa. The 18 million people figure for Sub-Saharan Africa was obtained by subtracting the number of people flooded in Egypt (about 8 million), Tunisia (0.5 million), and Morocco (0.5 million).

29 About 15,000 people are projected to be forced to migrate in 2100 under this sea-level rise scenario in the whole of Africa. The figure of 12,000 people for Sub-Saharan Africa was obtained by subtracting the number of people forced to migrate in Egypt (about 2,000) and in Morocco (about 1,000).

30 About 40,000 people are projected to be forced to migrate in 2100 under this sea-level rise scenario in the whole of Africa. The figure of 33,000 people for Sub-Saharan Africa was obtained by subtracting the number of people forced to migrate in Egypt (about 5,000) and in Morocco (about 2,000).

31 Note that using an undiscounted 1995 dollar may contribute to an overestimation of future damage costs.

32 Hinkel et al. (2012)the number of people flooded reaches 168 million per year in 2100. Mitigation reduces this number by factor 1.4, adaptation by factor 461 and both options together by factor 540. The global annual flood cost (including dike upgrade cost, maintenance cost and residual damage cost project $8.9 billion in damages in 2100 under this sea-level rise scenario in Africa. The $3.3 billion damage figure for Sub-Saharan Africa was obtained by subtracting the damage cost in Egypt (about $5 billion), Tunisia, Morocco ($0.5 billion), and in Libya ($0.1 billion).

water, is relatively more resilient to climate variability as long as it is sufficiently[33] recharged from precipitation (Kundzewicz and Döll 2009; Taylor et al. 2012).

The Sub-Saharan African region's vulnerability to changes in water availability is particularly high because of its dependence on rainfed agriculture (Calzadilla, Zhu, Rehdanz, Tol, and Ringler 2009; Salvador Barrios, Outtara, Strobl, and Ouattara 2008) and its lack of water-related infrastructure (Brown and Lall 2006).

Present Threats to Water Availability

Because of a lack of investment in water-related infrastructure that could alleviate stressors, Sub-Saharan Africa is among the regions in the world most seriously threatened by an absence of water security (Vörösmarty et al. 2010). Vörösmarty et al. (2010) find that large parts of Sub-Saharan Africa have medium to high threats[34] arising from semi-aridity and highly seasonally variable water availability, compounded by pollution and human and agricultural water stresses.

Threats are especially high along the Guinea coast and East Africa. This contrasts to regions, such as Europe, where even higher levels of water availability threats are circumvented because of massive investments in water-related infrastructure. According to Vörösmarty et al. (2010), even to alleviate present-day vulnerabilities, a central challenge for Sub-Saharan Africa lies in improving water security by investing in water resource development without undermining riverine biodiversity, as has happened in developed regions similar to Europe.

The index assessed in Vörösmarty et al. (2010) refers to the threat of scarcity in access to clean blue water; green water security seems presently less at risk. Rockström et al. (2009) found that many of the areas classified as blue water scarce (that is, with less than 1,000 m³ per capita per year as is the case for Burkina Faso, Nigeria, Sudan, Uganda, Kenya, Somalia, Rwanda, Burundi, parts of Zimbabwe, and South Africa) can at present provide an adequate overall supply of green water required for producing a standard diet (1,300 m³ per capita per year). Since these indicators refer to water availability per capita, one way to interpret these findings is that there is a better match between population density and available green water (for agricultural production) than between population and available blue water.

Groundwater often is the sole source of safe drinking water in rural areas of Sub-Saharan Africa (MacDonald et al. 2009). Unlike the major aquifer systems in northern Africa, most of Sub-Saharan Africa has generally low permeability and minor aquifers, with some larger aquifer systems located only in the Democratic Republic of" before Congo, parts of Angola, and southern Nigeria (MacDonald et al. 2012). A lack of assessments of both groundwater resources and water quality are among the large uncertainties in assessing the yield of African aquifers (MacDonald et al. 2012). Given that groundwater can act as a buffer for projected climate change, the main challenge will be to quantify whether projected recharge rates would balance with increasing demand-driven exploitation (Taylor et al. 2012).

Projected Impacts on Water Availability

The future impacts of climate change on water availability and stress for Sub-Saharan Africa have been studied for many years. A critical uncertainty is projecting changes in regional precipitation (see Chapter 3 on "Precipitation Projections"). One of the important messages from these projections is that large regions of uncertainty remain, particularly in West Africa and East Africa, but that the uncertainties are reduced with increasing levels of warming. In other words, model projections tend to converge when there is a stronger climate change signal. Projected future population levels and the scale of economic activity have a major impact on indices of water scarcity and availability: a larger population reduces water availability per person, all other circumstances being equal.

Gerten et al. (2011) investigate the changes in water availability per capita. Considering the impacts of climate change alone,[35] they drive a hydrological model with a large ensemble of CMIP3, or earlier generation, climate models. For the 2080s (with a global-mean warming of 3.5°C above pre-industrial levels), they found decreases in green water availability of about 20 percent relative to 1971–2000 over most of Africa[36] and increases of about 20 percent for parts of East Africa (Somalia, Ethiopia, and Kenya). Although green water availability and the Aridity Index assessed in Chapter 3 under "Aridity" are driven by different measures of demand, the analysis undertaken for this report found a strong consistency between the patterns of decreased green water availability and increased aridity across Africa. Gerten et al. (2011) further assessed changes in blue water availability, indicating a 10–20 percent increase in East Africa, Central Africa, and parts of West Africa. The latter is not fully consistent with the more recent multi-model studies discussed below and in Chapter 3 under "Crops", which found a decrease of blue water availability over virtually all of West Africa (Schewe et al. 2013). Taken together and assuming a constant population, most of East Africa and Central Africa

33 Kundzewicz and Döll 2009 define renewable groundwater resources as those where the extraction is equal to the long-term average groundwater recharge. If the recharge equals or exceeds use, it can be said to be sufficient.

34 The threats are defined using expert assessment of stressor impacts on human water security and biodiversity, using two distinctly weighted sets of 23 geospatial drivers organized under four themes (catchment disturbance, pollution, water resource development, and biotic factors). The threat scale is defined with respect to the percentiles of the resulting threat distribution (e.g., moderate threat level (0.5), very high threat (0.75)).

35 In this scenario, population is held constant at the year 2000 level under the SRESA2 scenario (arriving at 4.1°C by the end of the century).

36 South Africa is excluded because changes were found to be insignificant.

show an increase of total green and blue water availability, while Southern Africa and most of West Africa is expected to experience reductions of up to 50 percent. If projected population increases are taken into account, these results indicate with high consensus among models that there is at least a 10-percent reduction in total water availability per capita for all of Sub-Saharan Africa.

A scarcity index can be defined by relating the total green and blue water availability to the amount needed to produce a standard diet and taking into account population growth. For East Africa, Angola, the Democratic Republic of Congo, and most of West Africa, the scarcity index indicates that these countries are very likely to become water scarce; most of Southern Africa is still unlikely to be water scarce.[37] In the latter case, this is mainly because of much lower projections of population growth than for the other parts of the region, with at most a twofold increase (compared to a fourfold increase for the Sub-Saharan African average). It should be noted that the study by Gerten et al. assumes that the CO_2 fertilization effect reduces the amount of water needed to produce a standard diet. The CO_2 fertilization effect, however, and therefore the extent to which the effect of potential water shortages might be offset by the CO_2 fertilization effect, remain very uncertain. Without CO_2 fertilization, Gerten et al. (2011) note that water scarcity deepens, including in South Africa and Sudan, and adds countries like Mauritania, the Democratic Republic of Congo, Zimbabwe, and Madagascar to the list of African countries very likely to be water scarce.

For many countries, the estimate of water availability at the country level may imply that a large portion of its population could still suffer from water shortages because of a lack of sufficient water-related infrastructure among other reasons (Rockström et al. 2009).

In a more recent study of water availability, Schewe et al. (2013) use a large ensemble of the most recent CMIP5 generation of climate models combined with nine hydrological models. They investigate the annual discharge (that is, runoff accumulated along the river network) for different levels of warming during the 21st century under the high warming scenario (RCP8.5 ~3.5°C above pre-industrial levels by 2060–80).[38]

Under 2.7°C warming above pre-industrial levels within regions with a strong level of model agreement (60–80 percent)—Ghana, Côte d'Ivoire, and southern Nigeria—decreases in annual runoff of 30–50 percent are projected. For southern Africa, where there is much greater consensus among impact models, decreases of 30–50 percent are found, especially in Namibia, east Angola, and western South Africa (all of which feature arid climates), Madagascar, and Zambia; there are also local increases. Large uncertainties remain for many regions (e.g., along the coast of Namibia, Angola and in the central Democratic Republic of Congo). With over 80-percent model consensus, there is a projected increase of annual discharge of about 50 percent in East Africa (especially southern Somalia, Kenya, and southern Ethiopia).

This multi-model study found that the largest source of uncertainty in West Africa and East Africa results from the variance across climate models, while in Southern Africa both climate and hydrological models contribute to uncertainty. Uncertainty in hydrological models dominates in western South Africa and in the western Democratic Republic of Congo.

These projected regional changes are enhanced by up to a factor of two for a warming of ~3.5°C above pre-industrial levels, compared to 2.7°C warming above pre-industrial levels, and there is more consensus across the models. These findings are consistent with the changes in aridity previously discussed.

While these broad patterns are consistent with earlier studies, there are important differences. For example, Fung, Lopez, and New (2011) and Arnell et al. (2011) found even more pronounced decreases in Southern Africa of up to 80 percent for a warming of 4°C above 1961–90 levels (which corresponds to ~4.4°C above pre-industrial levels). Gosling et al. (2010) use one hydrological model with a large ensemble of climate models for a range of prescribed temperature increases. The projections for 4°C warming relative to 1961–90 (which corresponds to ~4.4°C above pre-industrial levels) are largely consistent with the findings of Schewe et al. (2013), albeit with some regional differences (e.g., more rather than less runoff in Tanzania and northern Somalia).

In general, effects are found to be amplified in a 4°C world toward the end of the 21st century and, with population growth scenarios projecting steady increases in the region, large parts of Sub-Saharan Africa are projected to face water scarcity (Fung et al. 2011). To help alleviate vulnerability to changes in surface water, the more resilient groundwater resources can act as a buffer—if used sustainably under population growth. However, Sub-Saharan Africa has mostly small discontinuous aquifers; because of a lack of geologic assessments as well as projected increased future land use, large uncertainties about their yields remain. Furthermore, with regions such as South Africa facing a strong decrease in groundwater recharges (Kundzewicz and Döll 2009), the opportunities to balance the effects of more variable surface water flows by groundwater are severely restricted.

The Role of Groundwater

As noted before, groundwater can provide a buffer against climate change impacts on water resources, because it is relatively more resilient to moderate levels of climate change in comparison to surface

37 Large parts of Sub-Sahara Africa (except for Senegal, The Gambia, Burkina Faso, Eritrea, Ethiopia, Uganda, Rwanda, Burundi, and Malawi) are projected to be very unlikely to be water scarce by 2100 in the A2 scenario, for a constant population, due to climate change alone.

38 Note that Schewe et al. (2013) only discuss annual discharges; the distribution of discharges across the season can have severe impacts.

water resources (Kundzewicz and Döll 2009). Döll (2009) studies groundwater recharge for 2041–79 compared to the 1961–90 average using two climate models for the SRES A2 and B2 scenarios (global-mean warming 2.3°C and 2.1°C respectively above pre-industrial levels). For both scenarios, Döll finds a decrease in recharge rates of 50–70 percent in western Southern Africa and southern West Africa, while the recharge rate would increase in some parts of eastern Southern Africa and East Africa by around +30 percent. Note that these increases might be overestimated, as the increased occurrence of heavy rains, which are likely in East Africa (Sillmann, Kharin, Zwiers, Zhang, and Bronaugh, 2013), lowers actual groundwater recharge because of infiltration limits which are not considered in this study. MacDonald et al. (2009) also note that increased rainfall, especially heavy rainfall—as is projected for East Africa—is likely to lead to contamination of shallow groundwater as water tables rise and latrines flood, or as pollutants are washed into wells.

Döll (2009) determine the affected regions in western Southern Africa and southern West Africa as highly vulnerable when defining vulnerability as the product of a decrease in groundwater recharge and a measure of sensitivity to water scarcity. The sensitivity index is composed of a water scarcity indicator as an indicator of dependence of water supply on groundwater and the Human Development Index.

The prospects of alleviating surface water scarcity by using groundwater are severely restricted for those areas where not only surface water availability but also groundwater recharge is reduced because of climate change (as is the case for western Southern Africa and southern West Africa) (Kundzewicz and Döll 2009).

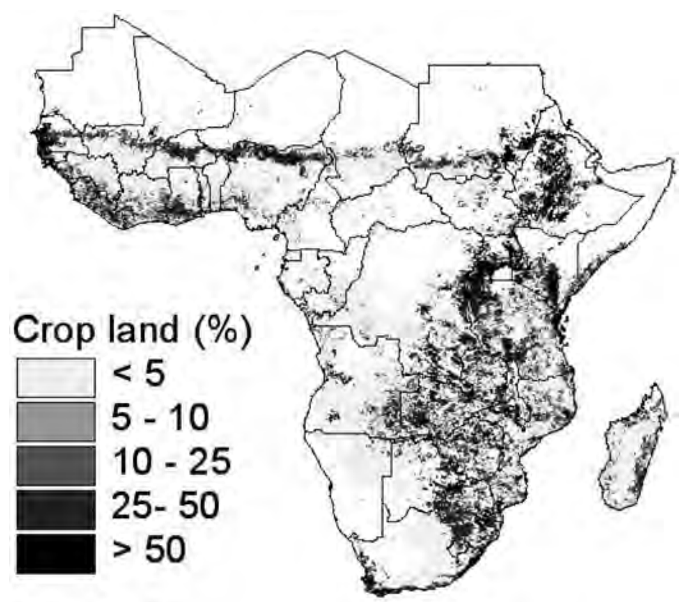
Apart from uncertainty in precipitation projections in Döll (2009), which only used two climate models as drivers, sources of uncertainty lie in the hydrological model used and the lack of knowledge about groundwater aquifers (MacDonald et al. 2009). A further uncertainty relates to changes in land use because of agriculture, which responds differently to changes in precipitation compared to natural ecosystems (R G Taylor et al. 2012). There is more certainty about rises in groundwater extraction in absolute terms resulting from population growth, which threatens to overexploit groundwater resources, particularly in semiarid regions where projected increases of droughts, as well as the projected expansion of irrigated land, is expected to intensify groundwater demand (Taylor et al. 2012).

Agricultural Production

Agriculture is often seen as the most weather dependent and climate-sensitive human activity. It is particularly exposed to weather conditions in Sub-Saharan Africa, where 97 percent of total crop land is rainfed (Calzadilla et al. 2009). Given that 60 percent of the labor force is involved in the agricultural sector, livelihoods are also exposed (Collier, Conway, and Venables 2008).

It is widely accepted that agricultural production in Sub-Saharan Africa is particularly vulnerable to the effects of climate change because of a number of environmental characteristics (Barrios, Outtara, and Strobl 2008). Sub-Saharan Africa is characterized by large differences in water availability because of the diversity of geographical conditions. While the tropics are humid throughout the year, rainfall in the subtropics is limited to the wet season(s). Further poleward, the semiarid regions rely on the wet seasons for water and, together with the arid regions, receive little runoff from permanent water sources. This is exacerbated by high temperatures and dry soils, which absorb more moisture. Average runoff is therefore about 15-percent lower in Sub-Saharan Africa than in any other continent (Barrios et al. 2008). As the tropical regions are not suitable for crop production, crop production in Sub-Saharan Africa is typically located in semiarid regions. The same holds for livestock production, which for animals other than pigs, is not practiced in humid regions because of susceptibility of diseases and low digestibility of associated grasses (Barrios et al. 2008; see Figure 3.12). This, taken together with the fact that less than 4 percent of cultivated area in Sub-Saharan Africa is irrigated (You et al. 2010), makes food production systems highly reliant on rainfall and thus vulnerable to climatic changes, particularly to changes in precipitation and the occurrence of drought.

Figure 3.12: Crop land in Sub-Saharan Africa in year 2000



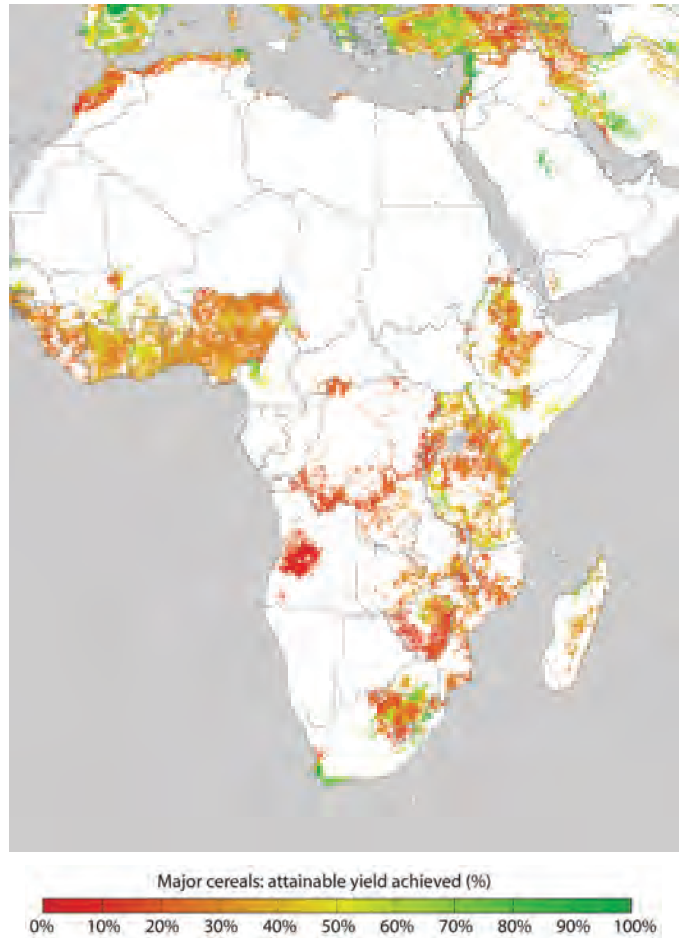
Source: You, Wood, and Wood-Sichra (2009).

The following render agricultural productivity critically vulnerable to climate change: high dependence on precipitation combined with observed crop sensitivities to maximum temperatures during the growing season (Asseng et al. 2011; David B Lobell, Schlenker, and Costa-Roberts 2011a; Schlenker and Roberts 2009); varying and often uncertain responses to factors such as increasing CO_2 concentration; and low adaptive capacities (Müller 2013). As a consequence, climate change is expected to affect agriculture by reducing the area suitable for agriculture, altering the growing season length, and reducing the yield potential (Kotir 2011; Thornton, Jones, Ericksen, and Challinor 2011a). The impacts of extreme events are as yet uncertain but are expected to be significant (Rötter, Carter, Olesen, and Porter 2011).

Africa has already seen declines in per capita agricultural output in recent decades, especially for staple foods; the most important staple foods are cassava, rice, soybean, wheat, maize, pearl millet, and sorghum (Adesina 2010; Liu et al. 2008). Important factors include high levels of population growth, volatile weather, and climatic conditions that have seen droughts or flooding destroy or limit harvests. A number of other factors have also contributed, including use of low-productivity technologies and limited and costly access to modern inputs (Adesina 2010). Levels of malnutrition[39] are high, partly as a result of this limited productivity and the high dependence on domestic production. The prevalence of malnutrition among children under five exceeds 21 percent (2011 data; World Bank 2013n) and one in three people in Sub-Saharan Africa is chronically hungry (Schlenker and Lobell 2010). The prevalence of undernutrition in Sub-Saharan Africa has decreased only slightly since the 1990s, from 32.8 percent (1990–92) to 26.8 percent (projections for 2010–12; Food and Agriculture Organization of the United Nations 2012a).

An important factor remains: the yield potential of arable land in Sub-Saharan Africa is significantly higher than actually achieved (see Figure 3.13). Factors that limit yield differ across regions and crops. For example, nutrient availability is the limiting factor for maize in Western Africa, while water availability is an important co-limiting factor in East Africa (Mueller et al. 2012).

Figure 3.13: Average "yield gap" (difference between potential and achieved yields) for maize, wheat, and rice for the year 2000



Source: Adapted from Mueller et al. (2012).

The agricultural areas in Sub-Saharan Africa that have been identified as the most vulnerable to the exposure of changes in climatic conditions are the mixed semiarid systems in the Sahel, arid and semiarid rangeland in parts of eastern Africa, the systems in the Great Lakes region of eastern Africa, the coastal regions of eastern Africa, and many of the drier zones of southern Africa (Thornton et al. 2006). Faures and Santini (2008) state that relative poverty, which limits adaptive capacities of the local population and thus increases vulnerability, is generally highest in highland temperate, pastoral, and agro-pastoral areas. Those areas classified in the study as highland temperate areas include, for example, Lesotho and the highlands of Ethiopia and Angola; the pastoral zones include much of Namibia, Botswana, and the Horn of Africa; and the agro-pastoral zones include parts of the Sahel region and of Angola, Namibia, Botswana, Zimbabwe, Zambia, Kenya, and Somalia.

Although (changes in) rainfall patterns are crucial for the Sahel region and a drying since the 1960s is well documented (Box 3.2), climate model projections of precipitation in this region diverge widely even in the sign of future change, not just for the generation of models at the time of IPCC's AR4 but also for the latest CMIP5 generation of models used for AR5 (Roehrig et al. 2012). Sahel rainfall is closely linked to sea-surface temperatures in the

39 Defined as a physical condition that is caused by the interaction of an inadequate diet and infection, and of which under-nutrition or insufficient food energy intake is one form (Liu et al. 2008; Roudier et al. 2011).

Box 3.2: The Sahel Region

The Sahel, often cited in the literature as a highly vulnerable area, is a belt of land located between the Sahara desert to the north and tropical forests to the south, with the landscape shifting between semiarid grassland and savanna (Sissoko, Van Keulen, Verhagen, Tekken, and Battaglini 2011). Water is scarce and the soil quality is poor, in part because of human-induced degradation. While the exact nature and cause of observed changes in patterns of rainfall in this region is debatable, there appears to have been an overall shift toward increased temperatures and lower annual average rainfall since the 1960s in the semiarid regions of West Africa (Kotir 2011). These conditions have undermined agricultural production in the region since the 1970s (Barrios et al. 2008). The high levels of climatic risk and relative scarcity of natural resources makes livelihoods in areas such as the Sahel particularly precarious. The repercussions of a climatic disruption to agriculture for affected populations may be more severe here, where people are living nearer the margins of subsistence, than in areas with more abundant resources (Roncoli, Ingram, and Kirshen 2001).

equatorial Atlantic, which are set to increase under global warming (Roehrig et al. 2012), with local rainfall changes amplified by land-surface feedbacks, including vegetation patterns (Giannini et al. 2008). Anthropogenic aerosols over the North Atlantic, however, may have contributed to historic Sahel drying (Rotstayn and Lohmann 2002; Ackerley et al. 2011; Booth et al. 2012), so that drying might be alleviated as aerosol emissions in the Northern Hemisphere are reduced due to air-quality policy or low-carbon development. Total rainfall has recovered somewhat from the 1980s, although there are indications that precipitation frequency has remained at a low level while individual rainfall events have become more intense (Giannini et al. 2008). This is consistent with a basic understanding of a warming world that increases the moisture capacity of the atmosphere and leads to more intense precipitation events.

Crops

Climate change is expected to affect crop yields through a range of factors.

Climatic Risk Factors

One risk factor to which the region is exposed is increasing temperature. High temperature sensitivity thresholds for important crops such as maize, wheat, and sorghum have been observed, with large yield reductions once the threshold is exceeded (Luo 2011). Maize, which is one of the most common crops in Sub-Saharan Africa, has been found to have a particularly high sensitivity to temperatures above 30°C within the growing season. Each day in the growing season spent at a temperature above 30°C reduces yields by one percent compared to optimal, drought-free rainfed conditions (David B Lobell, Schlenker et al. 2011). The optimal temperature of wheat, another common crop, is generally between 15 and 20°C, depending on the varieties of wheat. The annual average temperature across Sub-Saharan Africa is already above the optimal temperature for wheat during the growing season (Liu et al. 2008), and it is expected to increase further. Increases in temperature may translate into non-linear changes in crop yields when high temperature thresholds are crossed. Long-term impacts (toward the end of the 21st century) could be more than twice those in the shorter term to 2050 (Berg, De Noblet-Ducoudré, Sultan, Lengaigne, and Guimberteau 2012).

Drought represents a continuing threat to agriculture, and Africa might be the region most affected by drought-caused yield reductions in the future (Müller, Cramer, Hare, and Lotze-Campen 2011). Recent projections by Dai (2012) indicate that the Sahel and southern Africa are likely to experience substantially increased drought risk in future decades. Rainfall variability on intra-seasonal, inter-annual, and inter-decadal scales may also be a critical source of risk (Mishra et al. 2008). Some studies find that in Sub-Saharan Africa the temporal distribution of rainfall is more significant than the total amount (for example, Wheeler et al. 2005, cited in Laux, Jäckel, Tingem, and Kunstmann 2010).

Another factor that could play a role for future agricultural productivity is plant disease. Climate extremes can alter the ecology of plant pathogens, and higher soil temperatures can promote fungal growth that kills seedlings (Patz, Olson, Uejo, and Gibbs 2008).

One of the major sources of discrepancy between projections of crop yields lies in the disagreement over the relative significance of temperature and precipitation (see Lobell and Burke 2008 on this debate). Assessing the relative role of temperature and rainfall is difficult as the two variables are closely linked and interact (Douville, Salaa-Melia, and Tyteca 2006). The significance of each may vary according to geographical area. For example, Berg et al. (2012) find that yield changes in arid zones appear to be mainly driven by rainfall changes; in contrast, yield appears proportional to temperature in equatorial and temperate zones. Similarly, Batisane and Yarnal (2010) find that rainfall variability is the most important factor limiting dryland agriculture; this may not be so elsewhere. Levels of rainfall variability that would be considered low in some climate regions, such as 50 mm, can mean the difference between a good harvest and crop failure in semi-arid regions with rainfed agriculture.

CO_2 Fertilization Effect Uncertainty

Whether the CO_2 fertilization effect is taken into account in crop models also influences outcomes, with the studies that include it generally more optimistic than those that do not. The CO_2 fertilization effect may increase the rate of photosynthesis and water use efficiency, thereby producing increases in grain mass and number; this may offset to some extent the negative impacts of climate change (see Laux et al. 2010 and Liu et al. 2008). Crop yield and total production projections differ quite significantly depending on whether the potential CO_2 fertilization effect is strong, weak, or absent. See Chapter 3 on "Agricultural Production" for further discussion of the CO_2 fertilization effect.

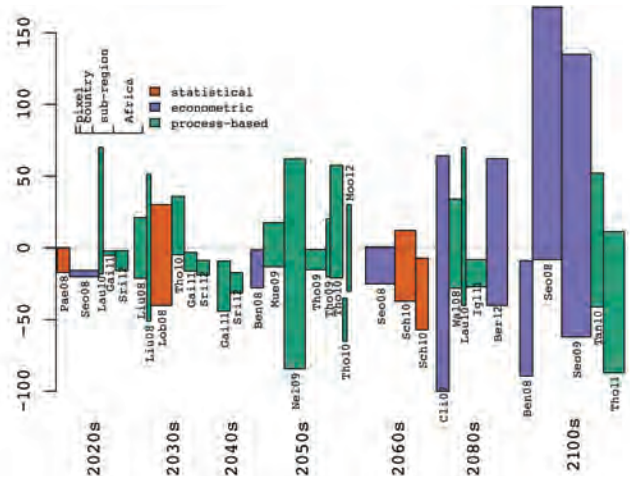
Projected Changes in Crop Yields

Many recent studies examining one or more climatic risk factors predict project significant damage to agricultural yields in Sub-Saharan Africa. These include Knox, Hess, Daccache, and Ortola (2011), Ericksen et al. (2011), Thornton, Jones, Ericksen, and Challinor (2011), and Schlenker and Lobell (2010). However, crop modeling suggests that there can be positive as well as negative impacts on agriculture in Africa, and impacts are expected to vary according to farm type and crop type (Müller et al. 2011) and depending on whether or not adaptation is assumed (Müller 2013). Müller (2013), in a literature review of African crop productivity under climate change, points out that uncertainty in projections increases with the level of detail in space and time. Despite uncertainties, Müller (2013) emphasizes that there is a very substantial risk based on projections of a substantial reduction in yield in Africa. According to Müller (2013), yield reductions in the near term, while often not as severe as in the long term, are particularly alarming as they leave only little time to adapt.

A substantial risk of large negative impacts on crop yields in the West African region, with a median 11-percent reduction by the 2080s, is found in recent meta-analysis of 16 different studies (Roudier et al. 2011). The West African region presently holds over 40 percent of Sub-Saharan Africa's population and over half of the area for cereal, root, and tuber crops. Rainfall in West Africa depends on the West African monsoon, for which climate change projections differ widely. Some project a drier climate and some a wetter climate, which is reflected in the broad range of yield projections.

Larger impacts are found in the northern parts of West Africa, with a median 18-percent reduction in yield projected, compared to the southern West African region, with 13-percent reductions. Dry cereal production in Niger, Mali, Burkina Faso, Senegal, and The Gambia is expected to be more severely affected than those in Benin, Togo, Nigeria, Ghana, Liberia, Sierra Leone, Cameroon, Guinea, Guinea-Bissau, and Côte d'Ivoire, with relative changes of −18 percent and −13 percent respectively. This difference can be explained by a greater warming over continental Africa, the Sahel, and the Sahara in particular, compared to the western parts of the region (where temperatures are expected to increase more slowly).

Figure 3.14: Climate change impacts on African agriculture as projected in recent literature after approval and publication of the IPCC Fourth Assessment Report (AR4)



Impacts are expressed as percent changes relative to current conditions; bar width represents spatial scale of the assessment, colors denote the model type employed (statistical in orange, econometric in purple, and process-based in green). Seo08 refers to the livestock sector only; Tho10 reports pixel-based results only for a random selection of strongly impacted pixels; Sch10 shows country data only for maize; Wal08 employs stylized scenarios that are representative for the climate in 2070–2100; Tan10 refers to NE Ghana only; Gai11 and Sri12 refer to Upper Ouémé basin in the Republic of Benin only.

Source: Müller (2013). The reference information for the studies included in this graph can be found in Appendix 4.

From Müller C. (2013). African lessons on climate change risks for agriculture. Annual Reviews of Nutrition, 33, 1-35. ANNUAL REVIEW OF NUTRITION by Darby, William J. ; Broquist, Harry P. ; Olson, Robert E. Reproduced with permission of ANNUAL REVIEWS in the format Republish in a book via Copyright Clearance Center. Further permission required for reuse." after "... Copyright Clearance Center.

Consistent with other work, this review finds that negative impacts on production are intensified with higher levels of warming (Roudier et al. 2011). It finds close to zero or small negative changes for the 2020s for most scenarios (1.1–1.3°C above pre-industrial levels globally); median losses in the order of −5 percent by the 2050s (1.6–2.2°C above pre-industrial levels globally); and, for the 2080s, a range of reductions of around −5 percent to −20 percent, with the median reduction being greater than 10 percent (2.4–4.3°C above pre-industrial levels globally).

The smallest reductions or largest increases are with the CO_2 fertilization effect taken into account and the greatest reductions are all without it. Analyzing the subset of studies, which also account for CO_2 fertilization, Roudier et al. (2011) find that the CO_2 fertilization effect, which is particularly strong in high emission scenarios and for such C3 crops as soybean and groundnut, leads to significant differences in projections. It may even reverse the direction of impacts. However, major crops in West Africa are C4 crops, such as maize, millet, and sorghum, for which the CO_2 fertilization effect is less pronounced, so that the positive effect may be overestimated (Roudier et al. 2011).

Schlenker and Lobell (2010) estimated the impacts of climate change on five key African crops, which are among the most important calorie, protein, and fat providers in Sub-Saharan Africa: maize, sorghum, millet, groundnuts, and cassava (rice and wheat are excluded from the study as they are usually irrigated). They estimated country-level yields for the 2050s (2046–65) by obtaining future temperature and precipitation changes from 16 GCMs for the A1B SRES scenario and by applying these future changes to two historical weather data series (1961 to 2000 and 2002, respectively) with regression analysis. In this study, for a 2050s global-mean warming of about 2.2°C above pre-industrial levels the median impacts across Sub-Saharan Africa on the yield of maize, sorghum, millet, groundnut, and cassava[40] are projected to be negative, resulting in aggregate changes of –22 percent, –17 percent, –17 percent, –18 percent, and –8 percent. This important work also estimates the probability of yield reductions, which is useful for risk assessments looking at the tales of the probability distribution of likely future changes. It finds a 95-percent probability that the yield change will be greater than –7 percent for maize, sorghum, millet, and groundnut, with a 5-percent probability that damages will exceed 27 percent for these crops.[41] The results further indicate that the changes in temperature appear likely to have a much stronger impact on crop yield than projected changes in precipitation.

The negative results of this work for sorghum are reinforced by more recent work by Ramirez-Villegas, Jarvis, and Läderach (2011). They find significant negative impacts on sorghum suitability in the western Sahelian region and in Southern Africa in this timeframe, which corresponds to a warming of about 1.5°C above pre-industrial levels globally.[42]

In interpreting the significance and robustness of these results there are a number of important methodological caveats. It should be kept in mind that the methodological approach of Schlenker & Lobell (2010) does not consider the potential fertilization effect of increased CO_2 concentration, which might improve projected results. However, maize, sorghum, and millet are C4 crops with a lower sensitivity to higher levels of CO_2 than other crops. The authors also do not take into account any potential future developments in technology, shifts in the growing season as a potential adaptation measure, or potential changes in rainfall distribution within growing seasons (though temperature has been identified as the major driver of changes in crop yield in this study). Further, a potential disadvantage of the panel data used by Schlenker and Lobell (2010) is that responses to permanent changes in climatic conditions might be different compared to responses to weather shocks, which are measured by the observational data. The estimates presented should be assumed as conservative, but relevant as a comparison of predicted impacts on maize yields to previous studies (Schlenker and Lobell 2010).

Further evidence of the potential for substantial yield declines in Sub-Saharan Africa comes from a different methodological approach applied by Berg et al. (2012). Berg et al. assess the potential for impacts on the crop productivity on one of the most important staple foods, a C4 millet cultivar, in a tropical domain, including Africa and India, for the middle (2020–49) and end of the century (2070–99), compared to the 1970–99 baseline. Across both regions and for all climatic zones considered, the overall decline in productivity of millet was –6 percent (with a range of –29 to + 11 percent) for the highest levels of warming by the 2080s. Changes in mean annual yield are consistently negative in the equatorial zones and, to a lesser extent, in the temperate zones under both climate change scenarios and both time horizons.

A robust long-term decline in yield in the order of 16–19 percent is projected for the equatorial fully humid climate zone (which includes the Guinean region of West Africa, central Africa, and most parts of East Africa) under the SRESA1B scenario (3.6°C above pre-industrial levels globally) and the SRESA2 scenario (4.4°C), respectively, for 2100. Although projected changes for the mid-century are smaller, changes are evident and non-negligible, around 7 percent under the A1B – (2.1°C) and –6 percent under the A2 (1.8°C) scenario for the equatorial fully humid zone.

The approach of Berg et al. (2012) accounts for the potential of an atmospheric CO_2 effect on C4 crop productivity for the A2 scenario; the projections show that, across all models, the fertilization effect is limited (between 1.6 percent for the equatorial fully humid zone and 6.8 percent for the arid zone). This finding is consistent with the results of prior studies.

The yield declines by Berg et al. (2012) are likely to be optimistic in the sense that the approach taken is to estimate effects based on assumptions that are not often achieved in practice: for example, optimal crop management is assumed as well as a positive CO_2 fertilization effect. Berg et al. (2012) also point out that the potential to increase yields in Sub-Saharan Africa through improved agricultural practices is substantial and would more than compensate for the potential losses resulting from climate change. When considering annual productivity changes, higher temperatures may facilitate shorter but more frequent crop cycles within a year. If sufficient water is available, no changes in total annual yield would occur, as declining yields per crop cycle are compensated by an increasing number of cycles (Berg et al. 2012). As this much-needed progress has not been seen in past decades, it can be assumed that climate change will represent a serious additional burden for food security in the region.

40 Note that the model fit for cassava is poor because of its weakly defined growing season.

41 These are damages projected for the period 2045–2065, compared to the period 1961–2006.

42 The authors use an empirical model (EcoCrop) and analyze the impact of the SRESA1B scenario driven by 24 general circulation models in the 2030s for sorghum climate suitability.

Reductions in the Length of the Growing Period

A recent study conducted by Thornton et al. (2011) reinforces the emerging picture from the literature of a large risk of substantial declines in crop productivity with increasing warming. This work projects changes in the average length of growing periods across Sub-Saharan Africa, defined as the period in which temperature and moisture conditions are conducive to crop development, the season failure rate, and the climate change impact on specific crops.[43] The projections are relatively robust for large areas of central and eastern Sub-Saharan Africa (20 percent or less variability in climate models) and more uncertain for West Africa and parts of southern Africa (variability of climate models up to 40 percent) and for southwest Africa and the desert in the north (more than 50 percent variability).

The length of the growing period is projected to be reduced by more than 20 percent across the whole region by the 2090s (for a global-mean warming of 5.4°C above pre-industrial levels); the only exceptions are parts of Kenya and Tanzania, where the growing season length may moderately increase by 5–20 percent. The latter is not expected to translate into increased crop production; instead, a reduction of 19 percent is projected for maize and 47 percent for beans, while no (or only a slightly) positive change is projected for pasture grass (Thornton et al. 2011). Over much of the rest of Sub-Saharan Africa, reductions for maize range from –13 to –24 percent, and for beans from –69 to –87 percent, respectively, but the variability among different climate models is larger than the variability for East Africa. The season failure rate is projected to increase across the whole region, except for central Africa. For southern Africa, below the latitude of 15°S, Thornton et al. (2011) project that rainfed agriculture would fail once every two years absent adaptation.

Another risk outlined in the study by Philip K Thornton, Jones, Ericksen, and Challinor (2011) is that areas may transition from arid-semiarid, rainfed, mixed cropland to arid-semiarid rangeland, with consequential loss of cropland production. The authors project that about 5 percent of the area in Sub-Saharan Africa (some 1.2 million km²) is at risk of such a shift in a 5°C world; this would represent a significant loss of cropland.

Relative Resilience of Sequential Cropping Systems

Waha et al. (2012) identify and assess traditional sequential cropping systems[44] in seven Sub-Saharan African countries in terms of their susceptibility to climate change.[45] Compared to single-cropping systems, multiple-cropping systems reduce the risk of complete crop failure and allow for growing several crops in one growing season. Thus, multiple cropping, which is a common indigenous agricultural practice, is a potential adaptation strategy to improve agricultural productivity and food security.

The study by Waha et al. (2012) finds that, depending on the agricultural management system and the respective climate change scenario, projected crop yields averaged over all locations included in the analysis decrease between 6–24 percent for 2070–99. Projections indicate that the decline is lowest for traditional sequential cropping systems (the sequential cropping system most frequently applied in the respective district is composed of two short-growing crop cultivars) as compared to single cropping systems (only one long-growing cultivar) and highest-yielding sequential cropping systems (a sequential cropping system composed of two short-growing crop cultivars with the highest yields).[46] There are significant spatial differences. While maize and wheat-based traditional sequential cropping systems in such countries as Kenya and South Africa might see yield increases of more than 25 percent, traditional sequential cropping systems based on rice in Burkina Faso and on groundnut in Ghana and Cameroon are expected to see declines of at least 25 percent (Waha et al. 2012).

The study indicates that sequential cropping is the preferable option (versus single cropping systems) under changing climatic conditions. However, the survey data show that farmers apply sequential cropping in only 35 percent of the administrative units studied and, in some countries, such as Senegal, Niger, and Ethiopia, growing seasons are too short for sequential cropping. Waha et al. (2012) point out that the high labor intensity of sequential cropping systems, lack of knowledge, and lack of market access are also reasons for not using sequential cropping. Capacity development and improvements in market access have been identified in the scientific literature as likely support mechanisms to promote climate change adaptation.

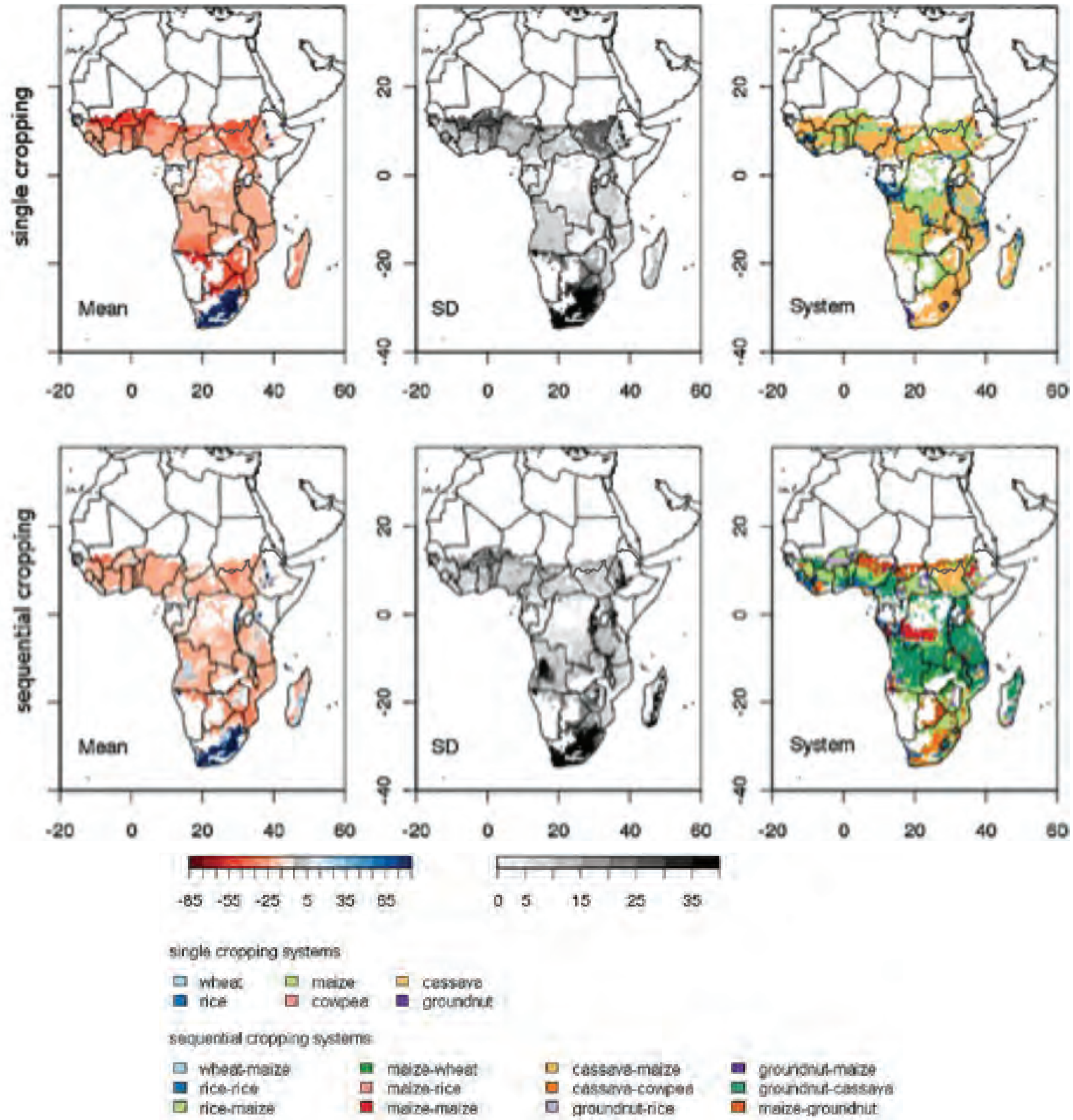
43 The study uses three SRES scenarios, A2, A1B, and B1, and 14 GCMs and increased both the spatial and temporal resolution of the model with historical gridded climate data from WorldClim and daily temperature, precipitation, and solar radiation data by using MarkSim (a third-order Markov rainfall generator). Crop simulations are projected by the models in the decision support system for agro-technology transfer.

44 Waha et al. (2012) define this as "a cropping system with two crops grown on the same field in sequence during one growing season with or without a fallow period. A specific case is double cropping with the same crop grown twice on the field." See their Table 1 for definitions of different systems.

45 For their assessment, Waha et al. (2012) use historical climate data for the 30-year period 1971–2000 and climate projections for 2070–2099 generated by three GCMs (MPI-ECHAM5, UKMO-HadCM3, and NCAR-CCSM3) for the A2 SRES emissions scenario (global-mean warming of 3°C for 2070–2099 above pre-industrial levels). Atmospheric CO_2 concentrations are kept constant in the study. Growing periods and different cropping systems are identified from a household survey dataset, encompassing almost 8,700 households. To simulate yields of different crop cultivars, a process-based global vegetation model (LPJmL) is applied.

46 On average, single cropping systems only attain 38–54 percent of crop calorific yields of sequential cropping systems). While the highest-yielding sequential cropping systems do obtain higher absolute yields, traditional sequential cropping systems are more resilient to climate change impacts. Further, the results indicate that adjusting the sowing dates to the start of the main rainy season is beneficial, as mean future crop yields are higher than in corresponding scenarios where sowing dates are kept constant with only few exceptions. Exceptions may be explained by the fact that temperature and precipitation are the limiting factors in the respective region, which is especially the case in mountainous areas (Waha et al. 2012)

Figure 3.15: Mean crop yield changes (percent) in 2070–2099 compared to 1971–2000 with corresponding standard deviations (percent) in six single cropping systems (upper panel) and thirteen sequential cropping systems (lower panel)



Maps in the last column show the systems with lowest crop yield declines or highest crop yields increases. White areas in Sub-Saharan Africa are excluded because the crop area is smaller than 0.001 percent of the grid cell area or the growing season length is less than five months. The high standard deviation in Southern Africa is mainly determined by the large difference in climate projections.

Source: Waha et al. (2012).

Shifting Crop Climates

A different perspective on risks to crop production can be gained by looking at the changes in land area suitable for different kinds of crops under climate change. This method does not specifically calculate changes to crop production. It can show the changes in regional distribution of suitable crop areas, as well as the emergence of novel climates that are quite dissimilar from the climatic zones in which crops are presently grown. The latter is also an indicator of risk as it implies a need to adjust agricultural practices, crop cultivars, and policies to new climatic regimes.

Applying this framework, Burke, Lobell, and Guarino (2009) estimated shifts in crop climates for maize, millet, and sorghum. They find that the majority of Sub-Saharan African countries are projected to be characterized by novel climatic conditions in more than half of the current crop areas by 2050 (see below), for a warming of about 2.1°C above pre-industrial levels.[47]

Increasing warming leads to greater fractions of cropping area being subject to novel climatic conditions. For specific crops, Burke et al. (2009) estimate that the growing season temperature for any given maize crop area in Africa will overlap[48] on average 58 percent with observations of historical conditions by 2025 (corresponding approximately to 1.5°C above pre-industrial levels), 14 percent by 2050 (2.1°C), and only 3 percent by 2075 (3°C). For millet, the projected overlaps are 54 percent, 12 percent, and 2 percent, respectively; for sorghum 57 percent, 15 percent, and 3 percent. Departures from historical precipitation conditions are significantly smaller than those for temperature (Burke et al. 2009).

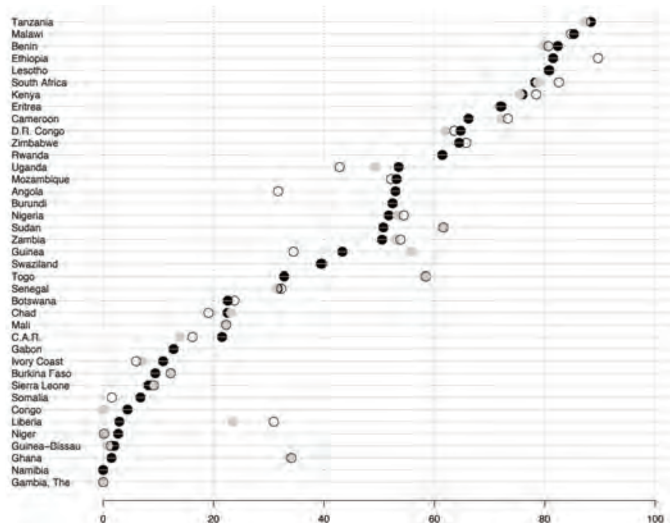
In a second step in this analysis, present and projected crop climates are compared within and among countries in order to determine to what extent the future climate already exists in the same or in another country on the continent. Diminishing climate overlap means that current cultivars would become progressively less suitable for the crop areas.

If, as this study suggests, some African countries (mostly in the Sahel) could as early as 2050 have novel climates with few analogs for any crop, it might not be possible to transfer suitable cultivars from elsewhere in the world. Formal breeding of improved crop varieties probably has an important role to play in adaptation. However, current breeding programs are likely to be insufficient for adapting to the severe shifts in crop climates projected and, given the quick changes of growing season temperatures, a severe time lag for the development of suitable crops can be expected (Burke et al. 2009).

Implications for Food Security

A recent assessment by Nelson and colleagues is a fully integrated attempt to estimate global crop production consequences of climate change. Nelson et al. (2009, 2010)[49] estimate the direct effects of climate change on the production of different crops with and without the effect of CO_2 fertilization under a global-mean warming of about 1.8–2°C above pre-industrial levels by 2050. Without climate change, crop production is projected to increase significantly by 2050; however, the population is projected to nearly triple by that time. Consequently, per capita cereal production is projected to be about 10 percent lower in 2050 than in 2000. When food trade is taken into account, the net effect is a reduction in food availability per capita (measured as calories per capita) by about 15 percent compared to the availability in 2000. There is also an associated projected increase in malnutrition in children under the age of five. Without climate change, the number of children with malnutrition is projected to increase from 33 million to 42 million; climate change adds a further 10 million children by 2050.

Figure 3.16: Percentage overlap between the current (1993–2002 average) distribution of growing season temperatures as recorded within a country and the simulated 2050 distribution of temperatures in the same country



In areas of little overlap, current cultivars become less suitable for the current crop areas as climatic conditions shift. Black: maize; grey: millet; white: sorghum.

Source: Burke et al. (2009).

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In summary, there is substantial evidence that climate change impacts may have detrimental effects on agricultural yields in

47 Projections of temperature and precipitation change are derived from the 18 climate models running the A1B scenario, which lead to temperatures approximately 1.6°C in 2050 above 1980–99 temperatures globally (2.1°C above pre-industrial levels). The projections are based on a comparison of historical (1960–2002) climatic conditions at a specific location, crop area, and months constituting the growing season with the projected climate for that location for different time slices.

48 An overlap occurs when land on which a crop is presently growing overlaps with the land area projected to be suitable for growing that crop type at a later time under a changed climate. In other words, the overlap area is an area where the crop type is presently grown and which continues to be suitable under a changed climate. A present crop growing region that is not in an overlap area is one in which the future climate is projected to be unsuitable for that crop type.

49 The estimates are based on the global agriculture supply and demand model IMPACT 2009, which is linked to the biophysical crop model DSSAT. Climate change projections are based on the NCAR and CSIRO models and the A2 SRES emissions scenario leading to a global mean warming of about 2.0°C above pre-industrial levels by 2050 (Nelson et al. 2009, 2010). To capture the uncertainty in the CO_2 fertilization effect, simulations are conducted at two levels of atmospheric CO_2 in 2050—the year 2000 level of 369 ppm (called the no-CO_2 fertilization scenario) and the projected level in 2050 of 532 ppm under the SRES A2 scenario (termed the with-CO_2 fertilization scenario).

Table 3.3: Sub-Saharan Africa crop production projections

	Crop Production (Year 2000 mmt)	Crop as % of Total 2000	Crop Production 2050 – No Climate Change (mmt)	Crop Production 2050 – with Climate Change and no CO_2 Fertilization Effect (mmt)
Rice	8	9%	18	16
Wheat	5	6%	11	7
Maize	37	46%	54	49
Millet	13	16%	48	45
Sorghum	19	23%	60	59
Total	81	100%	192	176
kg/capita	122		111	101
Calories per capita	2316		2452	1928
Total population (million)	666		1,732	1,732
Net cereal exports (mmt)	–23		–65	–29
Value of net cereal trade (million $)	–$2,995		–$12,870	–$11,034
Malnutrition (millions of children under 5)	33		42	52

Source: Nelson et al. (2010).Based on the global agriculture supply and demand model IMPACT 2009, which is linked to the biophysical crop model DSSAT. Climate change projections are based on the NCAR and the CSIRO models and the A2 SRES emissions scenario leading to a global-mean warming of about 2.0°C above pre-industrial levels by 2050 (see footnote 48).

Sub-Saharan Africa. Further, potential reductions in yields have to be seen in view of future population growth in Africa and the fact that agricultural productivity must actually grow in the region in order to improve and ensure food security (Berg et al. 2012; Müller 2013). There is still great uncertainty in model projections, mainly because of different assumptions and simplifications underlying the diverse methodological approaches but also because of uncertainty in climate projections, especially projections of precipitation.

Roudier et al. (2011) highlighted important general sources of uncertainty: the uncertainties about the response of different crops to changing climatic conditions, the coupling of climate and crop models, which are regularly based on different temporal and spatial scales and require downscaling of data, and assumptions about future adaptation. Furthermore, different cultivars, which are not specified in most of the studies, may respond differently to changing climatic conditions; this may partly explain the broad range of projections. The majority of studies included in the review of Roudier et al. (2011) do not explicitly take adaptation into account.

Despite the broad range of projections, robust overall conclusions on the risks to agricultural production in Sub-Saharan Africa can be drawn based on several lines of evidence:

- The projections for crop yields in Sub-Saharan Africa agree that changing climatic conditions, in particular higher temperatures and heat extremes, pose a severe risk to agriculture in the region. The risk is greater where rainfall declines.
- High temperature sensitivity thresholds for crops have been observed. Where such thresholds are exceeded, reductions in yield may result. With temperature extremes projected to grow, there is a clear risk of large negative effects.
- Reductions in growing season length are projected in many regions.
- Large shifts in the area suitable for present crop cultivars are projected.

The magnitude of the CO_2 fertilization effect remains uncertain and, for many African crops, appears to be weak.

While there is also evidence that, with agricultural development and improvement in management techniques, the potential to increase yields relative to current agricultural productivity is substantial, it is also clear that such improvements have been difficult to achieve. Adaptation and general improvements in current agricultural management techniques are key for short and long-term improvements in yield productivity. There would be mounting challenges in the next few decades, however, as some countries in Sub-Saharan Africa may even see novel crop climatic conditions develop quickly with few or no analogs for current crop cultivars.

The Impacts of Food Production Declines on Poverty

Agricultural production shocks have led to food price increases in the past, and particular types of households have been found to be more affected than others by food price increases because of climate stressors and other economic factors. Kumar and Quisumbing (2011), for example, found that rural female-headed households are particularly vulnerable to food price increases. Hertel, Burke, and Lobell (2010) show that, by 2030, poverty implications because of food price rises in response to productivity shocks have the strongest adverse effects on non-agricultural, self-employed households and urban households, with poverty increases by up to one third in Malawi, Uganda, and Zambia. On the contrary, in some exporting regions (for example, Australia, New Zealand, and Brazil) aggregate trade gains would outweigh the negative effect of direct crop losses. Overall, Hertel et al. (2010) expect global trade to shrink, which leads to an overall efficiency loss and climate change impacts on crop production are projected to decrease global welfare by $123 billion, which would be the equivalent of approximately 18 percent of the global crops sector GDP. In contrast to other regions assessed in this study, no poverty reduction for any stratum of society is projected in most countries in Sub-Saharan Africa when assuming a low or medium agricultural productivity scenario.

Similarly, in a scenario approaching 3.5°C above pre-industrial levels by the end of the century, Ahmed, Diffenbaugh, and Hertel (2009) project that urban wage-labor-dependent populations across the developing world may be most affected by once-in-30-year climate extremes, with an average increase of 30 percent in poverty compared to the base period. This study finds that the poverty rate for this group in Malawi, for example, is estimated to as much as double following a once-in-30-year climate event, compared to an average increase in poverty of 9.2 percent among rural agricultural households. The work by Thurlow, Zhu, and Diao (2012) is consistent with this claim that urban food security is highly sensitive to climatic factors; it indicates that two-fifths of additional poverty caused by climate variability is in urban areas.

Of a sample of 16 countries across Latin America, Asia, and Africa examined in a study by Ahmed et al. (2009), the largest "poverty responses" to climate shocks were observed in Africa. Zambia's national poverty rate, for example, was found to have increased by 7.5 percent over 1991–92, classified as a severe drought year, and 2.4 percent over 2006–07, classified as a severe flood year (Thurlow et al. 2012). (See Box 3.3).

Livestock

Climate change is expected to have impacts on livestock production in Sub-Saharan Africa, which would have implications for the many households that are involved in some way in the livestock industry across the Sub-Saharan African region (see Figure 3.17). These households can rely on livestock for food (such as meat and milk and other dairy products), animal products (such as leather), income, or insurance against crop failure (Seo and Mendelsohn 2007). In Botswana, pastoral agriculture represents the chief source of livelihood for over 40 percent of the nation's residents, with cattle representing an important source of status and well-being for the vast majority of Kalahari residents (Dougill, Fraser, and Mark 2010).

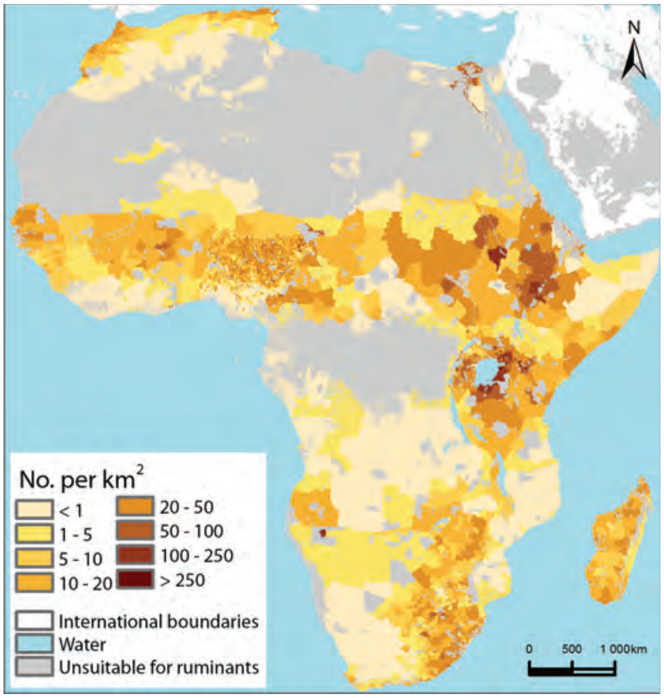
Box 3.3: Agricultural Production Declines and GDP

Several historical case studies have identified a connection between rainfall extremes and reduced GDP because of reduced agricultural yields. Kenya suffered annual damages of 10–16 percent of GDP because of flooding associated with the El Niño in 1997–98 and the La Niña drought 1998–2000. About 88 percent of flood losses were incurred in the transport sector and 84 percent of drought losses in hydropower and industrial production (World Bank 2004, cited in Brown 2011). Barrios et al. (2008) provide evidence that both rainfall and temperature have significantly contributed to poor economic growth in Africa.

Dell, Jones, and Olken (2012) show that historical temperature increases have had substantial negative effects on agricultural value added in developing countries. The authors find that a 1°C higher temperature in developing countries is associated with 2.66-percent lower growth in agricultural output. For developed countries, the temperature effect is substantially smaller and not statistically significant (0.22 percent lower growth in agricultural output for each additional 1°C of temperature). These results support Jones and Olken (2010), who also found that 1°C higher temperature in developing countries negatively affects agricultural production. Dell and Jones (2012) in turn estimate that, in poor countries, each degree of warming can reduce economic growth by an average of 1.3 percentage points (Dell and Jones 2012) and export growth by 2.0–5.6 percentage points (Jones and Olken 2010). Dell and Jones (2012) expect that (at least in one scenario studied) this temperature effect may be particularly pronounced in Sub-Saharan Africa.

While climate change poses a long-term risk to crop production and ecosystem services, Brown, Meeks, Hunu, and Yu (2011) present evidence that high levels of hydroclimatic variability, especially where it leads to drought, tends to have the most significant influence, with increasing poverty counts strongly associated (99 percent) with severe drought. Based on regression analysis and an index of rainfall extremes and taking into account GDP growth and agricultural production, Brown et al. (2011) find a significant and negative correlation between drought and GDP growth per capita: a 1-percent increase in the area of a Sub-Saharan African country experiencing moderate drought correlates with a 2–4 percent decrease in GDP growth. Agricultural value added (meaning the percentage of GDP from agriculture, including forestry, fishing, and hunting) and poverty headcount at $1/day were also observed to be significantly and negatively affected. This is consistent with evidence at the household scale.

Figure 3.17: Observed cattle density in year 2000



Source: Adapted from Robinson et al. (2007) with updated data, with permission from Veterinaria Italiana. Further permission required for reuse.

Regional climate change is found to be the largest threat to the economic viability of the pastoral food system (Dougill et al. 2010). However, pastoral systems have largely been ignored in the literature on climate impacts, which has a bias toward the effects of climate change on crop production (Dougill et al. 2010; Thornton, Van de Steeg, Notenbaert, and Herrero 2009). Less is known, therefore, about the effects of climate change on livestock (Seo and Mendelsohn 2007).

Climate change is expected to affect livestock in a many ways, including through changing means and variability of temperature and precipitation (Thornton et al. 2009), thereby potentially placing livelihoods dependent on the sector at risk (Box 3.4). The savannas and grasslands in which pastoral societies are often located are typically characterized by high variability in temperature and precipitation (Sallu, Twyman, and Stringer 2010). The pastoral systems of the drylands of the Sahel depend highly on natural resources, such as pasture, fodder, forest products, and water, all of which are directly affected by climate variability (Djoudi, Brockhaus, and Locatelli 2011). Sallu et al. (2010) note that historical drought events in the drylands of Botswana have reduced the diversity and productivity of vegetation, thereby limiting available grazing and fodder resources.

A study of pastoral farmers' responses to climate variability in the Sahel, Barbier, Yacoumba, Karambiri, Zorome, and Some (2009) reports that farmers are more interested in the specific characteristics of a rainy season, not necessarily total rainfall, reflecting the finding in some of the literature on crops about the importance of the temporal distribution of rainfall. Increased unpredictability of rainfall poses a threat to livestock (Sallu et al. 2010). Livestock is vulnerable to drought, particularly where it depends on local biomass production (Masike and Ulrich 2008), with a strong correlation between drought and animal death (Thornton et al. 2009).

Specific factors that are expected to affect livestock include the following:

- The quantity and quality of feeds: through changes in herbage because of temperature, water, and CO_2 concentration, and species composition of pastures, which in turn can affect production quantity and nutrient availability for animals and quality.
- Heat stress: altering feed intake, mortality, growth, reproduction, maintenance, and production).
- Livestock diseases, both due to change to diseases themselves and the spread of disease through flooding.
- Water availability: especially considering that water consumption increases with warmer weather.
- Biodiversity: the genetic variety of domestic animals is being eroded as some breeds die out, while the livestock sector is a significant driver of habitat and landscape change and can itself cause biodiversity loss. (Thornton et al. 2009; Thornton and Gerber 2010).

The factors listed above may interact in complex ways; for example, relationships between livestock and water resources or biodiversity can be two-way (Thornton et al. 2009). The ways in which climate change impacts interact with other drivers of change (such as population increases, land use changes, urbanization, or increases in demand for livestock) need to be considered (Thornton et al. 2009). Available rangeland may be

Box 3.4: Livestock Vulnerability to Droughts and Flooding

The impacts of climatic conditions on livestock can be severe. As a result of droughts between 1995 and 1997, pastoralists in southern Ethiopia lost 46 percent of their cattle and 41 percent of their sheep and goats (FAO 2008). Damage to livestock stocks by flooding in the 1990s has also been recorded in the Horn of Africa, with mortality rates as high as 77 percent (Little, Mahmoud, and Coppock 2001).

reduced by human influences, including moves toward increased biofuel cultivation (Morton 2012), veterinary fencing (Sallu et al. 2010), increasing competition for land (Sallu et al. 2010), and land degradation. Thorny bush encroachment, for example, is brought about by land degradation (Dougill et al. 2010), as well as rising atmospheric CO_2 concentrations ((Higgins and Scheiter 2012; see also Chapter 3 on "Agricultural Production"). Finally, the implications of climate change impacts on livestock for the human populations that depend on pastoral systems are equally complex. Deleterious effects on livestock health may directly affect food and economic security and human health where populations depend on the consumption or sale of animals and their products (Caminade et al. 2011; Anyamba et al. 2010). This issue is touched on briefly in Chapter 3 on "Human Impacts" in the context of Rift Valley fever.

In some cases, less specialized rural households have been observed to display higher resilience to environmental shocks. In the drylands of Botswana, households that previously had specialized in livestock breeding were forced to diversify their income strategy and take up hunting and crop farming (Sallu et al. 2010); this may be seen as a form of adaptation. However, climate change impacts are expected to affect not only livestock production but also all alternative means of subsistence, such as crop farming and harvesting wild animals and plant products. Droughts in Botswana, for example, have resulted in declines in wild animal populations valued as hunting prey, wild herbs and fruits, wild medicines, and plant-based materials used for building construction and crafts (Sallu et al. 2010). It would appear, therefore, that diversification is not necessarily always a solution to dwindling agricultural production.

Furthermore, in some instances, pastoralists—particularly nomadic pastoralists—appear to be less vulnerable than crop farmers, as they may be afforded some flexibility to seek out water and feed. Mwang'ombe et al. (2011) found that extreme weather conditions in Kenya appeared to affect the agro-pastoralists more than the pastoralists. Corroborating this, Thornton et al. (2009) describe livestock as "a much better hedge" against extreme weather events, such as heat and drought, despite their complex vulnerability. In fact, in southern Africa, reductions in growing season length and increased rainfall variability is causing some farmers to switch from mixed crop-livestock systems to rangeland-based systems as farmers find growing crops too risky in these marginal areas. These conversions are not, however, without their own risks—among them, animal feed shortages in the dry season (P. K. Thornton et al. 2009). In Sahelian Burkina Faso, for example, farmers have identified forage scarcity as a factor preventing expansion of animal production (Barbier et al. 2009). Furthermore, pastoralists who rely at least in part on commercial feed may be affected by changes in food prices (Morton 2012).

Projected Impacts on Livestock

Butt, McCarl, Angerer, Dyke, and Stuth (2005) present projections of climate change impacts on forage yields and livestock on a national scale. They compare 2030 to the 1960–91 period using two global circulation models and a range of biophysical models. For local temperature increases of 1–2.5°C, forage yield change in the Sikasso region in Mali is projected to be –5 to –36 percent, with variation in magnitude across parts of the region and the models. The livestock considered are cattle, sheep, and goats; these are affected through their maintenance requirements and loss of appetite as a result of thermal stress. Food intake for all livestock decreases. The rate of cattle weight gain is found to be –13.6 to –15.7 percent, while the rate of weight gain does not change for sheep and goats. The CO_2 fertilization effect is accounted for in this study.

Decreased rainfall in the Sahelian Ferlo region of northern Senegal has been found to be associated with decreases in optimal stocking density, which can lead to lower incomes for affected farmers, especially if combined with increased rainfall variability. A 15-percent decrease in rainfall, for example, in combination with a 20-percent increase in rainfall variability, would lead to a 30-percent reduction in the optimum stocking density. Livestock keeping is the main economic activity and essential to local food security in this region (Hein, Metzger, and Leemans 2009).

In contrast with these findings, Seo and Mendelsohn (2007) project precipitation decreases to negatively affect livestock revenues. They analyze the sensitivity of livestock revenue to higher temperatures and increased precipitation across nine Sub-Saharan African countries (Ethiopia, Ghana, Niger, Senegal, Zambia, Cameroon, Kenya, Burkina Faso, and South Africa) and Egypt. This is because although precipitation increases the productivity of grasslands it also leads to the encroachment of forests (see Chapter 3 on "Terrestrial Ecosystems") and aids the transmission of livestock diseases.

Seo and Mendelsohn (2007) analyze large and small farms separately as they function in different ways. Small farms use livestock for animal power, as a meat supply, and, occasionally for sale; large farms produce livestock for sale. The study finds that higher temperatures reduce both the size of the stock and the net value per stock for large farms but not for small farms. It is suggested that the higher vulnerability of larger farms may be due to their reliance on breeds, such as beef cattle, that are less suited to extreme temperatures, which smaller farms tends to be able to substitute with species, such as goats, that can tolerate higher temperatures. Interestingly, the discrepancy in the vulnerability of large and small farms observed with temperature increases is not as marked when it comes to precipitation impacts; here, both large and small farms are considered vulnerable.

The apparent inconsistencies in the above findings with respect to how changes in precipitation is projected to affect livestock yield and the relative vulnerability of large and small farms underline the inadequacy of the current understanding of the impacts that climate change may have on pastoral systems. The impacts on forage yields and livestock sensitivity to high temperatures and associated diseases, however, do highlight the sector´s vulnerability to climate change.

Projected Ecosystem Changes

The impacts on livestock described in the previous section are closely tied to changes in natural ecosystems, as changes in the species composition of pastures affect livestock productivity (Thornton et al. 2009; Seo and Mendelsohn 2007). Processes, such as woody plant encroachment, threaten the carrying capacity of grazing land (Ward 2005). Thus, food production may be affected by climate-driven biome shifts. This is a particular risk to aquatic systems, as will be discussed below.

Africa's tourism industry highly depends on the natural environment; it therefore is also exposed to the risks associated with climate change. It is currently growing at a rate of 5.9 percent compared to a global average of 3.3 percent (Nyong 2009). Adverse impacts on tourist attractions, such as coral reefs and other areas of natural beauty, may weaken the tourism industry in Sub-Saharan Africa. It is believed that bleaching of coral reefs in the Indian Ocean and Red Sea has already led to a loss of revenue from the tourism sector (Unmüßig and Cramer 2008). Likewise, the glacier on Mount Kilimanjaro, a major attraction in Tanzania, is rapidly disappearing (Unmüßig and Cramer 2008).

Terrestrial Ecosystems

Sub-Saharan Africa encompasses a wide variety of biomes, including evergreen forests along the equator bordering on forest transitions and mosaics south and north further extending into woodlands and bushland thickets and semi-arid vegetation types. Grasslands and shrublands are commonly interspersed by patches of forest (W J Bond, Woodward, and Midgley 2005).

Reviewing the literature on ecosystem and biodiversity impacts in southern Africa, Midgley and Thuiller (2010) note the high vulnerability of savanna vegetation to climate change. Changes in atmospheric CO_2 concentration are expected to lead to changes in species composition in a given area (Higgins and Scheiter 2012). In fact, during the last decades, the encroachment of woody plants has already affected savannas (Buitenwerf, Bond, Stevens, and Trollope 2012; Ward 2005). The latter are often unpalatable to domestic livestock (Ward 2005).

Grasslands and savannas up to 30° north and south of the equator are typically dominated by heat tolerant C4 grasses and mixed tree-C4 grass systems with varying degrees of tree or shrub cover (Bond et al. 2005), where the absence of trees demarks grasslands in contrast to savannas. Forest trees, in turn, use the C3 pathway, which selects for low temperatures and high CO_2 concentrations (Higgins and Scheiter 2012). However, William J. Bond and Parr (2010) classify as savannas those forests with a C4 grassy understory that burn frequently. At a global scale, the rainfall range for C4 grassy biomes ranges from approximately 200 mm mean annual precipitation (MAP) to 3000 mm MAP, with tree patches associated with higher precipitation (Bond and Parr 2010). According to Lehmann, Archibald, Hoffmann, and Bond (2011), however, the wettest African savanna experiences 1750 mm MAP.

The Role of Fire

Fires contribute to the stability of these biomes through a positive feedback mechanism, effectively blocking the conversion of savannas to forests (Beckage, Platt, and Gross 2009). C4 grasses are heat-tolerant and shade-intolerant, such that a closed tree canopy would hinder their growth. Efficient growth of C4 plants at high growing season temperatures allows for accumulation of highly flammable material, increasing the likelihood of fire that in turn hinders the encroachment of woody plant cover. Fire-promoting ground cover is absent in the humid microclimate of closed canopy woods, further stabilizing these systems (Lehmann et al. 2011). A further factor promoting the wider spread of savannas in Africa compared to other continents is the prevalence of mega-herbivores, as browse disturbance reduces woody plant cover in arid regions (Lehmann et al. 2011). However, grazing and trampling simultaneously reduce fuel loads and promote tree growth (Wigley, Bond, and Hoffman 2010).

While short-term responses of and biological activity in African biomes are typically driven by water availability and fire regimes, in the longer term African biomes appear highly sensitive to changes in atmospheric CO_2 concentrations (Midgley and Thuiller 2010). Increases in CO_2 concentrations are expected to favor C3 trees over C4 grasses, as at leaf-level the fertilization effect overrides the temperature effect; this shifts the competitive advantage away from heat tolerant C4 plants, resulting in a risk of abrupt vegetation shifts at the local level (Higgins and Scheiter 2012). The effect may be further enhanced by a positive feedback loop. Trees are expected to accumulate enough biomass under elevated atmospheric CO_2 concentrations to recover from fires (Kgope, Bond, and Midgley 2009). This might shade out C4 grass production, contributing to lower severity of fires and further promoting tree growth. Fire exclusion experiments show that biome shifts associated with the processes above can occur on relatively short time scales. High rainfall savannas can be replaced by forests in less than 20–30 years (Bond and Parr 2010).

The Role of Changing Land Uses

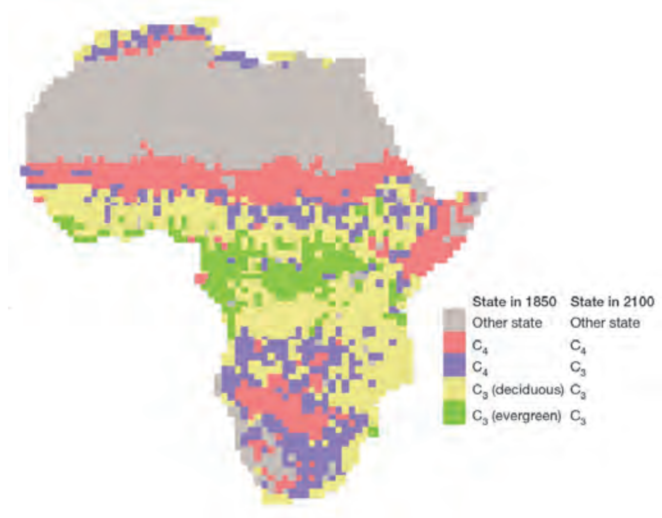
In order to determine to what extent tree cover is affected by land-use practices (as opposed to global processes, such as climate change), Wigley et al. (2010) compared woody increases in three neighboring areas in the Hlabisa district, KwaZulu-Natal, South Africa, in 1937, 1960, and 2004. Overall, they observe the prevalence of a global driver over local factors. Different management of the otherwise comparable study sites did not yield predicted outcomes, where conservation and communal sites was expected to result in a decrease of tree cover (because of the prevalence of browsers, frequent fires, and wood harvesting in the latter). Instead, total tree cover increased from 14 percent in 1937 to 58 percent in 2004 in the conservation area, and from 6 percent to 25 percent in the communal farming area. The third area, used for commercial ranching that is associated with high cattle and low browser density and suppressed fires, experienced an increase from 3 percent to 50 percent. These results lead Wigley et al. (2010) to conclude that either increased CO_2 or atmospheric nitrogen deposition drove the observed changes during the study period. Kgope et al. (2009) further corroborated this result by conducting an open-top chamber experiment with two African acacia species and a common C4 savanna grass under different CO_2 levels (150, 240, 387, 517, 709, and 995 ppm). Fire effects on seedling establishment were simulated by clipping the plants after the first growing season. Results show that because of increased root reserves under elevated CO_2 concentrations, trees should be more resistant to fire than at pre-industrial levels, such that fires are less likely to kill seedlings and effectively control tree growth. In this experiment, CO_2 sensitivity was observed to be highest at sub-ambient and ambient CO_2 levels and decreasing with above-present levels.

Projected Vegetation Shifts

To assess future potential vegetation shifts in grassland, savanna, and forest formation based on the changing competitive advantages of C3 and C4 vegetation types, Higgins and Scheiter (2012) applied a dynamic vegetation model under the SRES A1B scenario (3.5°C above pre-industrial levels). Their results yielded marked shifts in biomes in 2100 (compared to 1850) in which parts of deserts replace grasslands, grasslands are replaced by savannas and woodlands, and savannas are replaced by forests. The most pronounced change appears in savannas, which in this study are projected to decrease from 23 percent to 14 percent of total land coverage. The overall area dominated by C3 vegetation (woodlands, deciduous forests, and evergreen forests) increases from 31 percent to 47 percent in this projection (see Figure 3.18).

The rate of temperature change appears to influence the timing of the transition, as rapid temperature shifts allow for competitive

Figure 3.18: Projections of transitions from C4-dominated vegetation cover to C3-dominated vegetation for SRES A1B, in which GMT increases by 2.8°C above 1980–99



Source: Higgins & Scheiter (2012).

advantage of C4 plants. Furthermore, with rising CO_2 concentration, C4 vegetation is more likely to occur in regions with low rainfall (less than 250 mm). It is essential to note that rainfall was kept constant in this projection.

Risks to Forests

Although the above projections indicate that climate-change-induced vegetation shifts would often favor forests, forests are also at risk from changes in temperature and precipitation. Bond and Parr (2010) note that if extreme weather conditions increase because of climate change, forests may shrink at the expense of grasses (Box 3.5).

In their literature review, C. A. Allen et al. (2010) note the increasing number of instances where climate-related tree mortality has been observed, spanning a wide array of forest ecosystems (including savannas). Despite insufficient coverage and comparability between studies precluding the detection of global trends in forest dieback attributable to climate change, observations are consistent with the present understanding of responses to climatic factors (particularly drought) influencing tree mortality. These climatic factors include carbon starvation because of water stress leading to metabolic limitations, often coinciding with increases in parasitic insects and fungi resulting from warmer temperatures. Furthermore, warmer winters

Box 3.5: Tree Mortality in the Sahel

At a regional scale, Gonzalez, Tucker, and Sy (2012) observe a 20-percent decline in tree density in the western Sahel and a significant decline in species richness across the Sahel in the last half of the 20th century. Based on an econometric model and field observations, they attribute the observed trend to changes in temperature and rainfall variability, which in turn are attributable to climate change. Furthermore, available data on tree density at Njóobéen Mbataar (Senegal) and precipitation data suggests a threshold of resilience to drought stress for Sudan and Guinean tree species at approximately one standard deviation below the long-term average five out of six years (Gonzalez et al. 2012).

can lead to elevated respiration at the expense of stored carbon, again posing the risk of carbon starvation (McDowell et al. 2008). These mechanisms and their interdependencies are likely to be amplified because of climate change (McDowell et al. 2011). Despite persistent uncertainties pertaining to these mechanisms and thresholds marking tree mortality, C. A. Allen et al. (2010) conclude that increases in extreme droughts and temperatures pose risks of broad-scale climate-induced tree mortality. According to Allen et al. (2010), the potential for abrupt responses at the local level, once climate exceeds physiological thresholds, qualifies this as a tipping point of non-linear behavior (Lenton et al. 2008).

In light of the opposing trends described above, William J. Bond & Parr (2010) conclude that “it is hard to predict what the future holds for forests vs. grassy biomes given these contrasting threats.” Thus, whether drought-related tree feedback may prevail over CO_2- stimulated woody encroachment, remains unclear.

Aquatic Ecosystems

Climate change is expected to adversely affect freshwater as well as marine systems (Ndebele-Murisa, Musil, and Raitt2010; Cheung et al. 2010including declines in key protein sources and reduced income generation because of decreasing fish catches (Badjeck, Allison, Halls, and Dulvy 2010). Non-climatic environmental problems already place stress on ecosystem services. For example, overfishing, industrial pollution, and sedimentation have degraded water resources, such as Lake Victoria (Hecky, Mugidde, Ramlal, Talbot, and Kling 2010), reducing fish catches.

Freshwater Ecosystems

Reviewing the literature on changes in productivity in African lakes, Mzime R. Ndebele-Murisa et al. (2010) note that while these lakes are under stress from human usage, much of the changes observed are attributable to years of drought. Associated reductions in river inflow can contribute to a decrease in nutrient concentrations. Increasing water temperatures and higher evaporation further lead to stronger thermal stratification, further inhibiting primary productivity as waters do not mix and nutrients in the surface layers are depleted. Similarly, Mzime R. Ndebele-Murisa, Mashonjowa, and Hill (2011) state that temperature is an important driver of fish productivity in Lake Kariba, Zimbabwe, and best explains observed declines in *Kapenta* fishery yields.

Inland freshwater wetlands are another freshwater ecosystem likely to be affected by climate change. One such wetland is the Sudd in Sahelian South Sudan, which provides a rich fishery, flood recession agriculture, grazing for livestock, handcrafts, and building materials, and plant and animal products (including for medicinal purposes). The Sudd, which is fed by the White Nile originating in the Great Lakes region in East Africa, could be depleted by reduced flows resulting from changes in precipitation patterns (Mitchell 2013).

Furthermore, increasing freshwater demand in urban areas of large river basins may lead to reducing river flows, which may become insufficient to maintain ecological production; this means that freshwater fish populations may be impacted (McDonald et al. 2011).

Ocean Ecosystems

Climate-change related changes in ocean conditions can have significant effects on ocean ecosystems. Factors influencing ocean conditions include increases in water temperature, precipitation, levels of salinity, wind velocity, wave action, sea-level rise, and extreme weather events. Ocean acidification, which is associated with rising atmospheric CO_2 concentrations, is another factor and is discussed in Chapter 4 under “Projected Impacts on Coral Reefs” in the context of coral reef degradation. Ocean ecosystems are expected to respond to altered ocean conditions with changes in primary productivity, species distribution, and food web structure (Cheung et al. 2010). Theory and empirical studies suggest a typical shift of ocean ecosystems toward higher latitudes and deeper waters in response to such changes (Cheung et al. 2010a). However, there is also an associated risk that some species and even whole ecosystems will be placed at risk of extinction (Drinkwater et al. 2010).

Taking into account changes in sea-surface temperatures, primary production, salinity, and coastal upwelling zones, Cheung et al. (2010) project changes in fish species distribution and regional patterns of maximum catch potential by 2055 in a scenario leading to warming of approximately 2°C in 2050 (and 4°C by 2100). The results are compared to a scenario in which conditions stabilize at year 2000 values. Comparing both scenarios shows potential yield increases of 16 percent along the eastern and southeastern coast of Sub-Saharan Africa (Madagascar, Mozambique, Tanzania, and Kenya). However, for the same regions with closer proximity to the coast, yield changes of –16 to –5 percent are projected. Increases of more than 100 percent at the coast of Somalia and South Africa are projected. Apart from the southern coast of Angola, for the western African coast—where fish contributes as much as 50 percent of animal protein consumed (Lam, Cheung, Swartz, and Sumaila 2012)—significant adverse changes in maximum catch potential are projected of – 16 to –5 percent for Namibia, –31 to 15 percent for Cameroon and Gabon, and up to 50 percent for the coast of Liberia and Sierra Leone (Cheung et al. 2010). Lam et al. (2012), applying the same method and scenario, report decreases ranging from 52–60 percent, Côte d'Ivoire, Liberia, Togo, Nigeria, and Sierra Leone.

The analysis by Cheung et al. (2010) does not account for changes in ocean acidity or oxygen availability. Oxygen availability has been found to decline in the 200–700m zone and is related to reduced water mixing due to enhanced stratification (Stramma, Schmidtko, Levin, and Johnson 2010). At the same time, warming waters lead to elevated oxygen demand across marine taxa (Stramma, Johnson, Sprintall, and Mohrholz 2008). Hypoxia is known to negatively impact the performance of marine organisms, leading to additional potential impacts on fish species (Pörtner 2010). Accordingly, a later analysis by Cheung, Dunne, Sarmiento, and Pauly (2011), which built on that of William Cheung et al (2010), found that acidification and a reduction of oxygen content in the northeast Atlantic ocean lowered the estimated catch potentials by 20–30 percent relative to simulations not considering these factors.

Changes in catch potential can lead to decreases in local protein consumption in regions where fish is a major source of animal protein. For example, in their study of projected changes to fishery yields in West Africa by 2055 in a 2°C world, V. W. Y. Lam, Cheung, Swartz, and Sumaila (2012) compare projected changes in catch potential with projected protein demand (based on population growth, excluding dietary shifts). They show that in 2055 Ghana and Sierra Leone are expected to experience decreases of 7.6 percent and 7.0 percent respectively from the amount of protein consumed in 2000. Furthermore, they project economic losses of 21 percent of annual total landed value (from $732 million currently to $577 million, using constant 2000 dollars). Côte d'Ivoire, Ghana, and Togo, with up to 40 percent declines, are projected to suffer the greatest impacts on their land values. The job loss associated with projected declines in catches is estimated at almost 50 percent compared to the year 2000 (Lam et al. 2012). Of the whole of Sub-Saharan Africa, Malawi, Guinea, Senegal, and Uganda rank among the most vulnerable countries to climate-change-driven impacts on fisheries. This vulnerability is based on the combination of predicted warming, the relative importance of fisheries to national economies and diets, and limited adaptive capacity (Allison et al. 2009).

The vulnerability to impacts on marine ecosystems, however, differs from community to community. Cinner et al. (2012) measure the vulnerability to observed climate impacts on reef ecosystems in 42 communities across five western Indian Ocean countries (Kenya, Tanzania, Madagascar, Mauritius, and the Seychelles). The study provides evidence that not all sites are equally exposed to factors that cause bleaching. Reefs in Tanzania, Kenya, the Seychelles, and northwest Madagascar are found to experience more severe bleaching, while southwest Madagascar and Mauritius are less exposed because of lower seawater temperatures and UV radiation and higher wind velocity and currents. These findings caution against generalizations about the exposure of both ecosystems and the people dependent on them. The sensitivity of human communities to the repercussions of bleaching events is highest in those communities in Tanzania and parts of Kenya and Madagascar that are most dependent on fishing livelihoods.

Human Impacts

Climate change impacts as outlined above are expected to have further repercussions for affected populations. Other impacts may also occur and interact with these to result in severe threats to human life. The human impacts of climate change will be determined by the socio-economic context in which they occur. The following sections discuss some of the identified risk factors to affected populations and the potential repercussions for society.

Human Health

The increased prevalence of undernutrition is one of the most severe climate-related threats to human health in Sub-Saharan Africa. Insufficient access to nutrition already directly impacts human health, with high levels of undernutrition across the region. Undernutrition is the result of inadequate food intake or inadequate absorption or use of nutrients. The latter can result from diarrheal disease (Cohen, Tirado, Aberman, and Thompson 2008). Undernutrition increases the risk of secondary or indirect health implications because it heightens susceptibility to other diseases (World Health Organization 2009; World Bank Group 2009). It can also cause child stunting, which is associated with higher rates of illness and death and which can have long-term repercussions into adulthood, including reduced cognitive development (Cohen et al. 2008). In fact, undernutrition has been cited as the single most significant factor contributing to the global burden of disease; it is already taking a heavy toll, especially among children (IASC 2009).

In Sub-Saharan Africa in 2011, the prevalence of undernourishment in the population ranges from 15–65 percent depending on the sub-region (Lloyd, Kovats, & Chalabi, 2011). Lloyd et al.

(2011) anticipates modest reductions in these rates in the absence of climate change; with warming of 1.2–1.9°C by 2050,[50] the proportion of the population that is undernourished is projected to increase by 25–90 percent compared to the present. The proportion of moderately stunted children, which ranges between 16–22 percent in the 2010 baseline, is projected to remain close to present levels in a scenario without climate change. With climate change, the rate is projected to increase approximately 9 percent above present levels. The proportion of severely stunted children, which ranges between 12–20 percent in the 2010 baseline, is expected to decrease absent climate change by approximately 40 percent across all regions. With climate change, this overall reduction from present levels would be only approximately 10 percent. The implications of these findings are serious, as stunting has been estimated to increase the chance of all-cause death by a factor of 1.6 for moderate stunting and 4.1 for severe stunting (Black et al. 2008).

Other threats to health that are likely to be increased by climate change include fatalities and injuries due to extreme events or disasters such as flooding (McMichael and Lindgren 2011; World Health Organization 2009). An indirect health effect of flooding is the damage to key infrastructure. This was observed in a case in Kenya in 2009 when approximately 100,000 residents of the Tana Delta were cut off from medical services by floods that swept away a bridge linking the area with Ngao District Hospital (*Daily Nation* September 30, 2009, cited in Kumssa and Jones 2010).

Another risk is heat stress resulting from higher temperatures. Lengthy exposure to high temperatures can cause heat-related illnesses, including heat cramps, fainting, heat exhaustion, heat stroke, and death. More frequent and intense periods of extreme heat have been linked to higher rates of illness and death in affected populations. The young, the elderly, and those with existing health problems are especially vulnerable. Heat extremes are expected to also particularly affect farmers and others engaged in outdoor labor without adequate protective measures (Myers 2012). The populations of inland African cities are expected to be particularly exposed to extreme heat events, as the built-up environment amplifies local temperatures (known as the "urban heat island effect"; UN Habitat 2011). However, as the heat extremes projected for Sub-Saharan Africa are unprecedented, the extent to which populations will be affected by or will be able to adapt to such heat extremes remains unknown. This remains an understudied area of climate-change-related impacts.

Vector and Water-borne Diseases

Further risks to human health in Sub-Saharan Africa include the following: vector-borne diseases including malaria, dengue fever, leishmaniasis, Rift Valley fever, and schistosomiasis, and water and food-borne diseases, including cholera, dysentery and typhoid fever, and diarrheal diseases; all of these diseases can be influenced by local climate (Costello et al. 2009). The diseases most sensitive to environmental changes are those that are vector-borne or food and water-borne. Flooding can be associated with outbreaks of diseases, such as cholera; while drought has been linked to such diseases as diarrhea, scabies, conjunctivitis, and trachoma (Patz et al. 2008). As cold-blooded arthropods (including mosquitoes, flies, ticks, and fleas) carry most vector-borne diseases, a marginal change in temperature can dramatically alter their populations. They are also highly sensitive to water and vegetation changes in their environment. Changes in these factors can, therefore, increase the incidence, seasonal transmission, and geographic range of many vector-borne diseases (Patz et al. 2008).

The incidence of malaria is notoriously difficult to predict, There is great uncertainty about the role of environmental factors vis-à-vis endogenous, density-dependent factors in determining mosquito prevalence; many studies indicate, however, a correlation between increased malaria incidence and increased temperature and rainfall (Chaves and Koenraadt, 2010). In Botswana, for example, indices of ENSO-related climate variability have predicted malaria incidence (Thomson 2006); in Niger, total mosquito abundances showed strong seasonal patterns, peaking in August in connection with the Sahel water cycle (Caminade et al. 2011). This is consistent with observations that the drought in the Sahel in the 1970s resulted in a decrease in malaria transmission (Ermert, Fink, Morse, and Peeth 2012). Land-use patterns can also play a role in determining vector populations, with deforestation affecting temperature, and agricultural landscapes potentially providing suitable microhabitats for mosquito populations (Chaves and Koenraadt 2010).

The areas where malaria is present is projected to change, with malaria pathogens potentially no longer surviving in some areas while spreading elsewhere into previously malaria-free areas. Even today malaria is spreading into the previously malaria-free highlands of Ethiopia, Kenya, Rwanda, and Burundi, with the frequency of epidemics there increasing, and may also enter the highlands of Somalia and Angola by the end of the century (Unmüßig and Cramer 2008). In the Sahel, the northern fringe of the malaria epidemic belt is projected to have shifted southwards (by 1–2 degrees) with a warming of 1.7°C by 2031–50 because of a projected decrease in the number of rainy days in the summer (Caminade et al. 2011); this means that it is possible that fewer people in the northern Sahel will be exposed to malaria.

Outbreaks of Rift Valley fever (RVF), which are episodic, occur through mosquitos as the vector and infected domestic animals as secondary hosts and are linked to climate variability (including ENSO) (Anyamba et al. 2009). Intra-seasonal rainfall

50 The study use the NCAR and CSIRO scenarios, which project a temperature increase of 1.9°C and 1.2°C above pre-industrial levels, respectively, by 2050.

variability, in particular, is a key risk factor, as outbreaks tend to occur after a long dry spell followed by an intense rainfall event (Caminade et al. 2011). In light of projections of increased rainfall variability in the Sahel, RVF incidence in this area can be expected to increase. Caminade et al. (2011) identify northern Senegal and southern Mauritania as risk hotspots, given these areas' relatively high livestock densities.

Rift Valley fever can spread through the consumption or slaughter of infected animals (cases of the disease in Burundi in May 2007 were believed to originate from meat from Tanzania; Caminade et al. 2011). Because of this, RVF outbreaks can also have implications for economic and food security as livestock contract the disease and become unsuitable for sale or consumption. An outbreak in 1997–98 for example, affected five countries in the Horn of Africa, causing loss of human life and livestock and affecting the economies through bans on exports of livestock (Anyamba et al. 2009).

Africa has the largest number of reported cholera cases in the world. Cholera is an acute diarrheal illness caused by ingestion of toxigenic *Vibrio Cholerae* and is transmitted via contaminated water or food. The temporal pattern of the disease has been linked to climate. The relative significance of temperature and precipitation factors remains somewhat uncertain in projections of future incidence under climate change. Past outbreaks of cholera have been associated with record rainfall events (Tschakert 2007), often during ENSO events (Nyong 2009). The risk increases when water supplies and sanitation services are disrupted (Douglas et al. 2008). This occurred during the severe flooding in Mozambique in 2000, and again in the province of Cabo Delgado in early 2013 (Star Africa 2013; UNICEF 2013), when people lost their livelihoods and access to medical services, sanitation facilities, and safe drinking water (Stal 2009).

Repercussions of Health Effects

The repercussions of the health effects of climate change on society are complex. Poor health arising from environmental conditions, for instance, may lower productivity, leading to impacts on the broader national economy as well as on household incomes. Heat extremes and increased mean temperatures can reduce labor productivity, thereby undermining adaptive capacity and making it more difficult for economic and social development goals to be achieved (Kjellstrom, Kovats, Lloyd, Holt, and Tol 2009). Child undernutrition also has long-term consequences for the health and earning potential of adults (Victora et al. 2008).

The educational performance of children is also likely to be undermined by poor health associated with climatic risk factors. An evaluation of school children's health during school days in Yaounde and Douala in Cameroon found that, in the hot season, high proportions of children were affected by headaches, fatigue, or feelings of being very hot. Without any protective or adaptive measures, these conditions made students absentminded and slowed writing speeds, suggesting that learning performance could be undermined by increased temperatures (Dapi et al. 2010). Child stunting is associated with reduced cognitive ability and school performance (Cohen et al. 2008); in addition, diseases such as malaria have a significant effect on children's school attendance and performance. Sachs and Malaney (2002) found that, because of malaria, primary students in Kenya annually miss 11 percent of school days while secondary school students miss 4.3 percent.

The complexity of the range of environmental and human-controlled factors that affect human health is considerable. Among them, land-use changes (including deforestation, agricultural development, water projects, and urbanization) may affect disease transmission patterns (Patz et al. 2008). Moreover, population movements can both be driven by and produce health impacts. Forced displacement, often in response to severe famine or conflict, is associated with high rates of infectious disease transmission and malnutrition; this can lead to the exposure of some populations to new diseases not previously encountered and against which they lack immunity (McMichael et al. 2012). People who migrate to poor urban areas, are possibly also at risk of disaster-related fatalities and injuries (McMichael et al. 2012), especially in slum areas which are prone to flooding and landslides (Douglas et al. 2008).

Population Movement

Projections of future migration patterns associated with climate change are largely lacking. However, the observed movements outlined below illustrate the nature of potential patterns and the complexity of the factors that influence population movement.

Migration can be seen as a form of adaptation and an appropriate response to a variety of local environmental pressures (Tacoli 2009; Warner 2010; Collier et al. 2008). Migration often brings with it a whole set of other risks, however, not only for the migrants but also for the population already residing at their point of relocation. For example, the spread of malaria into the Sub-Saharan African highlands is associated with the migration of people from the lowlands to the highlands (Chaves and Koenraadt 2010). Some of the health risks to migrants themselves have been outlined above. Other impediments faced by migrants can include tensions across ethnic identities, political and legal restrictions, and competition for and limitations on access to land (Tacoli 2009); these, can also, potentially, lead to conflict (O. Brown, Hammill, and McLeman 2007). In turn, migration is a common response to circumstances of violent conflict (McMichael et al. 2012).

Migration can be driven by a multitude of factors, where notably the socioeconomic context also plays a key role (Tacoli 2009).

Environmental changes and impacts on basic resources, including such extreme weather events as flooding and cyclones, are significant drivers of migration. Drought can also be a driver of migration, according to S. Barrios, Bertinelli, and Strobl (2006), who attribute one rural exodus to rainfall shortages. When the Okovango River burst its banks in 2009 in a way that had not happened in more than 45 years, about 4,000 people were displaced on both the Botswanan and Namibian sides of the river and forced into emergency camps (IRIN 2009). Although this event has not been attributed to climate change, it does illustrate the repercussions that extreme events can have on communities.

Some permanent or temporary population movements are associated with other environmental factors, such as desertification and vegetation cover, which may be affected by human-induced land degradation or climate change (Tacoli 2009). Van der Geest, Vrieling, and Dietz (2010) find that, in Ghana, migration flows can be explained partly by vegetation dynamics, with areas that offer greater vegetation cover and rainfall generally attracting more in-migration than out-migration. This study found that the migration patterns observed also appeared to be related to rural population densities, suggesting that the per capita access to natural resources in each area was at least as important as the abundance of natural resources *per se*. Barbier et al. (2009) show that, in Burkina Faso, some pastoralists have opted to migrate from the more densely populated and more arid north to the south, where population density is lower, pastures are available, and the tsetse fly is under control. Other migrations from dryland areas in Burkina Faso are seasonal; that is, they occur for the duration of the dry season (Kniveton, Smith, and Black 2012). Migration as a response to environmental stresses, however, can be limited by non-climatic factors. In the Kalahari in Botswana, for example, pastoralists have employed seasonal migration as a means of coping with irregular forage, land tenure reform limits previously high herd mobility (Dougill et al. 2010).

Urbanization

The connection between the challenges posed by climate change and by urbanization is particularly noteworthy. Africa has the highest rate of urbanization in the world; this is expected to increase further, with as much as half the population expected to live in urban areas by 2030 (UN-HABITAT 2010a). In the face of mounting pressures on rural livelihoods under climate change, even more people may people may migrate to urban areas (Adamo 2010). For example, patterns of urbanization in Senegal have been attributed to desertification and drought, which have made nomadic pastoral livelihoods less feasible and less profitable (Hein et al. 2009).

Urbanization may constitute a form of adaptation and provide opportunities to build resilient communities, and the potential benefits may extend beyond the urban area. There are, are for example, cases in which urban migrants are able to send remittances to family members remaining in rural areas (Tacoli 2009).

Large numbers of urban dwellers, however, currently live in precarious situations. For example, the residents of densely populated urban areas that lack adequate sanitation and water drainage infrastructure depend on water supplies that can easily become contaminated (Douglas et al. 2008). As discussed above, heat extremes are also likely to be felt more in cities. Levels of poverty and unemployment are often high in these areas, with many unskilled subsistence farmers who move to urban areas experiencing difficulty in finding employment (Tacoli 2009). As discussed in Chapter 3 on "The Impacts of Food Production Declines on Poverty", the urban poor are also among the most vulnerable to food production shocks.

The vulnerability of new urban dwellers is also increased by the pressure that urbanization puts on the natural environment and urban services (Kumssa and Jones 2010). Absent careful urban planning, such pressure can exacerbate existing stressors (for example, by polluting an already limited water supply; Smit and Parnell 2012), and heighten the vulnerability of these populations to the impacts of disasters, including storm surges and flash floods (McMichael et al. 2012). Many settlements are constructed on steep, unstable hillsides, along the foreshores of former mangrove swamps or tidal flats, or in low-lying flood plains (Douglas et al. 2008). Flooding severity is heightened as, for example, natural channels of water are obstructed, vegetation removed, ground compacted, and drains blocked because of uncontrolled dumping of waste (Douglas et al. 2008). Urbanization can hence be seen as both a response to and a source of vulnerability to climate change (see also Chapter 4 on "Risks to Coastal Cities").

Conflict

There are several scenarios under which climate change could trigger conflict (Homer-Dixon,1994; Scheffran, Brzoska, Kominek, Link, and Schilling 2012). Decreased or unequal access to resources following extreme events has been identified as a possible contributing factor to human conflict (Hendrix and Glaser 2007; Nel and Righarts 2008). Similarly, on both long and short time-scales, depletion of a dwindling supply of resources could lead to competition between different groups and increase the threat of conflict (Homer-Dixon 1994; Hendrix and Glaser 2007).

For example, Blackwell (2010) links cattle raiding and violent disputes over scarce water resources to escalating competition for shrinking pasture and water sources. Rowhani, Degomme, Guha-Sapir, and Lambin (2011), who investigated the same phenomena in East Africa, found no strict causal mechanisms, but they did find associations between variables, with both malnutrition and inter-annual ecosystem variability correlated with violent conflict. They argue that the impact of environmental change on human security is indirect and mediated by several political and economic factors. This more nuanced picture is consistent with the analysis of J. Barnett and Adger (2007), who argue that, in some circumstances, climate change impacts on human security may increase the risk of violent conflict.

There is some evidence that the causal connection operates in the opposite direction, with conflict often leading to environmental degradation and increasing the vulnerability of populations to a range of climate-generated stressors (Biggs and et al. 2004). The breakdown of governance due to civil war can also exacerbate poverty and cause ecosystem conservation arrangements to collapse; both of these factors can potentially cause further exploitation of natural resources (Mitchell 2013).

The potential connection between environmental factors and conflict is a highly contested one, and the literature contains evidence both supporting and denying such a connection. Gleditsch (2012), summarizing a suite of recent studies on the relationship between violent conflict and climate change, stresses that there is to date a lack of evidence for such a connection (see Buhaug 2010 for a similar line of argument). However, given that unprecedented climatic conditions are expected to place severe stresses on the availability and distribution of resources, the potential for climate-related human conflict emerges as a risk—and one of uncertain scope and sensitivity to degree of warming.

Conclusion

Key impacts that are expected to affect Sub-Saharan Africa are summarized in Table 3.4, which shows how the nature and magnitude of impacts vary across different levels of warming.

Agriculture livelihoods are under threat and the viable options to respond to this threat may dwindle. For maize crop areas, for example, the overlap between historical maize growing areas and regions where maize can be grown under climate change decreases from 58 percent under 1.5°C warming above pre-industrial levels to 3 percent under 3°C warming. In other words, even at 1.5°C warming about 40 percent of the present maize cropping areas will no longer be suitable for current cultivars. Risks and impacts grow rapidly with increasing temperature. Recent assessments project significant yield losses for crops in the order of 5–8 percent by the 2050s for a warming of about 2°C, and a one-in-twenty chance that yield losses could exceed 27 percent. As warming approaches 3°C, large areas of Sub-Saharan Africa are projected to experience locally unprecedented growing season temperatures. In a 2°C world, countries with historically high temperatures begin to move toward globally unprecedented crop climates. This means that it becomes increasingly unlikely that existent cultivars can be obtained that are suitable for the temperature ranges in these regions. Should this become impossible, the breeding of new more drought-resistant cultivars tolerant of higher temperatures would appear to be necessary. In a 4°C world, the likelihood that suitable existent cultivars are available further decreases, and the uncertainty surrounding the potential of novel cultivar breeding may increase.

Similarly, diversification options for agro-pastoral systems may decline as heat stress and indirect impacts reduce livestock productivity and CO_2-driven woody plant encroachment onto grasslands diminishes the carrying capacity of the land. Livelihoods dependent on fisheries and other ecosystem services would be similarly placed under threat should critical species cease to be locally available.

Impacts in these sectors are likely to ripple through other sectors and affect populations in Sub-Saharan Africa in complex ways. Undernutrition increases the risk of other health impacts, which are themselves projected to become more prevalent under future climate change. This may undermine household productivity and can cause parents to respond by taking their children out of school to assist in such activities as farm work, foraging, and the fetching of fuel and water. This may ultimately have long-term implications for human capital and poverty eradication in Sub-Saharan Africa.

Threats to agricultural production, which place at risk the livelihoods of 60 percent of the labor force of Sub-Saharan Africa, may further exacerbate an existing urbanization trend. Migration to urban areas may provide migrants with new livelihood opportunities but also expose them to climate impacts in new ways. Some health risk factors, such as heat extremes, are particularly felt in urban areas. Other impacts tend to affect the poorest strata of urban society, to which urban migrants often belong. Conditions that characterize poor urban areas, including overcrowding, inadequate access to water, and poor drainage and sanitation facilities, aid the transmission of vector- and water-borne diseases. As many cities are located in coastal areas, they are exposed to coastal flooding because of sea-level rise. The poorest urban dwellers tend to be located in the most vulnerable areas, further placing them at risk of extreme weather events. Impacts occurring even far removed from urban areas can be felt in these communities. Food price increases following production shocks have the most deleterious repercussions within cities. The high exposure of poor people to the adverse effects of climate change implies the potential for increasing inequalities within and across societies. It is as yet unclear how such an effect could be amplified at higher levels of warming and what this would mean for social stability.

Thus, the range of climate-change-related risks already confronting Sub-Saharan Africa at relatively low levels of warming could have far-reaching repercussions for the region´s societies and economies well into the future. Even in a situation in which warming is limited to below 2°C, there are substantial risks and damages; as warming increases these only grow. With a 2°C warming, and despite persistent uncertainties, large regional risks to development emerge, particularly if adaptation measures fail to adequately anticipate the threat.

Table 3.4: Impacts in Sub-Saharan Africa

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (≈2030s[1])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C and Above (≈2080s)
Regional Warming				Warm nights expected approximately 45 percent of the time in tropical west and east Africa and about 60 percent of the time in southern Africa		Warm nights approximately 95 percent of time in tropical West and East Africa and about 85 percent of time in southern Africa[2]
Heat Extremes		Virtually absent	About 20–25 percent of land in austral summer months (Dec, Jan, Feb) (DJF)	About 45 percent of land in austral summer months (DJF)	About 70 percent of land in austral summer months (DJF)	>85 percent of land in austral summer months (DJF)
		Absent	About 3–5 percent of land in austral summer months (DJF)	About 15 percent of land in austral summer months (DJF)	About 35 percent of land in austral summer months (DJF)	>55 percent of land in austral summer months (DJF)
Precipitation	**West Africa**			Weak (<10 percent) change in annual precipitation, sign of change uncertain		Weak (<10 percent) change in annual precipitation, sign of change uncertain
	East Africa	Recent abrupt decline since 1999[3] and likely human influence on 2011 long rains failure[4]		Wetter (>10 percent); however, there is significant uncertainty[5]		Substantially wetter (≈30 percent); however, there is significant uncertainty[6]
	Southern Africa			Weak (<10 percent) change in annual precipitation, sign uncertain		Decrease of annual precipitation up to 30 percent
Drought		Increasing drought trends observed since 1950.[7] The recent 2011 drought in East Africa affected 13 million people and led to extremely high rates of malnutrition.[8] Lott et al (2013) show that human influence on climate has increased the probability of East African long rains as dry, or drier than in 2011	Increasing drought risk in southern, central and West Africa, decrease in East Africa, but West and East African projections are uncertain	Likely risk of severe drought in southern and central Africa, increased risk in West Africa, decrease in East Africa but West and East African projections are uncertain	Likely risk of extreme drought in southern Africa and severe drought in central, Africa, increased risk in West Africa, decrease in East Africa[9], but West and East African projections are uncertain[10]	Likely risk of extreme drought in southern Africa and severe drought in central Africa, increased risk in West Africa, decrease in East Africa [11], but West and East African projections are uncertain[12]
Aridity		Increased drying	Little change expected	Area of hyper-arid and arid regions grows by 3 percent. Total arid area increases by 1 percent in a 2°C world		Area of hyper-arid and arid regions grows by 10 percent. Total arid area increases by 5 percent
Sea-level Rise above present (1985–2005)		About 21 cm to 2009[13]	30cm[14]–2040s, 50cm–2070, 70 cm (60–80) cm by 2080–2100.[15] Likely exceeds 50 cm by 2070s and 100 cm not likely exceeded until late 22nd century	30cm–2040s, 50cm–2070, 70cm (60–80) cm by 2080–2100. Likely exceeds 50 cm by 2070s and 100 cm not likely exceeded until mid 22nd century	30cm–2040s, 50cm–2060, 85 cm (70–100) cm by 2080–2100. Likely exceeds 50 cm by 2070s and 100 cm by early 22nd century	30cm–2040s, 50cm–2060, 105 (85–125) cm by 2080–2100. Likely exceeds 50 cm by 2060s and 100 cm by 2080s. Five cm higher rise along east coast Southern Africa (for example, Maputo)

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Table 3.4: Impacts in Sub-Saharan Africa

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (≈2030s[1])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C and Above (≈2080s)
Ecosystem Shifts		A 20-percent decline in tree density in the western Sahel and significant decline in species richness across the Sahel in the last half of the 20th century.[16] Mali is experiencing a climate zone shift with a shift of agro-ecological zones to the south, evidenced by a decrease in average rainfall of about 200 mm over the past 50 years and an average increase in temperature of 0.5°C.[17] Reduction in river inflow because of droughts contributes to decrease nutrient concentrations and increasing water temperatures and higher evaporation lead to stronger thermal stratification further inhibiting primary productivity.[18] Most hoofed mammal species in Kruger National Park showed severe population declines between the late 1970s and mid 1990s correlated with extreme reduction in dry season rainfall[19]	41–51 percent loss in plant endemic species richness in South Africa and Namibia[20]	10 to 15 percent Sub-Saharan species at risk of extinction (assuming no migration of species)[21]	Savannas are projected to decrease from 23 percent to 14 percent of total land coverage. Area dominated by woodland, deciduous forest, and evergreen forest vegetation increases from 31 percent to 47 percent by 2100 compared to 1850[22] Projections, of 5,197 studied African plant species 25 percent to 42 percent could lose all suitable range by 2085;[23] 25 to 40 percent Sub-Saharan species at risk of extinction (assuming no migration of species)[24]	
Water Availability	**Runoff**				30–50 percent decreases in annual runoff[25] for parts of West Africa (Ghana, the Côte d'Ivoire and southern Nigeria)[26] and Southern Africa (Namibia, east Angola and western South Africa and Zambia)[27]	Increase 10–20 percent in blue water availability in East Africa and parts of West Africa,[28] 10 percent decrease in Ghana, Côte d'Ivoire, Mali, Senegal, 20 to 40 percent decrease in most of Southern Africa; 20 percent decrease in green water availability in most of Africa, except parts of East Africa (10 to 20 percent increase for Somalia, Ethiopia, and Kenya)[29]

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Table 3.4: Impacts in Sub-Saharan Africa

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (≈2030s[1])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C and Above (≈2080s)
	Groundwater Recharge			50–70 percent decrease in recharge rates in western Southern Africa and southern West Africa 30 percent increase in recharge rate in some parts of eastern Southern Africa and East Africa[30]		
Crop Yields, Areas and Food Production	**Crop Growing Areas**		Maize, millet, and sorghum crop areas are projected to overlap on average 58 percent, 54 percent, and 57 percent by 2025, respectively, compared to 1960–2002 conditions.[31] Increase in failure rate of primary season in mixed rainfed arid-semiarid systems by about 35–40 percent, to about one in four years, up from about one in five at present[32]	Maize, millet, and sorghum crop areas are projected to overlap on average 14 percent, 12 percent and 15 percent by 2050, respectively, compared to 1960–2002 conditions.[31] Increase in failure rate of primary season in mixed rainfed arid-semiarid systems by about 60–70 percent to about one in three years, up from about one in five at present[39]	Maize, millet, and sorghum crop areas are projected to overlap on average 3 percent, 2 percent, and 3 percent by 2075, respectively, compared to 1960–2002 conditions[31]	The length of growing period is projected to be reduced by more than 20 percent across the whole region by the 2090s.[34] In southern Africa, the rate of season failure could increase to one year in two. 20 percent decrease in growing season length in SSA[35]
	Crop Production	Baseline of approximately 81 million tonnes in 2000, about 121 kg/capita.[39]		Without climate change, a projected decrease of 192 million tonnes (111 kg/capita) and with climate change 176 million tonnes (101 kg/capita)[39]		
Yields	**All Crops**		Close to zero or small negative changes[36]	Median losses in the order of –5 percent[37] to –8 percent;[47] 95 percent probability crop damages exceed 7 percent, and 5 percent probability that they exceed 27 percent by the 2050s[38]	Median yield loss –11 percent range of around –50 percent to +90 percent[39]	–20 percent yield reduction[40]
	Maize	About 37 percent of 2000 crop production.[41] Historical data show non-linear heat effects on maize with large potential losses under climate warming[42]		–5 percent[47] to –22 percent[43]		–13 percent for central Africa, –19 percent for east Africa, –16 percent in southern Africa, and –23 percent in west Africa[35]

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Table 3.4: Impacts in Sub-Saharan Africa

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (≈2030s[1])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C and Above (≈2080s)
	Sorghum	About 19 percent of 2000 crop production[44]	Significant negative impacts on sorghum suitability in the western Sahelian region and Southern Africa[45]	–15[47] to –17 percent[43]		
	Wheat	About 5 percent of 2000 crop production[46]		–17 percent[47]		
	Rice			No trend[47]		
	Millet	About 13 percent of 2000 crop production[48]		–10[47] to –17[43] percent		–6 percent with a range of –29 to +11 percent.[49] –16 to 19 percent for the equatorial fully humid climate zone (Guinean region of West Africa, central Africa and most parts of East Africa)[50]
	Groundnut			–18[43] percent		
	Cassava			–8[43] percent		
Livestock		Severe drought impacts on livestock. Pastoralists in southern Ethiopia lost 46 percent of their cattle and 41 percent of their sheep and goats to droughts between 1995 and 1997.[51] Damage to livestock stocks by flooding in the 1990s has been recorded in the Horn of Africa[52]	Forage yield change in the Sikasso region in Mali is projected to be –5 to –36 percent, and as food intake for livestock decreases, rate of cattle weight gain is found to be reduced by –13.6 to –15.7 percent; while the rate of weight gain does not change for sheep and goats[53]			10 percent increase in yields of *B. decumbens* (pasture species) in east and southern Africa; 4 percent and 6 percent decrease in central and west Africa.[35]

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Table 3.4: Impacts in Sub-Saharan Africa

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (≈2030s[1])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C and Above (≈2080s)
Marine Fisheries				Potential offshore catch increases along eastern and Southeastern coast of Sub-Saharan Africa of 16 percent (Madagascar, Mozambique, Tanzania, and Kenya). With closer proximity to coast yield reductions of –16 to –5 percent projected. Catch increases up to 100 percent at the coast of Somalia and South Africa.[54] Significant reductions in maximum catch potential for western African coast of –16 to –5 percent for Namibia, –31 to 15 percent for Cameroon and Gabon[54], and up to 50 percent off the coast of Côte d'Ivoire, Ghana, Liberia, Togo, Nigeria, and Sierra Leone.[55] Significant reduction in available protein, economic and job losses projected		
Coastal Areas		Tanzania has 800 km of coast line and multiple islands where impact of sea level rise can already be seen (salination of wells, destruction of infrastructure)[56]	Close to 11 million people flooded every year by 2100 without adaptation.[57] The largest seaport in East Africa, Mombasa, faces major risks. For 0.3 m sea level rise around 17 percent of Mombasa's area could be submerged, and a "larger area rendered uninhabitable or unusable for agriculture because of water logging and salt stress"[58]. Tourism resources such as beaches, historic and cultural monuments, and port infrastructure, would be negatively affected[58]		Tanzania capital city, Dar es Salaam, 70cm sea-level rise by 2070s about US$10 billion of assets projected[59] to be exposed by 2070, corresponding to more than 10 percent of the projected city GDP. Damage to port infrastructure in Dar es Salaam, could have serious economic consequences. The seaport handles approximately 95 percent of Tanzania's international trade and serves landlocked countries further inland	Approximately 18 million people flooded per year[60] by 2100 without adaptation. Mozambique and Nigeria projected to be the most affected African countries with 6 and 3 million being flooded annually by 2100. Guinea-Bissau, Mozambique and Gambia the highest percentage of population affected (more than 10 percent). In Eritrea, a one meter sea level rise is estimated to cause damage of over US$ 250 million (~18 percent of GDP in 2007) as a result of the submergence of infrastructure and other economic installations in Massawa, one of the country's two port cities[61]

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Table 3.4: Impacts in Sub-Saharan Africa

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (≈2030s[1])	Around 2°C (≈2040s)	Around 3°C (≈2060s)	Around 4°C and Above (≈2080s)
Poverty		Africa has largest 'poverty responses' to climate shocks[62]. Zambia's national poverty rate increased by 7.5 percent over 1991–92, classified as a severe drought year, and 2.4 percent over 2006–07, classified as a severe flood year[63]		The proportion of undernourished children and those suffering from moderate and severe stunting is projected to decrease absent climate change. With climate change the proportion undernourished is expected to increase significantly. The proportion affected by moderate and severe stunting is expected to increase, with the most significant increase 31–55 percent for severe stunting[64]	Urban wage-labor-dependent populations across the developing world may be most affected by once-in-30-year climate extremes, with an average increase of 30 percent in poverty compared to the base period. The poverty rate for this group in Malawi, for example, is estimated to be as much as double following a once-in-30-year climate event, compared to an average increase in poverty of 9.2 percent among rural agricultural households[65]	

Notes to Table 3.4

[1] Years indicate the decade during which warming levels are exceeded with a 50 percent or greater change (generally at start of decade) in a business-as-usual scenario (RCP8.5 scenario). Exceedance with a likely chance (>66 percent) generally occurs in the second half of the decade cited.
[2] Monthly summer temperatures 5.3°C (5oC above the 1951–80 baseline) by 2100.
[3] Lyon and DeWitt (2012).
[4] Lott, Christidis, and Stott (2013).
[5] This is the general picture from CMIP5 models; however, significant uncertainty appears to remain. Observed drought trends (Lyon and DeWitt 2012) and attribution of the 2011 drought in part to human influence (Lott et al. 2013) leaves significant uncertainty as to whether the projected increased precipitation and reduced drought are robust (Tierney, Smerdon, Anchukaitis, and Seager 2013).
[6] This is the general picture from CMIP5 models; however, significant uncertainty appears to remain. Observed drought trends (Lyon and DeWitt 2012) and attribution of the 2011 drought in part to human influence (Lott et al. 2013) leaves significant uncertainty as to whether the projected increased precipitation and reduced drought are robust (Tierney et al. 2013).
[7] Dai (2011).
[8] Karumba (2013); Zaracostas (2011).
[9] Dai (2012). CMIP5 models under RCP4.5 for drought changes 2050–99, warming of about 2.6°C above pre-industrial levels.
[10] Tierney et al. (2013).
[11] Dai (2012).
[12] Tierney et al. (2013).
[13] Above 1880 estimated global mean sea level.
[14] Add 20 cm to get an approximate estimate above the pre-industrial sea level.
[15] For a scenario in which warming peaks above 1.5°C around the 2050s and drops below 1.5°C by 2100. Due to slow response of oceans and ice sheets, the sea-level response is similar to a 2°C scenario during the 21st century, but deviates from it after 2100.
[16] Gonzalez, Tucker, and Sy 2012) attribute changes to the observed trend to changes in temperature and rainfall variability.
[17] Economics of Climate Adaptation (2009).
[18] Ndebele-Murisa, Musil, and Raitt (2010).
[19] Midgley and Thuiller (2010).
[20] Broennimann et al. 2006).
[21] Parry et al. (2007).
[22] SRES A1B about 3.5°C above pre-industrial level.
[23] (Midgley and Thuiller 2010).
[24] Parry et al. (2007).
[25] Under a 2.7°C warming above pre-industrial levels.
[26] Within regions with a strong level of model agreement (60–80 percent).
[27] Much greater consensus among impact models (Schewe et al. 2013).
[28] Gerten et al. (2011).
[29] For 2080s (global-mean warming of 3.5°C above pre-industrial levels) and changes in water availability relative to 1971–2000. In this projection, population is held constant.
[30] Temperature increase of 2.3°C and 2.1°C for the period 2041–79 under SRES A2 and B2 (Döll 2009).
[31] Burke, Lobell, and Guarino (2009).
[32] Jones, P. G. G., & Thornton, P. K. K. (2009). Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. Environmental Science & Policy, 12(4), 427–437. doi:10.1016/j.envsci.2008.08.006
[33] Jones, P. G. G., & Thornton, P. K. K. (2009). Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. Environmental Science & Policy, 12(4), 427–437. doi:10.1016/j.envsci.2008.08.006
[34] A global-mean warming of 5.4°C above pre-industrial levels. Exceptions being parts of Kenya and Tanzania, where the growing season length may moderately increase by 5 to 20 percent. The latter is not expected to translate into increased crop production, however; instead a reduction of 19 percent is projected for maize and 47 percent for beans, while no or a slightly positive change is projected for pasture grass. Over much of the rest of SSA reductions for maize range from –13 percent to –24 percent, and for beans from –69 to –87 percent, respectively, but the variability among different climate models is larger than the variability for East Africa. (Thornton, Jones, Ericksen, and Challinor 2011).
[35] Thornton et al. (2011).
[36] For 2020s for most scenario, 1.1–1.3°C above pre-industrial levels globally (Roudier, Sultan, Quirion, and Berg 2011).
[37] By the 2050s 1.6–2.2°C above pre-industrial levels globally (Roudier et al. 2011).
[38] Schlenker and Lobell (2010).
[39] For the 2080s (2.4–4.3°C for SREA B1, B2, A2, A1F above pre-industrial levels globally) but only on data point for SRES A1F; the others are all closer to 3°C. Range is full range with and without CO_2 fertilization.
[40] One data point only for approximately 4°C (Roudier et al. 2011).
[41] Nelson et al. (2010).
[42] Lobell, Schlenker, and Costa-Roberts (2011).
[43] For a 2050s, global-mean warming of about 2.2°C above pre-industrial levels, median impacts across SSA (Schlenker and Lobell 2010).
[44] Nelson et al. (2010).
[45] Ramirez-Villegas, Jarvis, and Läderach (2011).
[46] Nelson et al. (2010).
[47] Knox, Hess, Daccache, and Wheeler (2012) for 2050s range of different scenarios and warming levels.
[48] Nelson et al. (2010).
[49] Across India and Sub-Saharan Africa and all climatic zones considered, for the highest levels of warming by the 2080s (Berg, De Noblet-Ducoudré, Sultan, Lengaigne, and Guimberteau 2012).
[50] SRESA1B scenario (3.6°C above pre-industrial levels globally) and SRESA2 scenario (4.4°C) or 2100 (Berg et al. 2012).
[51] FAO (2008).
[52] Little, Mahmoud, and Coppock (2001), cited in Morton (2012).
[53] For local temperature increases of 1 to 2.5°C, with variation in magnitude across parts of the region and models. (Butt, McCarl, Angerer, Dyke, and Stuth 2005).
[54] Under a 2°C scenario by 2055 (Cheung et al. 2010).
[55] Lam, Cheung, Swartz, and Sumaila (2012). Applying the same method and scenario as Cheung et al. (2010).
[56] ECA (2009).
[57] Hinkel et al. (2011). 64 cm SLR scenario by 2100. In the no sea-level rise scenario, only accounting for delta subsidence and increased population, up to 9 million people would be affected.
[58] Awuor, Orindi, and Adwera (2008).
[59] Socioeconomic changes and increased coastal flooding induced by sea level rise and natural subsidence (Kebede and Nicholls 2011).
[60] Hinkel et al. (2011). High SLR scenario 126 cm by 2100. In the no sea-level rise scenario, only accounting for delta subsidence and increased population, up to 9 million people would be affected.
[61] Boko et al., (2007).
[62] Ahmed, Diffenbaugh, and Hertel (2009). Of a sample of 16 countries across Latin America Asia, and Africa, the largest "poverty responses" to climate shocks were observed in Africa.
[63] Thurlow, Zhu, and Diao (2012).
[64] Lloyd, Kovats, and Chalabi (2011) estimate the impact of climate-change-induced changes to crop productivity on undernourished and stunted children under five years of age by 2050 and find that the proportion of undernourished children is projected to increase by 52 percent, 116 percent, 82 percent, and 142 percent in central, east, south, and west Sub-Saharan Africa, respectively. The proportion of stunting among children is projected to increase by 1 percent (for moderate stunting) or 30 percent (for severe stunting); 9 percent or 55 percent; 23 percent or 55 percent; and 9 percent or 36 percent for central, east, south, and west Sub-Saharan Africa.
[65] Ahmed et al. (2009) scenario approaching 3.5°C above pre-industrial levels by the end of the century.

Chapter 4

South East Asia: Coastal Zones and Productivity at Risk

REGIONAL SUMMARY

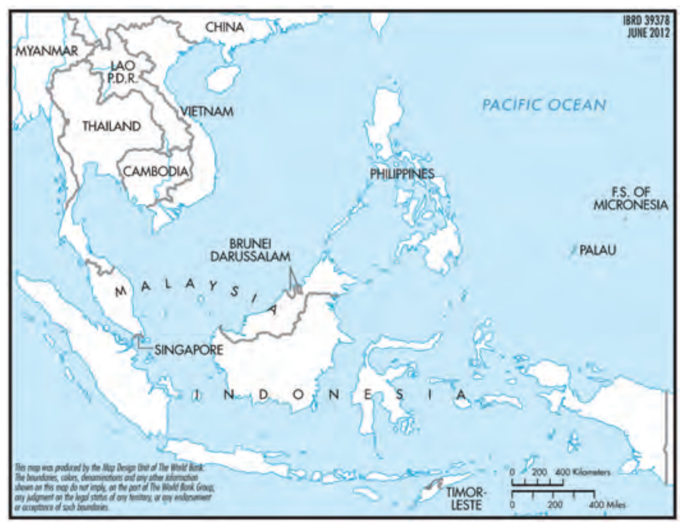
In this report, South East Asia refers to a region comprising 12 countries[51] with a population of ~590 million in 2010. In 2050, the population is projected to be around 760 million, 65 percent urban-based, and concentrated along the coast.

Major impacts on the region and its natural resources are projected for warming levels of 1.5–2°C, resulting in coral reefs being threatened with consequent damage to tourism- and fisheries-based livelihoods and decreases in agricultural production in the delta regions due to sea-level rise. For example, by the 2040s, a 30 cm sea-level rise is projected to reduce rice production in the region's major rice growing region—the Mekong River Delta—by about 2.6 million tons per year, or about 11 percent of 2011 production. Marine fish capture is also projected to decrease by about 50 percent in the southern Philippines during the 2050s due to warmer sea temperatures and ocean acidification.

With 4°C global warming, there could be severe coastal erosion due to coral reef dieback. Sea level is projected to rise up to 100 cm by the 2090s; this would be compounded by projected increases in the intensity of the strongest tropical cyclones making landfall in the region. In addition, unprecedented heat extremes over nearly 90 percent of the land area during the summer months (June, July and August) is likely to result in large negative impacts.

Current Climate Trends and Projected Climate Change to 2100

Climate projections for South East Asia are very challenging due to the region's complex terrain, comprising mountains, valleys, and



coastal zones across a diverse mix of mainland, peninsulas, and islands; the related regional sea-land interactions; and the large number of interacting climate drivers that give rise to the local climate.

Temperature

In a 2°C world, average summer warming in the region is projected to be around 1.5°C (1.0–2.0°C) by the 2040s. In a 4°C world, South East Asian average summer temperatures over land are projected to increase by around 4.5°C (3.5–6°C) by 2100. This is

51 Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, the Philippines, Singapore, Thailand, Timor Leste, and Vietnam.

substantially lower than the global-mean surface warming over land, because the region's climate is more strongly influenced by sea-surface temperatures that are increasing at a slower rate than in other regions with a larger continental land surface.

In tropical South East Asia, however, heat extremes are projected to escalate with extreme temperature events frequently exceeding temperature ranges due to natural climate variability. For example, under a 2°C global warming scenario, currently unusual heat extremes[52] during the summer are projected to cover nearly 60–70 percent of the land area. Unprecedented heat extremes could occupy up to 30–40 percent of land area. In a 4°C world, summer months that in today´s climate would be termed unprecedented might be the new normal, affecting nearly 90 percent of the land area during the summer months. More important, the South East Asia region is one of two regions (the other being the Amazon) which is projected to see, in the near-term, a strong increase in monthly heat extremes with the number of warm days[53] projected to increase from 45–90 days/year under a 2°C world to around 300 days for a 4°C world.

Rainfall

The use of climate models to project future rainfall changes is especially difficult for South East Asia because both the Asian and the Australian summer monsoons affect the region and large differences remain between individual models. For 4°C warming, there is no agreement across models for South East Asia, with changes either not statistically significant, or ranging from a decrease of 5 percent to an increase of 10 percent in monsoon rainfall. Despite these moderate changes, the latest model projections show a substantial and rising increase in both the magnitude and frequency of heavy precipitation events. The increase of extreme rainfall events[54] is projected to rise rapidly with warming, and to contribute more than a 10-percent share of annual rainfall for 2°C and a 50-percent share for 4°C warming, respectively. At the same time the maximum number of consecutive dry days, which is a measure for drought, is also projected to increase, indicating that both minimum and maximum precipitation extremes are likely to be amplified.

Likely Physical and Biophysical Impacts as a Function of Projected Climate Change

Sea-level Rise

Sea-level rise along the South East Asian coastlines is projected to be about 10–15 percent higher than the global mean by the end of the 21st century. In a 4°C world, the projected regional sea-level rise is likely[55] to exceed 50 cm above present levels[56] by 2060, and 100 cm by 2090, with Manila being especially vulnerable. In a 2°C world, the rise is significantly lower for all locations, but still considerable, at 75 (65–85) cm by 2090. Local land subsidence due to natural or human influences would increase the relative sea-level rise in specific locations.

Tropical Cyclone Risk

An increase in the frequency of the most intense storms[57] along with associated extreme rainfall is projected for South East Asia. Maximum surface wind speed during tropical cyclones is projected to increase by 7–18 percent for a warming of around 3.5°C above pre-industrial levels for the western North Pacific basin, but the center of activity is projected to shift north and eastward. The maximum wind speed of tropical cyclones making landfall is projected to increase by 6 and 9 percent respectively for mainland South East Asia and the Philippines, combined with a decrease of 35 and 10 percent respectively in the overall number of land-falling cyclones. As sea-surface temperatures rise, tropical-cyclone-related rainfall is expected to increase by up to a third, indicating a higher level of flood risk in low lying and coastal regions.

Saltwater Intrusion

For several South East Asia countries, salinity intrusion in coastal areas is projected to increase significantly with rising sea levels. For example, a 1 m sea-level rise by 2100 in the land area affected by saltwater intrusion in the Mahaka River region in Indonesia is expected to increase by 7–12 percent under 4°C warming. In the Mekong River Delta, it is projected that a 30-cm sea-level rise by the 2050s in both the 2°C and 4°C worlds would increase by over 30 percent the total current area (1.3 million ha) affected by salinity intrusion.

Coral Reef Loss and Degradation

Coral reefs flourish in a relatively narrow range of temperature tolerance and are hence highly vulnerable to sea-surface temperature increases; together with the effects of ocean acidification, this exposes coral reefs to more severe thermal stress, resulting in bleaching. Rising sea surface temperatures have already led to major, damaging coral bleaching events[58] in the last few decades. Under 1.5°C warming, there is a high risk (50-percent probability) of annual bleaching events occurring as early as 2030 in the

52 Extremes are defined by present-day, local natural year-to-year variability of around 1°C, which are projected to be exceeded frequently even with low levels of average warming. Unprecedented = record breaking over the entire measurement recording period.

53 Defined by historical variability, independent of emissions scenario, with temperature beyond the 90th percentile in the present-day climate.

54 Estimated as the share of the total annual precipitation.

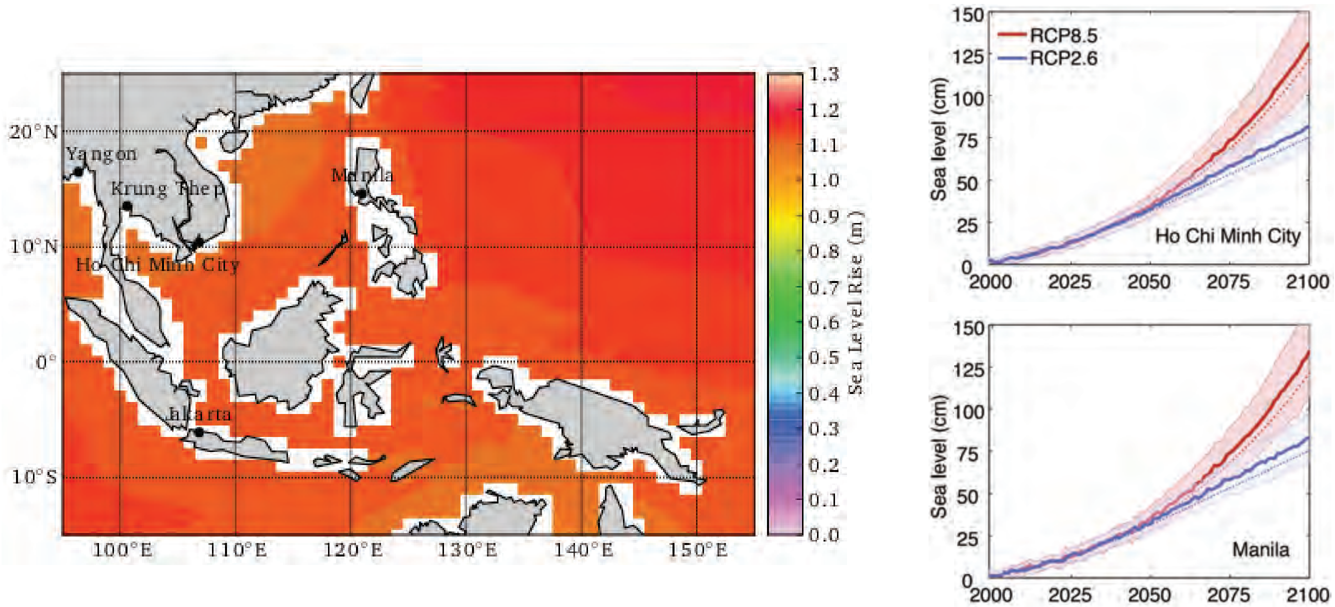
55 Where "likely" is defined as > 66 percent chance of occurring, using the modeling approaches adopted in this report.

56 1986–2005 levels.

57 Category 4 and 5 on the Saffir-Simpson wind scale.

58 Coral bleaching events can be expected when a regional, warm seasonal maximum temperature is exceeded by 1°C for more than four weeks, and bleaching becomes progressively worse at higher temperatures or longer periods over which the regional threshold temperature is exceeded. While coral reefs can survive a bleaching event, they are subject to high mortality and take several years to recover. When bleaching events become too frequent or extreme, coral reefs can fail to recover.

Figure 4.1: South East Asia - The regional pattern of sea-level rise in a 4°C world (left; RCP8.5) as projected by using the semi-empirical approach adopted in this report and time-series of projected sea-level rise for two selected cities in the region (right) for both RCP2.6 (2°C world) and RCP8.5 (4°C world)



region. Projections indicate that all coral reefs are very likely to experience severe thermal stress by the year 2050 at warming levels of 1.5°C–2°C above pre-industrial levels. In a 2°C world, coral reefs will be under significant threat, and most coral reefs are projected to be extinct long before 4°C warming is reached with the loss of associated marine fisheries, tourism, and coastal protection against sea-level rise and storm surges.

Sector-based and Thematic Impacts

River deltas, such as the Mekong River Delta, experience regular flooding as part of the natural annual hydrological cycle. Such flooding plays an important economic and cultural role in the region's deltas. Climate change projections for sea-level rise and tropical cyclone intensity, along with land subsidence caused by human activities, would expose populations to heightened risks, including excess flooding, saltwater intrusion, and coastal erosion. These consequences would occur even though deltaic regions tend to be relatively resilient to unstable water levels and salinity. The three river deltas of the Mekong, Irrawaddy, and Chao Phraya, all with significant land areas below 2 m above sea level, are highly threatened by these risk factors.

Coastal cities with large and increasing populations and assets are exposed to climate-change-related risks, including increased tropical storm intensity, long-term sea-level rise, and sudden-onset fluvial and coastal flooding. Estimating the number of people exposed to the impacts of sea-level rise is made difficult by uncertainties inherent to sea-level rise projections, as well as population and economic growth scenarios. Bangkok,[59] Jakarta, Ho Chi Minh City, and Manila stand out as being particularly vulnerable to climate-driven impacts. Many millions in Bangkok and Ho Chi Minh City are projected to be exposed to the effects of a 50 cm sea-level rise[60] by the 2070s. High levels of growth of both urban populations and GDP further increase exposure to climate change impacts in these areas. Further, the effect of heat extremes are also particularly pronounced in urban areas due to the urban heat island effect, caused in large part by the density of buildings and the size of cities, which results in higher human mortality and morbidity rates in cities than in the rural surroundings. The urban poor are particularly vulnerable to environmental stresses; floods associated with sea-level rise and storm surges pose significant flood damage and health risks to populations in informal settlements. In 2005, about 40 percent of the urban population of Vietnam and 45 percent of the urban population in the Philippines lived in informal settlements.

Agricultural production in the region, particularly rice production in the Mekong Delta, is exposed to sea-level rise due to

59 Without adaptation, the area of Bangkok is projected to be inundated resulting from flooding due to extreme rainfall events and sea-level rise increases from around 40 percent under a 15 cm sea-level rise above present levels (which could occur by the 2030s), to about 70 percent under an 88 cm sea-level rise scenario (which would be approached by the 2080s under 4°C warming).

60 Assuming 50 cm local subsidence.

Table 4.1: Summary of climate impacts and risks in South East Asia[a]

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C[b] (2030s[c])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C (2080s)
Regional warming		South China Sea warmed at average rate of 0.3–0.4°C per decade since the 1960s. Vietnam warmed at a rate of about 0.3°C per decade since 1971, more than twice the global average	Increasing frequency of warm nights	Warm nights in present-day climate the new normal		Almost all nights (~95 percent) beyond present-day warm nights
Heat extreme (in the Northern Hemisphere summer period)[d]	Unusual heat extremes	Virtually absent	50–60 percent of land	60–70 percent of land	85 percent of land	> 90 percent of land
	Unprecedented heat extremes	Absent 25–30 percentof land	30–40 percent of land	70 percent of land	> 80 percent of land	
Sea-level rise (above present)		About 20cm to 2010	30cm-2040s 50cm-2060s 75cm by 2080–2100	30cm-2040s 50cm-2060s 75cm by 2080–2100	30cm-2040s 50cm-2060 95cm by 2080–2100	30cm-2040s 50cm-2060 110cm by 2080–2100
Coral reefs		Unusual bleaching events	High risk of annual bleaching events occurring (50 percent probability) as early as 2030	Nearly all coral reefs projected to be experiencing severe bleaching		

[a] A more comprehensive table of impacts and risks for SSA is presented at the end of the Chapter.
[b] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario exceeding 4°C by the 2080s.
[c] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario, not in mitigation scenarios limiting warming to these levels, or below, since in that case the year of exceeding would always be 2100, or not at all.
[d] The mean across climate model projections is given. Illustrative uncertainty ranges across the models (minimum to maximum) for 4°C warming are 70–100 percent for unusual extremes, and 30–100 percent for unprecedented extremes. The maximum frequency of heat extreme occurrence in both cases is close to 100 percent as indicator values saturate at this level.

its low elevation above sea level. A sea-level rise of 30 cm, which could occur as early as 2040, is projected to result in the loss of about 12 percent of the cropping area of the Mekong Delta Province due to flooding (5 percent loss) and salinity intrusion (7 percent). Whilst some rice cultivars are more resilient than others, there is evidence that all rice is vulnerable to sudden and total inundation when this is sustained for several days, where flooding, sensitivity thresholds even of relatively resilient rice cultivars may be exceeded and production severely impacted. Temperature increases beyond thresholds during critical rice growth phases (tillering, flowering, grain filling) may further impact productivity.

Aquaculture, which is also at risk from several climate change impacts, is a rapidly growing and economically important industry in South East Asia. In Vietnam, for example, it has grown rapidly; in 2011, it generated about 5 percent of its GDP, up from about 3 percent in 2000. Rapid sectoral growth has also been observed in other South East Asian countries. Aquaculture also supplies nearly 40 percent of dietary animal protein in South East Asia derived from fish, and is thus critical to food security in the region. Aquaculture farms are projected to be damaged by increasingly intense tropical cyclones and salinity intrusion associated with sea-level rise, particularly for freshwater and brackish water aquaculture farms. In addition increasing temperatures may exceed the tolerance thresholds of regionally important farmed species. Extreme weather events, such as tropical cyclones and coastal floods, already affect aquaculture activities in South East Asia. For example, the category 4 Typhoon Xangsane devastated more than 1,200 hectares of aquaculture area in Vietnam in 2006 while the Indonesian Typhoons Vincente (Category 4) and Saola (Category 2) negatively impacted about 3,000 aquaculture farmers and resulted in over $9 million in damages to the fishery sector (Xinhua, 2012).

Fisheries, particularly coral reef fisheries, are expected to be effected by the impacts of sea-level rise, warmer oceans, and ocean acidification associated with rising atmospheric and ocean CO_2 concentrations. Substantial reductions in catch potential are projected. The projected changes in maximum catch potential range from a 16-percent decrease in the waters of Vietnam to a 6–16 percent increase around the northern Philippines. Additionally, marine capture fisheries production (not directly associated with coral systems) are projected to decline by 50 percent around the southern Philippines. Such shifts in catch potential are likely to place additional challenges on coastal livelihoods in the region.

Integrated Synthesis of Climate Change Impacts in the South East Asia Region

South East Asia is highly and increasingly exposed to slow onset impacts associated with sea-level rise, ocean warming and acidification, coral bleaching, and associated loss of biodiversity, combined with sudden-onset impacts associated with increased tropical cyclone intensity and greater heat extremes. The combined impacts are likely to have adverse effects on several sectors simultaneously**.** The cumulative effects of the slow-onset impacts may undermine resilience and increase vulnerability to more extreme weather events, with this complex pattern of exposure increasing with higher levels of warming and sea-level rise.

Growing Risks to Populations, Livelihoods and Food Production in River Deltas

Populations and associated cropping and fisheries systems and livelihoods along the rivers and in the river deltas are expected to be the most severely affected by risks from rising sea levels, more intense rainfall events, and storm surges associated with tropical cyclones.

For example, the Mekong River and its tributaries are crucial to rice production in Vietnam. A total of 12 provinces constitute the Mekong Delta, popularly known as the "Rice Bowl" of Vietnam; it is home to some 17 million people, of whom 80 percent are engaged in rice cultivation. The delta produces around 50 percent of the country's total production and contributes significantly to Vietnam's rice exports. Any shortfall in rice production in this area because of climate change would not only affect the economy in and food security of Vietnam but would also have repercussions for the international rice market.

The Mekong Delta is also Vietnam's most important fishing region. It is home to almost half of Vietnam's marine fishing vessels and produces two thirds of Vietnam's fish from aquaculture systems. Important industries such as aquaculture are projected to suffer increasing costs and damages associated with salinization and rising temperatures. Observed human vulnerability in deltas in the region is high: When tropical cyclone Nargis[61] hit the Irrawaddy River Delta in Myanmar in 2008 it resulted in over 80,000 deaths, temporarily displaced 800,000 people, submerged large areas of farming land, and caused substantial damage to food production and storage.

Health impacts associated with saltwater intrusion are likely to increase. Sea-level rise and tropical cyclones may increase salinity intrusion, thereby contaminating freshwater resources—an effect that can persist for years. The most common health implication is hypertension; however there are a broad range of health problems potentially linked to increased salinity exposure through bathing, drinking, and cooking. These include miscarriages, skin disease, acute respiratory infection, and diarrheal disease.

Increasing Pressure on Coastal Cities and Urban Exposure

Especially in South East Asia, coastal cities concentrate increasingly large populations and assets exposed to increased tropical storm intensity, long-term sea-level rise, sudden-onset coastal flooding, and other risks associated with climate change. Without adaptation, Bangkok is projected to be inundated due to extreme rainfall events and sea-level rise increases from around 40 percent under a 15 cm sea-level rise above present levels (which could occur by the 2030s) to about 70 percent under an 88 cm sea-level rise scenario (which could occur by the 2080s under 4°C warming). The effect of heat extremes are particularly pronounced in urban areas due to the urban heat island effect; this could result in high human mortality and morbidity rates in cities. These risks are particularly acute, as in the Philippines and Vietnam, where almost 40 percent of the population lives in informal settlements, where health threats can quickly be exacerbated by a lack of, and/or damage to, sanitation and water facilities. The high population density in such areas compounds these risks.

The projected degradation and loss of coral reefs, decreased fish availability, and pressures on other near-coastal rural production due to sea-level rise within the next few decades is likely to lead to diminishing livelihoods in coastal and deltaic areas. Increased migration to urban areas has already been occurring. Urban migration may result in more urban dwellers being exposed to climate impacts in the cities of South East Asia, especially new arrivals who are likely to crowd into existing and densely populated informal settlements.

Compound Risks to the Tourism Industry and to Businesses

Projected increases in sea-level rise, the intensity of tropical cyclones, and the degradation and loss of coral reefs pose significant risks to the tourism industry by damaging infrastructure and natural resources and assets that enhance the region's appeal as a tourist destination. Research indicates that the threat of tropical cyclones appears to have a negative effect on tourists' choice of destination on the same scale as deterrents such as terrorist attacks and political crises.

Loss of coastal assets due to erosion has already been observed and can be expected to accelerate. Sea-level rise has already contributed directly to increased coastal erosion in the Red River Delta and other regions. Coastal erosion in the Mekong River Delta is expected to increase significantly under a 100 cm sea-level rise by 2100. Projected beach losses for the San Fernando Bay area of the Philippines will substantially affect beach assets and a considerable number of residential structures.

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[61] Land fall as a Category 4 storm on the Saffir-Simpson scale.

Coral bleaching and reef degradation and losses are very likely to accelerate in the next 10–20 years; hence, revenue generated from diving and sport fishing also appears likely to be affected in the near term. The degradation of coral reefs could result in the loss of fisheries and the coastal protection offered by reefs, as well as the loss of tourists upon whom coastal populations and economies often depend.

The risks and damages projected for a warming level of 1.5–2°C in South East Asia are very significant. The physical exposure to climate change at this level of warming includes substantial areas of South East Asia subjected to unprecedented heat extremes, 50 cm of sea-level rise by the 2050s and 75 cm or more by 2100. The biophysical damages projected include the loss of large areas of coral reefs, significant reductions in marine food production, and more intense tropical cyclones with related storm surges and flooding. Substantial losses of agricultural production in important rice-growing regions are projected to result from sea-level rise, as is the risk of significant flooding in major coastal cities. Significant damages to the tourism industry and to aquaculture are also projected.

Introduction

This report defines South East Asia as Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, the Philippines, Singapore, Thailand, Timor-Leste, and Vietnam. Specific attention is given to Vietnam and the Philippines. For the projections on changes to temperature, precipitation, and sea-level rise, the definition of South East Asia from the IPCC´s special report on (SREX) region 24 is used.[62]

Despite continued strong economic growth and a burgeoning middle class, poverty and inequality remain significant challenges in the region. The socioeconomic conditions in these countries are diverse in terms of population size, income, and the distribution of the inhabitants across urban and rural areas. In addition, a number of geographic factors influence the nature and extent of the physical impacts of climate change. Parts of South East Asia are located within a tropical cyclone belt and are characterized by archipelagic landscapes and relatively high coastal population density. This makes the region particularly vulnerable to the following impacts:

- Sea-level rise
- Increases in heat extremes
- Increased intensity of tropical cyclones
- Ocean warming and acidification

These physical impacts are expected to affect a number of sectors, including human health, tourism, aquaculture, and fisheries. Although changes to precipitation and temperature are expected to have adverse effects on terrestrial ecosystems, these and other critical biophysical impacts are outside the scope of this report.

River deltas and coastal areas are a key focus of this regional analysis; these are areas where many of these impacts occur and they pose severe risks to coastal livelihoods. Further attention is given to coastal cities, which are often situated in these deltas and contain a high concentration of people and assets.

Regional Patterns of Climate Change

Making climate projections for South East Asia is challenging due to the complex terrain, the mix of mainlands, peninsulas, and islands, the related regional sea-land interactions, and the large number of complex climate phenomena characterizing the region. The region's climate is mainly tropical and determined by the East Asian monsoon, a sub-system of the Asian-Australian monsoon, which is interconnected with the Indian monsoon (P. Webster 2006).

Observed Trends

Observed trends show a mean temperature increase around the South East Asian Seas at an average rate of between 0.27–0.4°C per decade since the 1960s (Tangang, Juneng, and Ahmad 2006) and, for Vietnam, a rate of about 0.26°C per decade since 1971 (Nguyen, Renwick, and McGregor 2013). This is more than twice the global average rate of about 0.13°C per decade for 1956–2005 (P. D. Jones et al. 2007). Trends in extreme temperature reveal a significant increase in hot days and warm nights and a decrease in cool days and cold nights (Manton et al. 2001). There is some indication of an increase in total precipitation, although these trends are not statistically robust and are spatially incoherent (Caesar et al. 2011). While regionally different, an increase in frequency and intensity of extreme precipitation events is reported (Chang 2010).

Projected Temperature Changes

In a 4°C world the subset of CMIP5 GCMs used within the ISI-MIP framework and this report projects South East Asian summer temperatures over land to increase by 4.5°C (model range from 3.5°C to 6°C) by 2100 (Figure 4.2). This is substantially lower than the global-mean land-surface warming, since the region's climate is driven by sea surface temperature, which is increasing at a smaller rate. In a 2°C world, the absolute summer warming

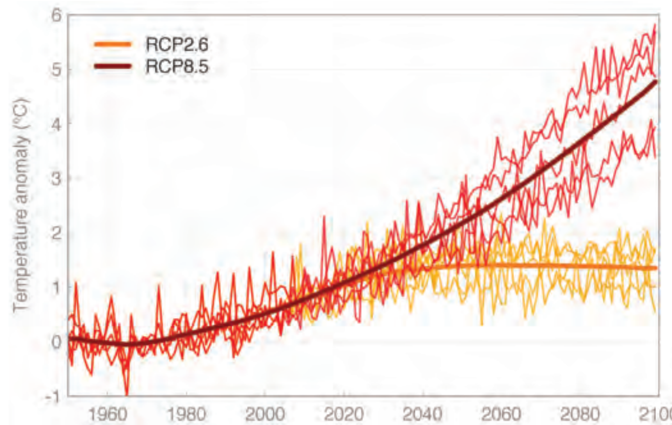
62 With minor changes at the northern boundary.

would be limited to around 1.5°C (model spread from 1.0–2.0°C) above the 1951–1980 baseline, to be reached in the 2040s. The strongest warming is expected in North Vietnam and Laos, with the multimodel mean projecting up to 5.0°C under 4°C global warming by 2071–2099 and up to 2°C under 2°C global warming (Figure 4.3). The expected future warming is large compared to the local year-to-year natural variability. In a 4°C world, the monthly temperature distribution of almost all land areas in South East Asia shifts by six standard deviations or more toward warmer values. In a 2°C world, this shift is substantially smaller, but still about 3–4 standard deviations.

Projected Changes in Heat Extremes

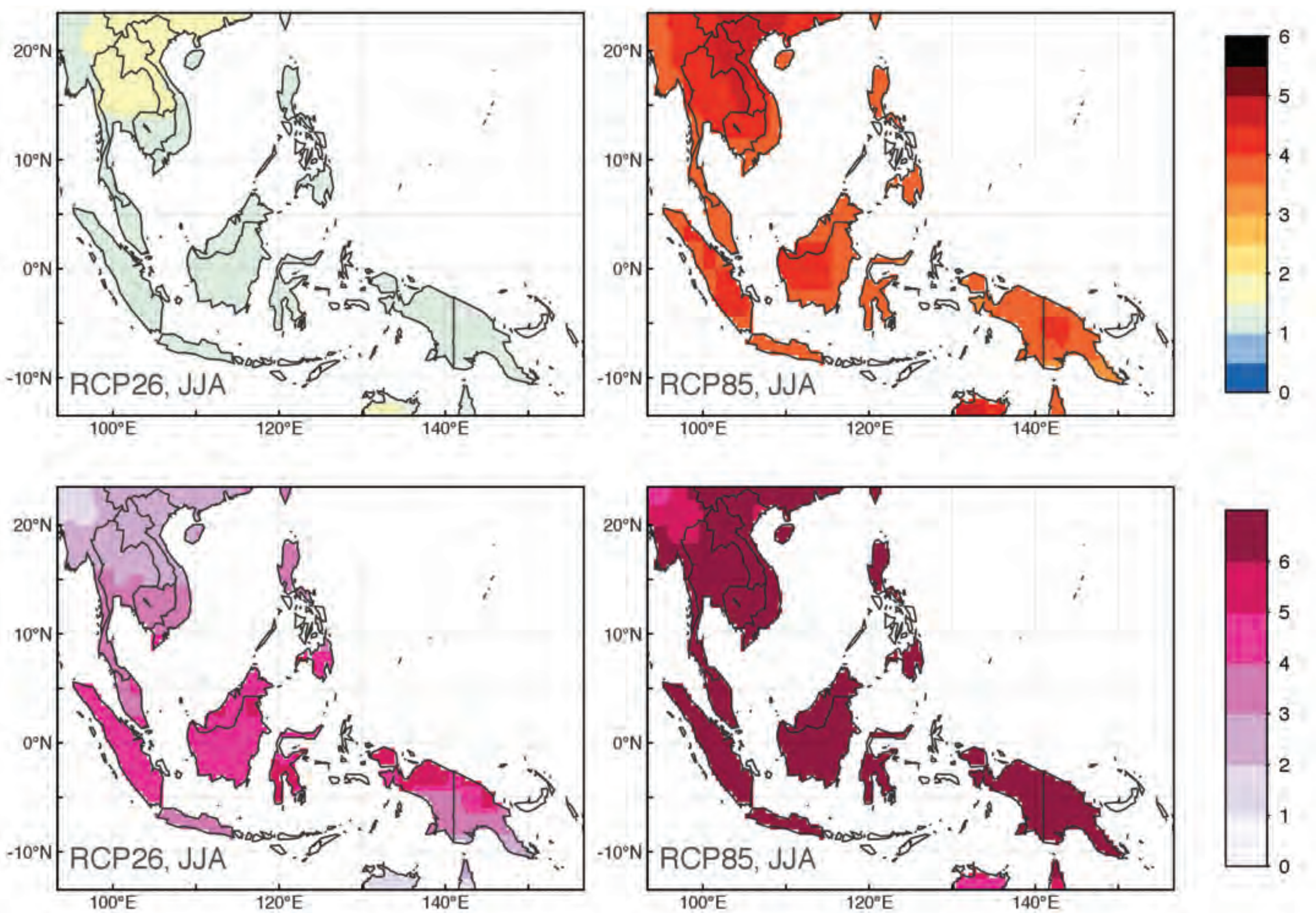
Heat extremes exceeding a threshold defined by the local natural year-to-year variability are projected to strongly increase in South

Figure 4.2: Temperature projections for South East Asian land area, for the multi-model mean (thick line) and individual models (thin lines) under RCP2.6 and RCP8.5 for the months of JJA



The multi-model mean has been smoothed to give the climatological trend.

Figure 4.3: Multi-model mean temperature anomaly for RCP2.6 (left) and RCP8.5 (right) for the months of JJA for South East Asia



Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–99 relative to 1951–80, and normalized by the local standard deviation (bottom row).

East Asia (Figures4.4 and 4.5). Even under the 2°C warming scenario, the multimodel mean projects that, during the second half of the 21st century, 30 percent of the South East Asian land area would be hotter than 5-sigma during boreal summer months (see Figure 4.5). Under the 4°C warming scenario, this value approaches 90 percent by 2100. It should be noted, however, that the model spread is large, as the averaging is performed over a small land surface area.

The strongest increases in frequency and intensity of extremes are projected for Indonesia and the southern Philippine islands (see Figure 4.4). Roughly half of the summer months is projected to be beyond 5-sigma under the 2°C warming scenario (i.e., 5-sigma would become the new normal) and essentially all summer months would be 5-sigma under the 4°C warming scenario (i.e., a present-day 5-sigma event would be an exceptionally cold month in the new climate of 2071–99). Mainland South East Asia is projected to be much less impacted; the conditions that are projected for Indonesia under the 2°C warming scenario only occur inland under the 4°C warming scenario. Thus, in the near term, the South East Asian region is projected to see a strong increase in monthly heat extremes, defined by the limited historical variability, independent of emissions scenario.

Consistent with these findings, Sillmann and Kharin (2013a) report that South East Asia is one of two regions (the other being the Amazon) where the number of heat extremes is expected to increase strongly even under a low-emission scenario (although the inter-model spread is substantial). Under a low-emission scenario, warm nights (beyond the 90th percentile in present-day climate) would become the new normal, with an occurrence-probability around 60 percent. In addition, the duration of warm spells would increase to somewhere between 45 and 90 days, depending on the exact location. Under emission scenario RCP8.5, warm spells

Figure 4.4: Multi-model mean of the percentage of boreal summer months in the time period 2071–2099 with temperatures greater than 3-sigma (top row) and 5-sigma (bottom row) for scenario RCP2.6 (left) and RCP8.5 (right) over South East Asia

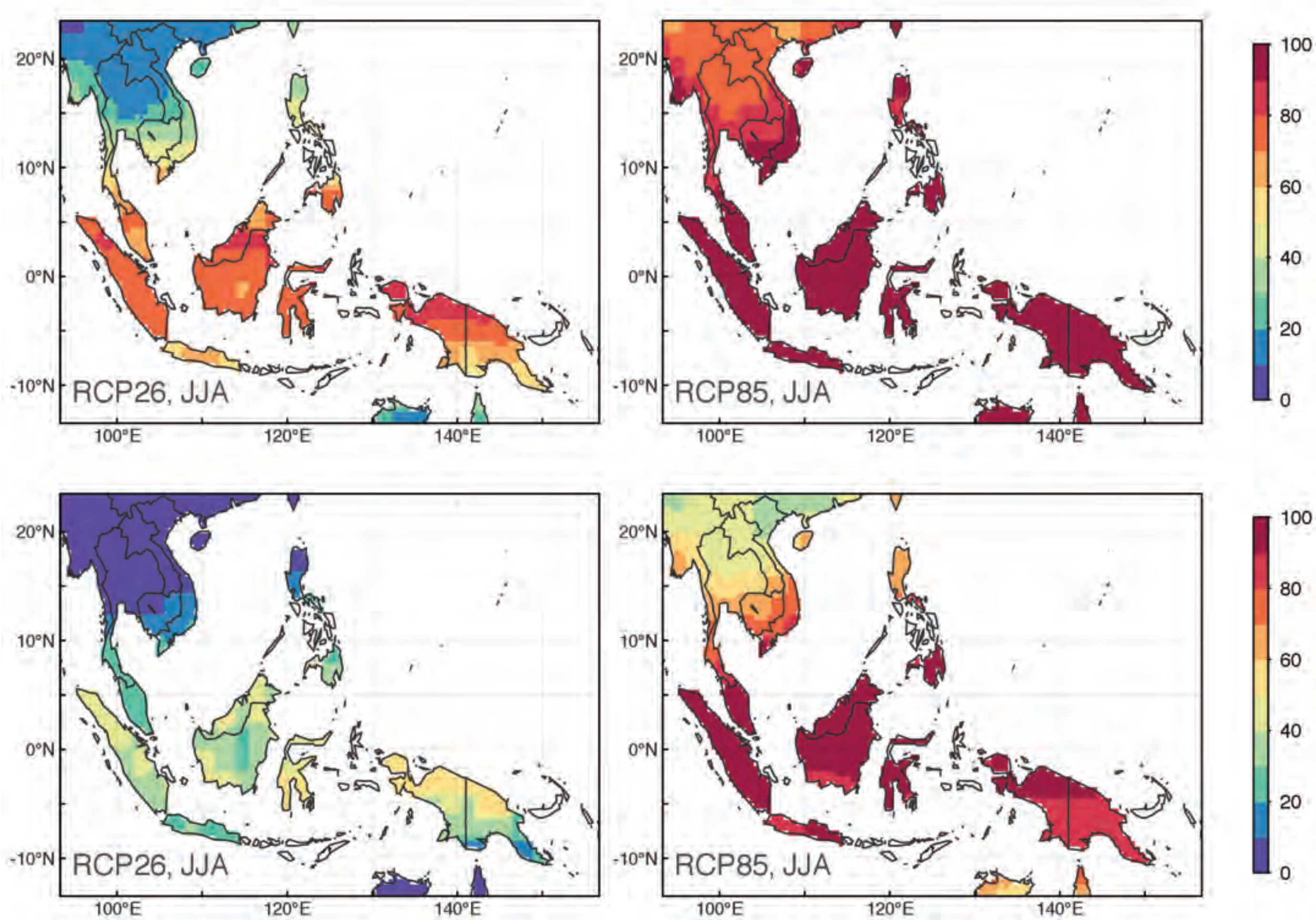
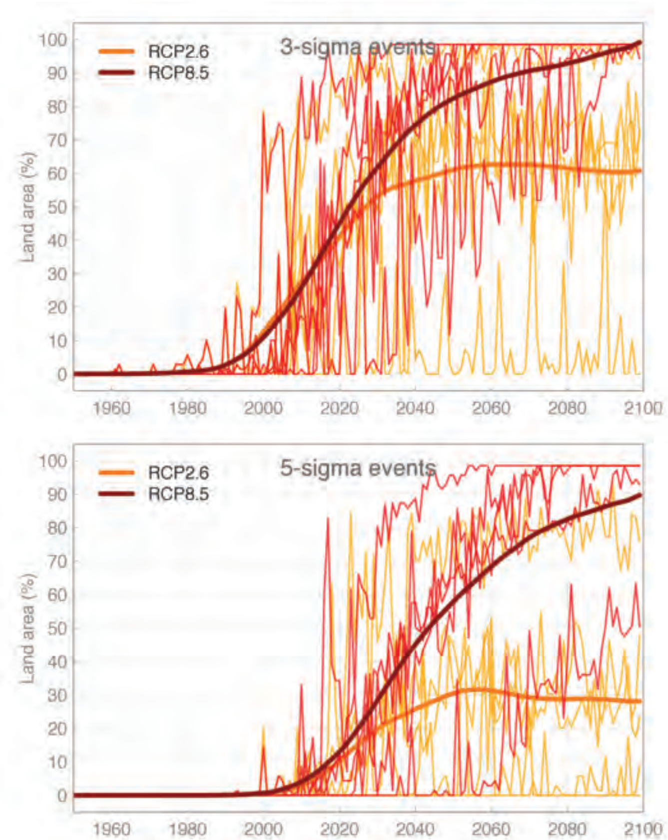


Figure 4.5: Multi-model mean (thick line) and individual models (thin lines) of the percentage of South East Asian land area warmer than 3-sigma (top) and 5-sigma during boreal summer months (JJA) for scenarios RCP2.6 and RCP8.5



would become nearly year-round (~300 days), and almost all nights (~95 percent) would be beyond the present-day 90th percentile (Sillmann and Kharin 2013a).

Precipitation Projections

While multimodel ensembles of GCMs do manage to represent monsoon systems, the difference is large among individual models; some completely fail in reproducing the observed patterns. The monsoon mechanisms in South East Asia are particularly hard to reproduce as both the Asian and the Australian summer monsoons affect the region (Hung, Liu, and Yanai 2004). Nicolas C. Jourdain et al. (2013) present monsoon projections based on CMIP5 models that perform best in reproducing present-day circulation patterns. Although they report an increase of 5–20 percent monsoon rainfall over the whole Indo-Australian region in the second half of the 21st century for 4°C warming, there is no agreement across models over South East Asia. The changes are either not statistically significant or range from a decrease of 5 percent to an increase of 10 percent in monsoon rainfall.

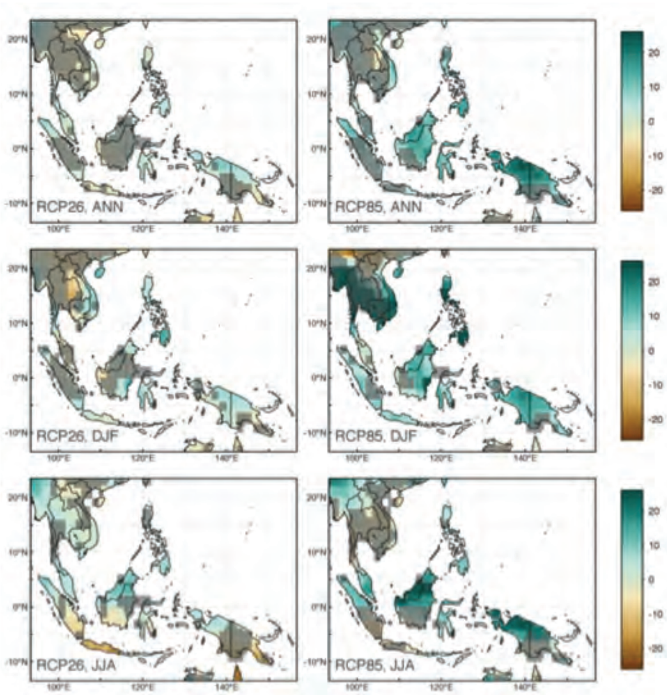
For the CMIP5 models included in the ISIMIP project (Figure 4.6), there is little change in annual mean precipitation over Vietnam and the Philippines in a 2°C world and a slight increase in a 4°C world relative to the 1951–80 reference period. Again, there is very little model agreement for this region. Precipitation appears to increase by about 10 percent during the dry season (DJF) for the 2°C warming scenario and more than 20 percent for the 4°C warming scenario—but it is important to note that these increases are relative to a very low absolute precipitation over the dry season.

In the Mekong River Basin, a United States Agency for International Development (2013) study[63] projects an increase in annual rainfall precipitation ranging from 3–14 percent. Seasonal variability is projected to increase; the wet season would see a rise in precipitation between 5–14 percent in the southern parts of the basin (southern Vietnam and Cambodia). In this area, as a consequence, the wet season is expected to become wetter and the dry season drier. Drier areas in the north of the basin are projected to experience relative increases in precipitation of 3–10 percent, corresponding to a slight increase of 50 to 100 mm per year.

Although global climate models are needed to project interactions between global circulation patterns of atmosphere and ocean, regional models, which offer a higher spatial resolution, provide a way to take into account complex regional geography. Chotamonsak, Salathé, Kreasuwan, Chantara, and Siriwitayakorn (2011) use the WRF regional climate model for studying climate change projections over South East Asia. Lacking global circulation patterns and interactions across regions, regional models need conditions at the model's boundaries prescribed by global models, for which the authors apply results from ECHAM5 for the A1B scenario by mid-century (about 2°C warming globally). Likewise, Lacombe, Hoanh, and Smakhtin (2012) use the PRECIS regional model—for mainland South East Asia only—with boundary conditions from ECHAM4 under the IPCC SRES scenario A2 and B2 (about 2°C warming globally). These studies find that the largest changes in annual mean precipitation, as well as the extremes, occur over the oceans. For land areas, the regional models largely confirm mean changes of global models (see Figure 4.6), with somewhat increased precipitation over the mainland. Chotamonsak et al. (2011) warn that such regional studies should be expanded with boundary conditions of multiple global models. They further note that changes in mean and

63 The United States Agency for International Development (2013) report projects the impacts of climate change for the period 2045–69 under the IPCC SRES scenario A1B (corresponding to about a 2.3°C temperature increase above pre-industrial levels) for the Lower Mekong Basin. For the study, authors used six GCMs (NCAR CCSM 3.0; MICRO3.2 hires; GISS AOM; CNRM CM3; BCCR BCM2.0; GFDL CM2.1) and used 1980–2005 as a baseline period.

Figure 4.6: Multi-model mean of the percentage change in annual (top), dry season (DJF, middle) and wet season (JJA, bottom) precipitation for RCP2.6 (left) and RCP8.5 (right) for South East Asia by 2071–99 relative to 1951–80



Hatched areas indicate uncertainty regions, with models disagreeing on the direction of change.

extreme precipitation in a regional model over South East Asia might be biased, since high-resolution models produce stronger spatial and temporal variability in tropical cyclones, which in one single model run might not be representative of the broader statistical probability.

Based on their projected changes in precipitation and temperature over mainland South East Asia only, Lacombe et al. 2012 suggest that these changes may be beneficial to the region and generate higher agricultural yields, as precipitation and temperatures may increase in the driest and coldest areas respectively. However, as the authors modelled only changes in climate variables and not in agricultural yields, and did not place their results into the context of literature on projections of the agricultural sector, there is little analytical evidence to support their assertion.[64]

Drought

Dai (2012) used global models to project changes in drought, resulting from the long-term balance of temperature, precipitation, and other variables. While soil-moisture content was projected to decrease over much of the mainland and southern Indonesia, increases were projected for Myanmar and other maritime parts of the region. None of the changes were found to be statistically significant. A different indicator of drought, the Palmer Drought Severity Index (PDSI), relates changes in water balance to locally "normal" conditions. On this relative scale, the projected pattern of drought risk is comparable. By contrast, Taylor et al. (2012) noted a consistent increase in drought risk indicated by PDSI for the whole region, with no significant change across Myanmar.

Extreme Precipitation Events

Despite the projections of moderate changes in mean precipitation, a substantial increase in the magnitude and frequency of heavy precipitation events is projected for South East Asia based on CMIP5 models (Sillmann and Kharin 2013a). The median increase of the extreme wet day precipitation share of the total annual precipitation is projected to be greater than 10 percent and 50 percent for 2°C and 4°C warming scenarios respectively. At the same time, the maximum number of consecutive dry days as a measure of drought is also projected to increase, indicating that both minimum and maximum precipitation extremes are amplified.

This general picture arising from global model results is confirmed by higher-resolution regional modeling studies (Chotamonsak et al. 2011; Lacombe et al. 2012), which add that the largest increase in extreme precipitation, expressed by an index combining changes in frequency and intensity, occurs over the oceans and over Cambodia and southern Vietnam.

Tropical Cyclone Risks

Tropical cyclones (TCs) pose a major risk to coastal human systems. In combination with future sea-level rise, the risk of coastal flooding due to strong TCs is already increasing and could be amplified in the event of future TC intensification (R. J. Nicholls et al. 2008). Tropical cyclones are strongly synoptic to meso-scale, low-pressure systems, which derive energy primarily from evaporation from warm ocean waters in the presence of high winds and low surface pressure and from condensation in convective clouds near their center (Holland 1993). According to their maximum sustained wind speed, tropical low-pressure systems are categorized from tropical depressions (below 63 km/h), tropical storms (63–118 km/h), and tropical cyclones (119 km/h and larger).

64 In addition, the modeled increase in mean precipitation only concerns Myanmar, for which the regional model of Chotamonsak et al. (2011) shows little change, while the temperature increase seems fairly uniform over mainland South East Asia and the largest increases reported by Lacombe et al. (2012) are found over eastern India and southern China—which is confirmed by Chotamonsak et al. (2011).

According to the Saffir-Simpson hurricane wind scale, TCs can be further classified into five categories according to their wind speed and resulting sea-level rise.

South East Asian Context

In South East Asia, tropical cyclones (TCs) are called typhoons and affect vast parts of the region, particularly the islands and coastal areas of the mainland. Most TCs reaching landfall in South East Asia originate from the western North Pacific basin, the region with the highest frequency of TCs in the world (Holland 1993). There are also some TCs that develop in the northern Indian Ocean basin, specifically in the Bay of Bengal.

Strong TCs have a devastating impact on human settlements, infrastructure, agricultural production, and ecosystems, with damages resulting from flooding due to heavy rainfall, high wind speeds, and landslides (Peduzzi et al. 2012) (Box 4.1). Storm surges associated with tropical cyclones can temporarily raise sea levels by 3–10 meters (Syvitski et al. 2009).

Observed Trends in Tropical Cyclone Frequency and Intensity

The influence of recent climate changes on past TC frequency and intensity is uncertain and shows low confidence regarding detectable long-term trends (Peduzzi et al. 2012). Recent analyses reveal neither a significant trend in the global TC frequency from 1970 to 2004 nor significant changes for individual basins worldwide. The North Atlantic is the notable exception (Knutson et al. 2010). The western North Pacific and northern Indian Ocean do not exhibit a recent change in TC frequency. For example, the number of land-falling TCs in Vietnam and the Philippines does not display a significant long-term trend over the 20th century (Chan and Xu 2009); there is, however, a distinct positive correlation with the phasing of the ENSO (Kubota and Chan 2009). During the same time, western North Pacific TCs exhibited a weak increase in intensity (Intergovernmental Panel on Climate Change 2012) and a significant co-variation with ENSO, with a tendency toward more intense TCs during El Niño years (Camargo and Sobel 2005). This was probably mediated by the associated sea-surface temperature patterns (Emanuel 2007; Villarini and Vecchi 2012).

In contrast to the general absence of a global trend in total TC frequency, there has been a clear upward trend in the global annual number of strong category 4 and 5 tropical cyclones since 1975, as seen in the western North Pacific (1975–89: 85; 1990–2004: 116) and the Northern Indian Ocean (1975–89: 1; 1990–2004: 7) (P. J. Webster, Holland, Curry, and Chang 2005). For the time period 1981–2006, there have been significant upward trends in the lifetime maximum TC wind speeds both globally and for the western North Pacific and Northern Indian Ocean basins (Elsner, Kossin, and Jagger 2008a), with the 30-percent strongest TCs shifting to higher maximum wind speeds.

The relationship between TC intensity and damage potential is generally highly non-linear. This implies that increases in the intensity of the strongest TCs can outperform even a decrease in the overall number of typhoons. Indeed, the observed tendency toward stronger TCs both globally and in South East Asia is accompanied by increasing economic losses. These are also strongly related to robust population and economic growth, especially in the most vulnerable low-lying coastal areas (Peduzzi et al. 2012).

Box 4.1: Observed Vulnerability

Category 4 Tropical Cyclone Nargis, which inundated a wide area up to six meters above sea level in the Irrawaddy River Delta in Myanmar in 2008, illustrates the region's vulnerability to these extreme weather events. Nargis´ official death toll was approximately 84,000, with 54,000 people missing in the aftermath of the disaster. Overall, 2.4 million people were affected and 800,000 people were temporarily displaced (Association of South East Asian Nations 2008). The cyclone severely affected the agricultural sector. The equivalent of 80,000 tons of agricultural production and 251,000 tons of stored crops were damaged, and approximately 34,000 hectares of cropland were affected. Nargis' cumulative damage to farm equipment and plantation crops accounted for Kyatt 47 billion, equal to about $55 million (Association of South East Asian Nations 2008).

Severe damage and losses have also occurred in Vietnam in recent years due to cyclones, including Xangsane in 2006. In the Philippines, 7–8 cyclones make landfall every year (Yumul, Cruz, and Servando 2011).

Projected Changes in Tropical Cyclones

The changes in tropical cyclones as a result of future climate change need to distinguish between TC frequency and TC intensity. Most literature on TC projections draws from climate model runs that reach on average about 3.5°C warming above pre-industrial levels. There appear to be no recent studies on TC projections for global-mean warming levels of 2°C.

Tropical Cyclone Frequency

On a global scale, TC frequencies are consistently projected to either decrease somewhat or remain approximately unchanged by 2100, with a less robust decrease in the Northern Hemisphere (Emanuel, Sundararajan, & Williams 2008; Knutson et al. 2010). Model projections vary by up to 50 percent for individual ocean basins.

Future changes in TC frequency are uncertain for the western North Pacific, which includes the South China Sea and the Philippine Sea and borders mainland South East Asia and countries like the Philippines and Malaysia. Studies that use atmospheric models that explicitly simulate TCs generally show an overall decrease in the frequency of TCs over this basin as a whole, with some exceptions (Sugi et al. 2009; Knutson et al. 2010; Held and Zhao 2011; Murakami et al. 2012). By contrast, projections of indices for cyclogenesis (the likelihood of TCs developing and hence an indicator of frequency) generally show an increase under warming for multimodel ensembles (Caron and Jones 2007; Emanuel et al. 2008). However, recent work (Zhao and Held 2011) shows that the statistical relationships between cyclogenesis parameters and the frequency of TCs, which are strong in most ocean basins, break down in the western North Pacific. This is particularly the case with the South China Sea, possibly because the interactions between monsoon circulation, sea-surface temperatures, and cyclone activity are not properly accounted for through commonly applied cyclogenesis parameters. Within the western North Pacific basin, the different methods and models generally agree on a north and/or eastward shift of the main TC development region (Emanuel et al. 2008; Held and Zhao 2011; Kim, Brown, and McDonald 2010; Li et al. 2010; Yokoi and Takayabu 2009); the strongest agreement across models and methods on a decrease in frequency is found for the South China Sea (Held and Zhao 2011; Murakami, Sugi, and Kitoh 2012; Yokoi and Takayabu 2009). In a recent study, these changes lead to a decrease in frequency of TCs making landfall of 35 percent and 10 percent for mainland South East Asia and the Philippines respectively (Murakami et al. 2011).

Tropical Cyclone Intensity

Future surface warming and changes in the mean thermodynamic state of the tropical atmosphere lead to an increase in the upper limit of the distribution of TC intensities (Knutson et al. 2010), which was also observed over the years 1981–2006 (Elsner, Kossin, and Jagger 2008). Consistently, the number of strongest category 5 cyclones is projected to increase in the western North Pacific, with both mean maximum surface wind speed and lifetime maximum surface wind speed during TCs projected to increase statistically significantly by 7 percent and 18 percent, respectively, for a warming of about 3.5°C above pre-industrial levels (Murakami et al. 2012). The average instantaneous maximum wind speed of TCs making landfall is projected to increase by about 7 percent across the basin (Murakami et al. 2012), with increases of 6 percent and 9 percent for mainland South East Asia and the Philippines, respectively (Murakami et al. 2011).

With higher sea-surface temperatures, atmospheric moisture content is projected to increase over the 21st century, which might lead to increasing TC-related rainfall. Various studies project a global increase in storm-centered rainfall over the 21st century of between 3–37 percent (Knutson et al. 2010). For the western North Pacific, a consistent corresponding trend is found, with rates depending on the specific climate model used (Emanuel et al. 2008).

Regional Sea-level Rise

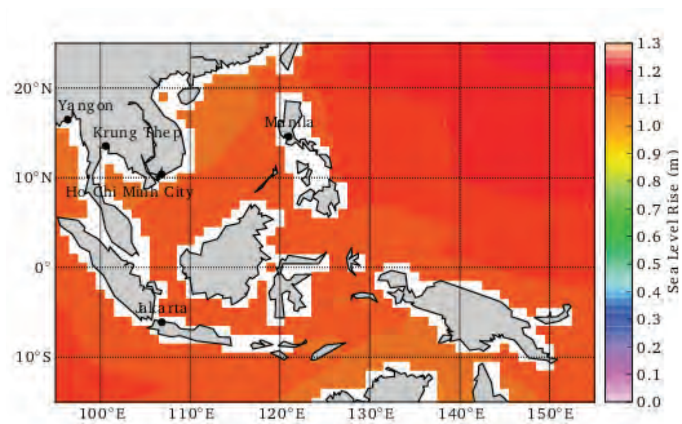
As explained in Chapter 2, current sea levels and projections of future sea-level rise are not uniform across the world. South East Asian coastlines stretch roughly from 25° north to 15° south latitude. Closer to the equator, projections of local sea-level rise generally show a stronger increase compared to higher latitudes. Land subsidence, in the tropics mainly induced by human activities, increases the risks to coastal areas due to sea-level rise. Without taking land subsidence into account, sea-level rise in the region is projected to reach up to 100 cm and 75 cm by the 2090s in a 4°C and 2°C world, respectively.

Climate Change-induced Sea-level Rise

Due to the location of the region close to the equator, sea-level rise along the South East Asian coastlines projected by the end of the 21st century relative to 1986–2005 is generally 10–15 percent higher than the global mean. Figure 4.7 shows the regional sea-level rise in 2081–2100 in a 4°C world. As described in Chapter 2, these projections rely on a semi-empirical approach developed by (Rahmstorf (2007) and Schaeffer, Hare, Rahmstorf, and Vermeer (2012) for global-mean rise, combined with Perrette, Landerer, Riva, Frieler, and Meinshausen (2013) to derive regional patterns.[65]

Figure 4.8 shows a time series for locations in South East Asia that receive special attention in Chapter 4 under "Risks to Coastal Cities" and "Coastal and Marine Ecosystems." In a 4°C world, locations in South East Asia are projected to face a sea-level rise around 110 cm (66 percent uncertainty range 85–130) by 2080–2100

Figure 4.7: Regional sea-level rise projections for 2081–2100 (relative to 1986–2005) under RCP8.5



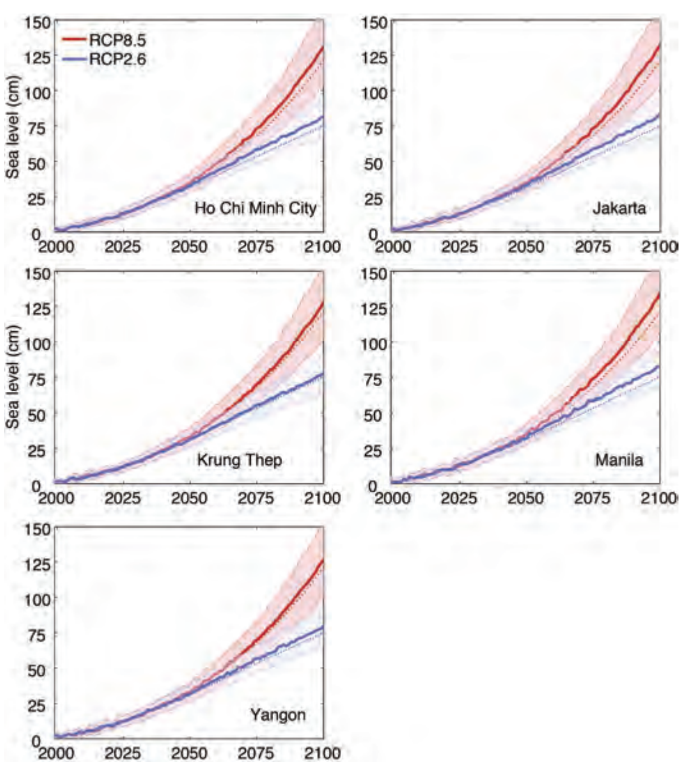
65 More details on the methodology used to assess regional sea-level rise in the report can be found in Chapter 2 on "Sea-level Rise."

(a common time period in the impact studies assessed in the following sections). The rise near Yangon and Krung Thep (Bangkok) is a bit lower (by 5 cm). For all locations, sea-level rise is projected to be considerably higher than the global mean and higher than the other regions highlighted in this report, with Manila at the high end. For these locations, regional sea-level rise is likely (> 66 percent chance) to exceed 50 cm above 1986–2005 levels by about 2060 and 100 cm by 2090, both about 10 years before the global mean exceeds these levels.

In a 2°C world, the rise is significantly lower for all locations, but still considerable at 75 (66 percent uncertainty range 65–85) cm. An increase of 0.5 meters is likely exceeded by about 2070, only 10 years after this level is exceeded under a pathway that reaches 4°C warming by the end of the century. However, by the 2050s, sea-level rise in the 2°C and 4°C scenarios diverges rapidly and 1 meter is not likely to be exceeded until well into the 22nd century under 2°C warming.

It should be noted that these projections include only the effects of human-induced global climate change and not those due to local land subsidence.

Figure 4.8: Local sea-level rise above 1986–2005 mean level as a result of global climate change (excluding local change due to land subsidence by natural or human causes)



Shaded areas indicate 66-percent uncertainty range and dashed lines indicate the global mean sea-level rise.

Additional Risk Due to Land Subsidence

Deltaic regions are at risk of land subsidence due to the natural process whereby accumulating weight causes layers of sediment to become compressed. Human activities such as drainage and groundwater extraction significantly exacerbate this process, which increases the threat of coastal flooding. The most prominent examples of such anthropogenic subsidence are found at the mega-deltas of Mekong, Vietnam (6 mm per year); Irrawaddy, Myanmar (3.4–6 mm per year); and Chao Phraya, Thailand (13–150 mm) (Syvitski et al. 2009). The Bangkok metropolitan area in the Chao Phraya delta has experienced up to two meters of subsidence over the 20th century and a shoreline retreat of one kilometer south of the city (Robert J. Nicholls and Cazenave 2010). The coastal zone of Semarang, among the ten largest cities in Indonesia with about 1.5 million inhabitants and one of the most important harbors in Central Java, is another example of the impact of land subsidence. The area is increasingly affected, with an estimated area of 2,227 hectares lying below sea-level by 2020 (Marfai and King 2008).

Risks to Rural Livelihoods in Deltaic and Coastal Regions

Flooding as part of the natural annual cycle plays an important economic and cultural role in the Mekong and other river deltas (Warner 2010). Processes of sea-level rise and land subsidence, however, increase the vulnerability of human populations and economic activities such as agriculture and aquaculture to risks, including saltwater intrusion and coastal erosion. Cyclones and other extreme events exacerbate these threats.

Observed and Projected Biophysical Stressors in Deltaic and Coastal Regions

Deltaic and coastal regions are already vulnerable to the consequences of coastal flooding and tropical cyclones. It is projected that saltwater intrusion and coastal erosion will adversely impact human and economic activities carried out in these areas. Agriculture and aquaculture occurring in coastal and deltaic regions, which are strong components of South East Asian livelihoods, are projected to be significantly affected by climate change.

Vulnerability Context

South East Asian deltas are densely populated areas. The population density of the Mekong River Delta province, at 427 people per square kilometer, is the third highest in the country (General Statistics Office Of Vietnam 2011). The river deltas are also the region's rice bowls. The Mekong River Delta province is densely farmed and home to approximately 47 percent of the farms in Vietnam (General Statistics Office Of Vietnam 2011). In 2011, this delta produced about 23.2 million tons of rice, or approximately 55 percent of the total Vietnamese rice production (General Statistics Office Of Vietnam 2013). The rice production of the Mekong Delta is of significant importance in terms of both food security and export revenues. In 2011, the Mekong River Delta produced 23.2 million tons of rice paddy (General Statistics Office Of Vietnam 2013); 18.4 million tons were supplied to the population. The Delta rice production represents about 125 percent of the Vietnamese rice supply for 2011. Furthermore, 72.4 percent of the aquaculture, an industry which accounts for nearly 5 percent of GDP in Vietnam, was located in the Mekong River Delta province in 2010 (General Statistics Office of Vietnam 2012).

Past flooding events have highlighted the vulnerability of the South East Asian deltas. Critical South East Asian rice-growing areas are already considered to be in increasingly greater peril (Syvitski et al. 2009). The area of land that lies below 2 m above sea level—which in the Mekong River Delta is as much as the total land area—is vulnerable to the risks associated with sea-level rise and land subsidence. The area affected by past storm surge and river flooding events indicates further vulnerability.

Table 4.2 shows the areas of land in the three main deltas in the region that are at risk.

Saltwater Intrusion

Saltwater intrusion poses risks to agricultural production as well as to human health. The movement of saline ocean water into freshwater aquifers can result in contamination of drinking water resources. For example, following high levels of saltwater intrusion in the Mekong River Delta in 2005, Long An province's 14,693 hectares of sugar cane production was reportedly diminished by 5–10 percent; 1,093 hectares of rice in Duc Hoa district were also destroyed (MoNRE 2010).

Factors Influencing Saltwater Intrusion

Salinity intrusion into groundwater resources occurs naturally to some extent in most coastal regions via the hydraulic connection between groundwater and seawater including through canals and drainage channels. Due to its higher density, saltwater can push inland beneath freshwater (Richard G. Taylor et al. 2012). Human activities (i.e., groundwater extraction from coastal wells that lowers the freshwater table, which is increasingly undertaken to expand shrimp farming) can considerably increase the level of saltwater intrusion and its extension inland (Richard G. Taylor et al. 2012; Ferguson and Gleeson 2012). In addition, long-term changes in climatic variables (e.g., precipitation, temperature) and land use significantly affect groundwater recharge rates and thus exacerbate the risk of saltwater intrusion associated with non-climatic drivers and reductions in inflows (Ranjan, Kazama, Sawamoto, and Sana 2009).

Sea-level rise and tropical cyclone-related storm surges may increase salinity intrusion in coastal aquifers (Werner and Simmons 2009; Anderson 2002; A. M. Wilson, Moore, Joye, Anderson, and Schutte 2011), thereby contaminating freshwater resources (Green et al. 2011; Richard G. Taylor et al. 2012). The effects of saltwater intrusion due to tropical cyclones remain long after the event itself; coastal aquifer contamination has been observed to persist for years (Anderson 2002). In the South East Asian mega-deltas, saltwater intrusion into coastal aquifers is expected to be more severely affected by storm surges than by mean sea-level rise (Taylor et al. 2012). The risk of saltwater intrusion is particularly relevant for smaller islands, where freshwater can only be trapped in small layers and the resulting aquifers are highly permeable (Praveena, Siraj, and Aris 2012).

There is an ongoing debate about the possible long-term effects of rising mean sea levels on saltwater intrusion. A case study in California revealed that groundwater extraction is a much larger contributor to saltwater intrusion than rising mean sea levels (Loáiciga, Pingel, and Garcia 2012). The response of coastal aquifers to seawater intrusion is highly non-linear, however, as depth, managerial status (volume of groundwater discharge), and timing of rise each act as critical factors determining the intrusion depth in response to even small rises in sea levels. This implies the potential existence of local tipping points, whereby a new state

Table 4.2: Areas at risk in South East Asian river deltas

Delta	Total Land Area (in km^2)	Area <2m Above Sea Level (km^2)	Area that Has Experienced Recent Flooding Due to Storm Surges (in km^2)	Area that Has Experienced Recent River Flooding (km^2)
Irrawaddy, Myanmar	20,571	1,100	15,000	7,600
Mekong, Vietnam	40,519 (for the Mekong River Delta Province)	20,900	9,800	36,750
Chao Phraya, Thailand	11,329	1,780	800	4,000

Source: Syvitski et al. (2009).

is reached in which responses to small changes in conditions are large and can rapidly lead to full seawater intrusion into a coastal aquifer (Mazi, Koussis, and Destouni 2013).

Projections of Saltwater Intrusion

Salinity intrusion into rivers is projected to increase considerably for several South East Asian countries. In the case of the Mahakam river region in Indonesia, for example, the land area affected by saltwater intrusion is expected to increase by 7–12 percent under a 4°C warming scenario and a 100 cm sea-level rise by 2100 (Mcleod, Hinkel, et al. 2010). In the Mekong River Delta, it is projected that the total area affected by salinity intrusion with concentrations higher than 4 g/l will increase from 1,303,000 hectares to 1,723,000 hectares with a 30 cm sea-level rise (World Bank 2010b).

A United States Agency for International Development (2013) study[66] also projects changes in salinity intrusion under a 30 cm sea-level rise during the 2045–2069 period, which are expected to be moderate during the wet season but significantly more severe during the dry season. During the wet seasons, salinity intrusion levels are projected to be close to 1980–2005 levels, both in terms of maximum salinity and duration at a level of 4g per liter. During the dry season, salinity is expected to increase over 133,000 hectares located in the Mekong River Delta. Maximum salinity concentration is projected to increase by more than 50 percent compared to the reference period and the salinity level is projected to exceed 4g/l.

While recent work by Ranjan et al. (2009) concludes that most parts of South East Asia display a relatively low-to-moderate risk of saltwater intrusion into coastal groundwater resources, this is for a sea-level rise of only about 40 cm above 2000 by 2100, significantly lower than this report's projections.[67] Using the approach to sea-level rise in this report, sea-level rise under the A2 scenario (corresponding to a warming of approximately 4°C), is about 100 cm by 2100. This projected value for sea-level rise, as well as that for a 2°C world, is well above the value used by Ranjan et al. (2009) and would certainly lead to a greatly increased risk of saltwater intrusion.

Health Impacts of Saltwater Intrusion

Coastal aquifers provide more than one billion people living in coastal areas with water resources. Saltwater intrusions already affect these coastal aquifers in different regions of the globe (Ferguson and Gleeson 2012). The consumption of salt-contaminated water can have detrimental health impacts (A. E. Khan, Ireson, et al. 2011; Vineis, Chan, and Khan 2011). The most common consequence of excessive salt ingestion is hypertension (He and MacGregor 2007). Along with hypertension, there is a broad range of health problems potentially linked with increased salinity exposure through bathing, drinking. and cooking; these include miscarriage (A. E. Khan, Ireson, et al. 2011b), skin disease, acute respiratory infection, and diarrheal disease (Caritas Development Institute 2005).

Coastal Erosion

Many South East Asian countries, notably Vietnam, Thailand, and the Philippines, are highly vulnerable to the effects of climate-change-induced coastal erosion. For example, about 34 percent of the increase in erosion rates in the south Hai Thinh commune in the Vietnamese Red River delta between 1965–95 and 12 percent for the period 1995–2005 has been attributed to the direct effect of sea-level rise (Duc et al. 2012).

Coastal erosion, leading to land loss, is one of the processes associated with sea-level rise (Sorensen et al. 1980) and storm surges. Increasing wind stress and loss of vegetation are further factors known to enhance coastal erosion (Prasetya 2007).

The mechanisms of coastal erosion and the associated impacts depend on the specific coastal morphology (Sorensen et al. 1980):

- Beaches: Sand transport on beaches can be affected by sea-level rise. At higher mean sea level, wind wave action and wind-generated currents change the beach profile.
- Cliffs: Thin protecting beaches can be removed due to rising sea levels, increasing the exposure to wave action and leading to an undermining of the cliff face—finally resulting in cliff recession.
- Estuaries: Because estuary shorelines are typically exposed to milder wave action and exhibit relatively flat profiles, rising sea levels are expected to result in land losses primarily due to inundation (rather than due to erosion).
- Reefed coasts: Reefs cause wave breaking and thus reduce wave action on the beach. Higher mean sea levels reduce this protecting effect and thus increase the coastline's exposure to wave stress, which results in increased coastal erosion (see also Chapter 4 on "Projected Impacts on Coral Reefs" for more on the implications of reef loss).

Sandy beach erosion can lead to increasing exposure and possible destruction of fixed structures (e.g., settlements, infrastructures) close to the coastline due to the direct impact of storm waves. In general, empirical results indicate that the rate of sandy beach erosion significantly outperforms that of actual sea-level rise (Zhang et al. 2004). However, deriving reliable projections of coastal erosion under future sea-level rise and other climate change-related effects, such as possible increases in wind stress and heavy rainfall, require complex modeling approaches (Dawson et al. 2009).

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66 The United States Agency for International Development (2013) report projects the impacts of climate change for the period 2045–69 under the IPCC SRES scenario A1B (corresponding to a 2.33°C temperature increase above pre-industrial levels) for the Lower Mekong Basin. For the study, authors used six GCMs (NCAR CCSM 3.0; MICRO3.2 hires; GISS AOM; CNRM CM3; BCCR BCM2.0; GFDL CM2.1) and used 1980–2005 as a baseline period.

67 This work assumed a global-mean temperature increase of about 4°C above pre-industrial levels (IPCC SRES scenario A2); however, the sea-level rise component came from the thermal expansion of the oceans only (i.e., no contribution from the melting of glaciers and ice caps that currently contribute about half of global sea-level rise).

In the Mekong River Delta, coastal erosion is expected to increase significantly by 2100 under a 100 cm rise (Mackay and Russell 2011). Under the same conditions, projected beach loss for the San Fernando Bay area of the Philippines amounts to 123,033 m², with a simultaneous land loss of 283,085 m² affecting a considerable number of residential structures (Bayani-Arias, Dorado, and Dorado 2012). The projected loss of mangrove forests due to sea-level rise[68] and human activities (which are known to increase coastal erosion) is also a significant concern and is likely to accelerate coastal erosion. The presence of the mangrove forests is known to provide coastal protection: for the coastline of southern Thailand, studies report an estimated 30-percent reduction in coastal erosion in the presence of dense mangrove stands (Vermaat and Thampanya 2006).

Impacts on Agricultural and Aquaculture Production in Deltaic and Coastal Regions

Agriculture and aquaculture are the two main components of rural livelihoods in the South East Asian rivers deltas and coastal areas. Salinity intrusion and coastal erosion, along with the increased frequency and intensity of extreme weather events, sea-level rise and coastal flooding, and increased air and water temperature are projected to severely impact rural economic activities.

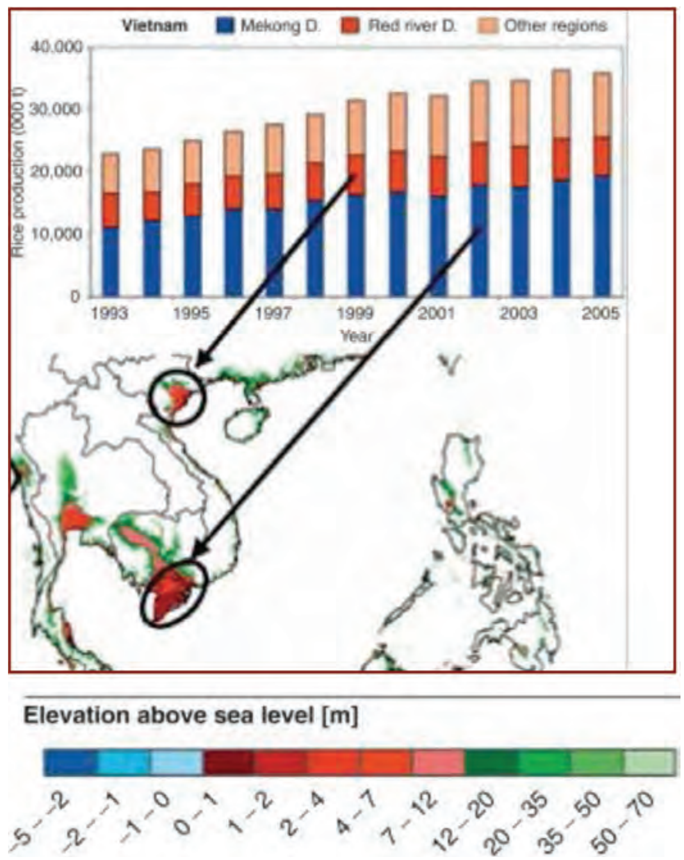
Agriculture

Agricultural production in deltaic regions is largely based on rice, a crop that is relatively resilient to unstable water levels and salinity. Nevertheless, rising sea levels and increasing tropical cyclone intensity leading to increasing salinity intrusion and inundation pose major risks to rice production in deltaic regions (Wassmann, Jagadish, Heuer, Ismail, and Sumfleth 2009). Impacts are known to vary according to a number of factors, such as cultivar and duration and depth of flooding (Jackson and Ram 2003). While some cultivars are more resilient than others, there is evidence that all rice is vulnerable to sudden and total inundation when flooding is sustained for several days. The effect can be fatal, especially when the plants are small (Jackson and Ram 2003). Temperature increases beyond thresholds during critical growing seasons may further impact productivity (Wassmann, Jagadish, Heuer, Ismail, and Sumfleth 2009). Rice production in the Mekong Delta is particularly exposed to sea-level rise due to its low elevation (see Figure 4.9).

The World Bank Economics of Adaptation to Climate Change estimated the impact of a 30 cm sea-level rise by 2050 in the Mekong River Delta. The projections undertaken for the present report find that this level of sea-level rise may be reached as early as the 2030s. Such sea-level rise is found to result in a loss of 193,000 hectares of rice paddies (about 4.7 percent of the province) due to inundation. A larger area of 294,000 hectares (about 7.2 percent of the Mekong River Delta province) might also be lost for agricultural purposes due to salinity intrusion. Without implementing adaptation measures, rice production could decline by approximately 2.6 million tons per year, assuming 2010 rice productivity. This would represent a direct economic loss in export revenue of $1.22 billion at 2011 prices (World Bank 2010b).

Furthermore, consistent with other studies estimating the impacts of climate change on crop yields in South East Asia (MoNRE 2010; Wassmann, Jagadish, Sumfleth, et al. 2009; World Bank 2010b), the United States Agency for International Development (2013)[69] projects a decrease in crop yields and, more specifically, in rice yields. The World Bank (2010b) estimates rice yield

Figure 4.9: Low elevation areas in the Vietnamese deltas



Source: Wassmann et al. (2009).

68 See Chapter 4 on "Coastal Wetlands."

69 The United States Agency for International Development (2013) projects the impacts of climate change for the period 2045–69 under the IPCC SRES scenario A1B (corresponding to a 2.33°C temperature increase above pre-industrial levels) for the Lower Mekong Basin. For the study, the authors used six GCMs (NCAR CCSM 3.0; MICRO3.2 hires; GISS AOM; CNRM CM3; BCCR BCM2.0; GFDL CM2.1) and used 1980–2005 as a baseline period.

declines from 6–12 percent in the Mekong River Delta. Other crops may experience decreases ranging from 3–26 percent by 2050 in a wet and dry scenario under the SRES scenario A1B.

In light of the importance of deltaic regions for rice production, impacts such as those outlined above pose a major risk to affected populations and the region's economy.

Aquaculture

Aquaculture in South East Asia plays a significant role in the region's economic and human development, and both the population and the national economies rely considerably on sea products and services. In Vietnam, for example, aquaculture output constitutes a growing share of the gross domestic product (GDP). Between 1996 and 2011, aquaculture output was multiplied by 24 and its share of GDP increased from 2.6 percent to about 4.8 percent. In addition, since 2001, aquaculture production has yielded higher output than capture fisheries (General Statistics Office of Vietnam 2012). Similar trends can be observed in the other South East Asian countries (Delgado, Wada, Rosegrant, Meijer, and Ahmed 2003). Fisheries and aquaculture also supply the region and populations with affordable seafood and fish, which constitute an average of 36 percent of dietary animal protein consumed in South East Asia (Food and Agriculture Organization of the United Nations 2010).

Sea-level rise, intense extreme weather events, associated saltwater intrusion, and warmer air temperatures may impact aquaculture—especially when it takes place in brackish water and deltaic regions (Box 4.2). The extent of the impact, however, remains uncertain (Silva and Soto 2009).

Heat waves and associated warmer water temperatures may affect aquaculture in South East Asia. The two most cultured species in the region, brackish water tiger shrimp (*Penaeus monodon*) and freshwater striped catfish (*Pangasianodon hypophthalmus*), have very similar temperature tolerance ranges around 28–30°C (Hargreaves and Tucker 2003; Pushparajan and Soundarapandian 2010). More frequent temperatures above the tolerance range would create non-optimum conditions for these species and would be expected to decrease aquaculture yields.

As a consequence of salinity intrusion, freshwater and brackish aquaculture farms may have to relocate further upstream. To respond to this new salinity pattern, local farmers may further have to breed more saline-tolerant species. Upstream relocation and farming more saline-tolerant species are expected to be economically costly. Implementing these measures and their associated costs would most certainly affect the socioeconomic status of aquaculture-dependant households. Neither the cost of adapting aquaculture farming practices to the consequences of salinity intrusion nor the direct economic losses for aquaculture-dependent livelihoods has yet been evaluated (Silva and Soto 2009).

Another study[70] (United States Agency for International Development 2013) finds that four climate stressors are projected to significantly affect aquaculture production: increased temperatures, changes in rainfall patterns, increased storm intensities, and higher sea levels. According to the study's projections, intensive aquaculture practices are expected to experience a decrease in yields due to the combination of these four climate stressors. Semi-intensive and extensive systems may only be vulnerable to extreme weather events such as droughts, floods, and tropical cyclones. The authors do not, however, provide aquaculture yield decrease estimates due to climate stressors.

Two recent studies estimated the cost of adapting shrimp and catfish aquaculture to climate change in the Mekong river delta. Estimates range from $130 million per year for the period 2010–50[71] (World Bank 2010b) to $190.7 million per year for the period 2010–20 (Kam et al. 2012). These valuations may, however, be underestimated. Kam et al. (2012) only took into account the costs of upgrades to dykes and water pumping. As explained earlier in this chapter, other climate-change-associated consequences may affect the final calculation of the adaptation costs in the aquaculture sector. First, the existing studies do not account for the costs of relocating aquaculture farms upstream of

Box 4.2: The Threat of Typhoons to Aquaculture

Extreme weather events, such as tropical cyclones and coastal floods, already affect aquaculture activities in South East Asia. For example, the category 4 typhoon Xangsane devastated 1,278 hectares of aquaculture area in Vietnam in 2006 (International Federation Of Red Cross and Red Crescent Societies 2006). Similarly, in Indonesia, typhoons Vicente (category 4) and Saola (category 2) jointly generated $9.26 million in damages to the fishery sector and affected about 3,000 aquaculture farmers (Xinhua 2012). The impacts on aquaculture farming include the physical destruction of facilities, the spread of diseases, and the loss of fish stock (Silva and Soto, 2009). More intense storms are expected to diminish the life span of aquaculture equipment and infrastructure and increase the maintenance costs of the installations (Kam, Badjeck, Teh, Teh, and Tran 2012).

70 The United States Agency for International Development (2013) report projects the impacts of climate change for the period 2045–69 under the IPCC SRES scenario A1B (corresponding to a 2.33°C temperature increase above pre-industrial level) for the Lower Mekong Basin. For the study, the authors used six GCMs (NCAR CCSM 3.0; MICRO3.2 hires; GISS AOM; CNRM CM3; BCCR BCM2.0; GFDL CM2.1) and used 1980–2005 as a baseline period.

71 For the World Bank study, projections were calculated from a set of 21 global models in the multimodel ensemble approach, from 1980–99 and 2080–99 under the IPCC A1B scenario, corresponding to a 2.8°C temperature increase globally (3.3°C above pre-industrial levels).

rivers, despite the fact that most aquaculture activities take place in low-lying areas below one meter of elevation above sea level (Carew-Reid 2008). Second, warmer air temperatures may force aquaculture farmers to dig deeper ponds in order to keep water pond temperatures in the tolerance range of the species being cultured (Silva and Soto 2009). Finally, the costs of coping with the consequences of tropical cyclones on aquaculture activities have not been taken into account. Since the intensity of tropical cyclones is expected to increase, so are the associated damages and losses (Mendelsohn et al. 2012).

Risks to Coastal Cities

South East Asian coastal cities are projected to be affected by several climate change stressors, including increased tropical cyclone intensity, sea-level rise, and coastal flooding (Brecht, Dasgupta, Laplante, Murray, and Wheeler 2012; Dutta 2011; Hanson et al. 2011; Muto, Morishita, and Syson 2010; Storch and Downes 2011). The consequences of these stressors are likely to be exacerbated by human-induced subsidence in low-lying, deltaic regions (Brecht et al. 2012a; Hanson et al. 2011). South East Asian cities have already been exposed to the consequences of coastal flooding, and significant economic losses have occurred due to flooding-induced damage to public and private infrastructure. Increasingly intense rainfall events that exacerbate river flooding (Kron 2012) and heat waves (World Bank 2011a) may also have a negative impact on coastal cities (see also Chapter 4 on "Regional Patterns of Climate Change").

Vulnerability Context

South East Asia currently experiences high rates of urban population growth, which are led by two converging drivers: a rural exodus and demographic growth (Tran et al. 2012). By 2025, the population of South East Asian cities is projected to be significantly higher than at present. Ho Chi Minh City, for example, is expected to have a population of approximately 9 million people (compared to close to 6 million in 2010); 8.4 million people are projected to be living in Bangkok (compared to 7 million in 2010) and 14 million in Manila (compared to 11.6 million in 2010) (UN Population Prospects 2009).

As a result, increasingly large populations and significant assets are projected to be exposed to sea-level rise and other climate change impacts in low-lying coastal areas. The effect of heat extremes are particularly pronounced in urban areas due to the urban heat island effect, caused in large part by the density of buildings and the size of cities. This results in higher human mortality and morbidity rates in cities than in the rural surroundings (Gabriel and Endlicher 2011). High levels of urban population growth and GDP further increase exposure to climate change impacts in coastal urban areas.

Most of the national economic production of the region is also concentrated in South East Asia's cities. It has been estimated, for example, that Ho Chi Minh City in 2008 accounted for approximately 26 percent ($58 billion) and Hanoi for 19 percent ($42 billion) of Vietnam's $222 billion GDP (based on Purchasing Power Parity). Metro Manila's GDP, at 49 percent ($149 billion), represented a significant share of that country's $305 billion GDP (PricewaterhouseCoopers 2009; World Bank 2013a). In addition, it is estimated that, by 2025, Metro Manila's GDP will be approximately $325 billion, Hanoi's GDP will be $134 billion, and Ho Chi Minh City's GDP will be $181 billion (PricewaterhouseCoopers 2009). In other words, the GDP values in these coastal cities are expected to double or even quadruple from the present day. Table 4.3 presents the population and GDP growth trends in these and other South East Asian cities.

Urban density is a further factor that may influence a city´s vulnerability to climate-driven impacts (World Bank 2011a). Figure 4.10 shows different types of cities in terms of population and density. Cities like Jakarta and Manila clearly stand out in

Table 4.3: Current and projected GDP and population of Jakarta, Manila, Ho Chi Minh, and Bangkok

Indicators	Current / Projected	Jakarta	Manila	Ho Chi Minh City	Bangkok	Yangon
GDP (US$ billion, PPP)	2008	92.0	149.0	58.0	119.0	24.0
	2025	231.0	325.0	181.0	241.0	53.0
Population (million)	2010	9.2	11.6	6.1	6.9	4.3
	2025	10.8	14.9	8.9	8.5	6.0
Urban Growth Rate in 2001 at Country Level	2001	4%	4%	3%	2%	3%

Sources: PricewaterhouseCoopers (2009); UN Population Prospects (2009); UN-HABITAT (2013).*

* Current and projected GDP data from PricewaterhouseCoopers (2009); urban growth rate in 2001 from UN-HABITAT (2013); and current and projection urban populations from UN Population Prospects (2009).

terms of population size; however, the density of Jakarta, for example, is lower than that of smaller cities like Yangon and Zamboanga. In cities where adequate infrastructure and institutional capacity are lacking to support large urban populations, density can increase the vulnerability to climate-driven impacts by exposing larger numbers of people and assets in a given area of land (Dodman 2009).

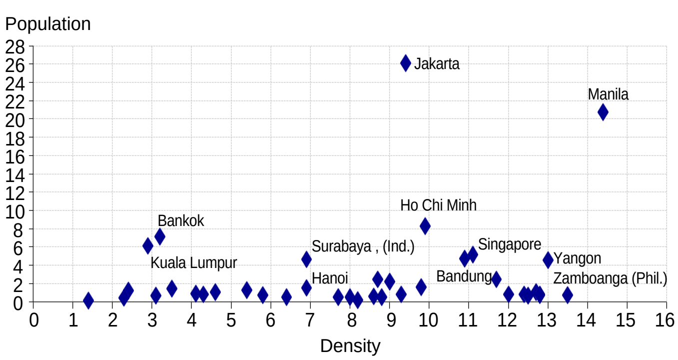
Informal Settlements

High urban growth rates, combined with inadequate responses to the housing needs of urban populations in the region, are leading to the expansion of informal settlements. For example, 79 percent of the urban population in Cambodia, 41 percent in Vietnam, and 44 percent in the Philippines lived in informal settlements in 2005 (UN-HABITAT 2013).

Informal settlements are characterized by a lack of water, a lack of sanitation, overcrowding, and nondurable housing structures (UN-HABITAT 2007). Durable housing, in contrast, has been defined as "a unit that is built on a non-hazardous location and has a structure permanent and adequate enough to protect its inhabitants from the extreme of climate conditions, such as rain, heat, cold, and humidity" (UN-HABITAT 2007). In informal settlements, populations are chronically exposed to health risks from perinatal complications to diarrheal diseases to physical injuries (C. McMichael et al. 2012). If the number of people living in informal settlements continues to grow, the number of people vulnerable to these threats will grow too (Box 4.3).

Water in South East Asia is a major vector for diseases such as diarrhea and cholera. Improved water sources and sanitation facilities contribute to keep water-borne diseases at bay. Despite significant improvements in South East Asian cities, large proportions of the region's urban populations (27 percent in Indonesia and nine percent in Vietnam) still lack access to improved sanitation facilities. In addition, eight percent of the urban population in Indonesia and one percent in Vietnam do not have access to clean water sources (World Bank 2013c). Lack of access to these resources contributes to the vulnerability of South East Asian cities to climate-change-induced impacts and associated health complications. Table 4.4 summarizes the key vulnerabilities of the South East Asian countries studied in this report.

Figure 4.10: Population size against density distribution. The population axis refers to population in millions; the density axis to population in thousands/km^2



Source: Demographia 2009.

Box 4.3: Freshwater Infrastructure

Cyclones can damage infrastructure, such as water treatment plants, pump houses, and pipes. Natural disasters reportedly contribute to the shortening of infrastructure and system life spans from 15–20 years to 3–4 years (SNV 2010). Recent tropical cyclones in the Philippines highlight the vulnerability of the country's freshwater infrastructure and systems to climate change. In the aftermath of category 2 cyclone Ondoy in 2009, over 100,000 households were left without piped-in water as 92 percent of the water supply capacity was suspended in Central Luzon province. In combination with damage incurred by cyclone Pepeng, Ondoy generated $24.3 million in damages to the water and sanitation sector in the Philippines (GFDRR 2009).

Projected Impacts on Coastal Cities

Projected Exposed Populations

Applying the Dynamic Interactive Vulnerability Assessment model, Hanson et al. (2011) project impacts of sea-level rise, taking into account natural subsidence (uplift), human-induced subsidence, and population and economic growth. They assume a homogenous sea-level rise of 50 cm above current levels by 2070 and a uniform decline in land level of 50 cm from 2005–70 to reflect human-induced subsidence. Note that the projections produced in this report give a global mean sea-level rise of 50 cm likely as early as the 2060s in a 4°C world (greater than 66-percent probability) and by the 2070s in a 2°C world. There is also a 10-percent chance of this level of rise occurring globally by the 2050s (above 2000 sea levels).

For tropical storms, Hanson et al. (2011) assume a 10 percent increase in high water levels with no expansion in affected areas; this may actually underestimate future exposure. They also estimate population in the cities in the 2070s according to three factors: projected regional population, the change in urbanization rate, and specific properties of each city. Population data are based on the United Nations' World Urbanization Prospects (2005). Urban population projections for 2070 are extrapolated from the 2005–30 trends in urbanization and assume that urbanization rates saturate at 90 percent. Depending on the national context, this may over- or underestimate future population exposure in urban areas.

Table 4.4: Vulnerability indicators in Indonesia, Myanmar, the Philippines, Thailand, and Vietnam

Indicators	Indonesia	Myanmar	The Philippines	Thailand	Vietnam
Urban population with access to improved sanitation	73%	83%	79%	95%	94%
Urban population living in areas where elevation is below 5 meters	5%	4%	4%	9%	9%
Population living in informal settlements (2005)	26%	46%	44%	26%	41%

Sources: Center for International Earth Science Information Network (2011); UN-HABITAT (2013); World Bank (2013c, 2013k).

The authors find that 3.9 million people in South East Asian cities were exposed to coastal flooding in 2005 caused by storm surges and sea-level rise. Based on these assumptions, they estimate that 28 million people are projected to be exposed to 50 cm sea-level rise, taking into account human-induced subsidence and increased storminess in the 2070s.

Jakarta, Yangon, Manila, Bangkok, and Ho Chi Minh City are projected to be among the cities in South East Asia most affected by sea-level rise and increased storm surges. Table 4.5 shows the number of people projected to be exposed to the impacts of sea-level rise, increased storminess, and human-induced subsidence for five cities in the region.

Brecht et al. (2012) examine the consequences for a 100 cm sea-level rise in the same region, making the assumption that the urbanization rate will remain constant between 2005 and 2100. Based on this fixed urbanization rate, which may significantly underestimate future population exposure, they find slightly lower numbers of affected people for a 100 cm sea-level rise scenario, increased tropical storm intensity, and human-induced subsidence. For 2100, the authors calculate the increased tropical storm intensity by multiplying projected sea-level rise by 10 percent. Their results are shown in Table 4.6.

Brecht et al. (2012) and Hanson et al. (2011) apply contrasting assumptions, therefore comparing the change in affected population in the different levels of sea-level rise (50 cm and 100 cm) is difficult. The estimates do, however, offer relevant indications concerning the order of magnitude of people projected to be exposed in coastal cities by these sea-level rises. Overall, the studies give a potential range of the total projected population exposed to sea-level rise and increased storminess in South East Asian of 5–22 million during the second half of the 21st century.

Projected Exposed Assets

Hanson et al. (2011) also estimate the current and projected asset exposure for South East Asian coastal cities. Their study is based

Table 4.6: Current population and projected population exposed

Key South East Asian Agglomerations	Population (2005, in millions)	Change in Affected Population (2100) – 100 cm SLR, 50 cm land subsidence and 10 percent wave height increase (in millions)
Jakarta	13.215	0.83
Yangon	4.1	0.38
Manila	10.7	3,44
Bangkok	6.6	0.55
Ho Chi Minh City	5.1	0.43
Total	39.7	5.63

Source: Brecht et al. (2012a).

Table 4.5: Current and projected population exposed to 50 cm sea-level rise, land subsidence and increased storm intensity in 2070 in Jakarta, Yangon, Manila, Bangkok, and Ho Chi Minh City

Key South East Asian Agglomerations	Population (2005, in millions)	Projected Exposed Population (2070, in millions)	Local Sea Level Rise Projections in a 4°C World in 2070 (above 1986–2005)
Jakarta	13.2	2.2	66cm
Yangon	4.1	4.9	63cm
Manila	10.6	0.5	66cm
Bangkok	6.5	5.1	65cm
Ho Chi Minh City	5.0	9.2	65cm

Source: Population data from Hanson et al. (2011); SLR RCP8.5 (in this report).

on the physical (i.e., sea level, storms, and subsidence) and demographic assumptions discussed in Chapter 4 under "Projected Impacts on Economic and Human Development.". To evaluate asset exposure, they estimate cities' future GDP by assuming that urban GDP grows at the same rate as the respective national or regional GDP per capita trends throughout the period 2005–75. The projected exposed population is transposed into exposed assets by multiplying each country's GDP per capita by five (projected exposed asset = projected exposed population * estimated GDP per capita * 5). According to Hanson et al. (2011), this methodology is widely used in the insurance industry.

The projected asset exposure for South East Asia in 2070 rises significantly due to the increased impacts of rising sea levels, more-intense tropical storms, and fast economic growth. Based on the assumptions and calculations, the authors project that coastal cities' asset exposure will rises by 2,100–4,600 percent between 2005–70. Table 4.7 summarizes the current and projected exposed assets.

The figures presented in this table should be interpreted with care as the asset exposure projections in the study by Hanson et al. are based on population exposure projections that assume a steady urbanization rate (saturating at 90 percent of the country population). As a consequence, projected asset exposure is extremely high. The table only displays an order of magnitude of the impacts of a 50-cm sea-level rise, increased storminess, and human-induced subsidence on exposed assets in coastal cities in South East Asia in 2070 if no adaptation measures are carried out.

Projected Impacts on Individual Cities

The current understanding of the impacts of sea-level rise on specific coastal cities in South East Asia is rather limited. Despite global studies for port and coastal cities (e.g., Brecht et al. 2012; Hanson et al. 2011), studies conducted at the city level on the impacts of sea-level rise and increased storm intensity are scarce. However, projections accounting for sea-level rise, increased cyclone intensity, and human-induced subsidence are available for Ho Chi Minh City, Manila, and Bangkok.

Table 4.7: Current and projected asset exposure to sea-level rise for South East Asian coastal agglomerations

South East Asian Agglomerations	Exposed Assets (billions of dollars in 2005)	Projected Exposed Assets (billions of dollars in 2070)	Projected Exposed Assets Growth (%)
Jakarta	10.10	321.24	3080.59%
Yangon	3.62	172.02	4651.93%
Manila	2.69	66.21	2361.34%
Bangkok	38.72	1117.54	2786.21%
Ho Chi Minh City	28.86	652.82	2162.02%

Source: Adapted from Hanson et al. (2011).

Ho Chi Minh City

Storch and Downes (2011) quantify current and future citywide flood risks to Ho Chi Minh City by taking into account urban development (population and asset growth) and sea-level rise scenarios. Due to the lack of data available on land subsidence for the city, however, their assessment does not include subsidence. They use two possible amplitudes of change for sea-level rise in the study: 50 cm and 100 cm. Combined with the current tidal maximum of 150 cm, they quantify built-up land exposed to water levels of 150 cm, 200 cm, and 250 cm. According to the report's projections, a 50-cm sea-level rise would be reached between 2055–65 in the RCP8.5 scenario and between 2065–75 in the RCP2.6 scenario. According to the draft land-use plan for 2010–25, the built-up areas increase by 50 percent (approximately 750 km^2). In these conditions, the authors project that up to 60 percent of the built-up area will be exposed to a 100 cm sea-level rise. In the absence of adaptation, the planned urban development for the year 2025 further increases Ho Chi Minh City's exposure to sea-level rise by 17 percentage points.

Bangkok

Dutta (2011) assesses the socioeconomic impacts of floods due to sea-level rise in Bangkok. He uses a model combining surface and river flows to simulate different magnitudes of sea-level rise and uses 1980 as the baseline year. The study takes into account two different sea-level rise scenarios: 32 cm in 2050 and 88 cm in 2100. For the projections of future population and urbanization, the author uses the IPCC SRES B1 scenario. For this simulation, the maximum population density is 20,000 people per square kilometer (compared to 16,000 in Manila, the highest urban population density in 2009), effectively leading to an expansion of the total area. Based on this simulation of flood and population, Dutta projects that 43 percent of the Bangkok area will be flooded in 2025, and 69 percent in 2100. The results are displayed in Table 4.8.

According to this simulation, the population is expected to be increasingly affected as the sea level rises. Dutta (2011) projects that, if no adaptation is carried out, 5.7 million people in 2025 and 8.9 million people in 2100 are going to be affected by inundations in Bangkok when the sea level reaches 88 cm. According to the report's projections, a sea-level rise of 88 cm in Bangkok may be reached between 2085 and 2095 in a 4°C world. In a 2°C world, sea-level rise of around 75 cm by the end of the 21st century would likely limit the percentage of total area of Bangkok exposed to inundations between 57–69 percent.

Manila

Muto et al. (2010) assess the local effects of precipitation, sea-level rise, and increased storminess on floods in metropolitan Manila

Table 4.8: Total flood inundation area in Bangkok for sea-level rise projections from 14cm to 88cm from 2025 to 2100

Year	2025	2050	2075	2100
Sea-level rise projection (cm)	14	32	58	88
Total flood inundation area (km^2)	1429	1611	1917	2311
Percentage of total Bangkok area	43%	48%	57%	69%

Source: Adapted from Dutta (2011).

in 2050 under the IPCC SRES scenarios B1 (1.6°C above pre-industrial levels) and A1F1 (2.2°C above pre-industrial levels). According to the study, these scenarios correspond to 19 cm and 29 cm increases in sea-level elevation and 9.4 percent and 14.4 percent increases in rainfall precipitations (in scenarios B1 and A1F1, respectively). The storm surge height as a consequence of the increased tropical storm intensity is projected to rise by 100 cm in both scenarios. In the A1F1 scenario, the authors find that a 100-year return-period flood is projected to generate damages of up to 24 percent of Manila's total GDP by 2050 and a 30-year return-period flood would generate damages of approximately 15 percent of GDP. The authors find, however, that projected damages would be only nine percent of the GDP for a 100-year return-period flood and three percent for a 30-year return-period flood if infrastructures improvements based on the Master Plan designed in 1990 are properly implemented.

Coastal and Marine Ecosystems

Livelihoods in the Asia-Pacific region, particularly in South East Asia, are often highly dependent on the ecosystem services provided by ocean and coastal environments. The associated ecosystem goods and services include food, building materials, medicine, tourism revenues, and coastal protection through reduced wave energy (Hoegh-Guldberg 2013; Villanoy et al. 2012). The fisheries supported by coral reefs, for example, are often vital to the livelihoods and diets of populations along reef coastlines (Ove Hoegh-Guldberg 1999; Cinner et al. 2012). Marine ecosystems are increasingly at risk from the impacts of climate change, including ocean acidification (Meissner, Lippmann, and Sen Gupta 2012), sea-surface water warming (Lough 2012), and rising sea levels (Gilman, Ellison, Duke, and Field 2008).

Coastal Wetlands

Coastal wetlands, including mangrove forests, provide important ecological services for the region. Mangroves contribute to human wellbeing through a range of activities, including provisioning (timber, fuel wood, and charcoal), regulating (flood, storm, and erosion control and the prevention of saltwater intrusion), habitat (breeding, spawning, and nursery habitats for commercial fish species and biodiversity), and cultural services (recreation, aesthetic, non-use). The mean economic value of these activities in South East Asia has been estimated at $4,185 per hectare per year as of 2007 (L. M. Brander et al. 2012). South East Asian countries shared mangrove forests covering an area of about six million hectares as of 2000 (L. M. Brander et al. 2012). Indonesia (3.1 million ha), Malaysia (505,000 ha), Myanmar (495,000 ha), and the Philippines (263,000 ha) are ranked 1, 6, 7 and 15 among countries worldwide with mangrove forests (Giri et al. 2011). Indonesia alone accounts for 22.6 percent of the total global mangrove area. Worldwide, mangrove forests are under significant pressure due to such human activities as aquaculture, harvesting, freshwater diversion, land reclamation, agriculture, and coastal development. These factors were responsible for at least 35 percent of the global mangrove loss between 1980 and 2000, particularly in South East Asia (Valiela, Bowen, and York 2001). Rapid sea-level rise poses additional risks (Mcleod, Hinkel, et al. 2010).

The vulnerability and response of mangrove forests to sea-level rise is connected to various surface and subsurface processes influencing the elevation of the mangroves' sediment surface (Gilman et al. 2008). In the long term, mangroves can react to rising mean sea level by landward migration. This option is limited in many locations, however, by geographic conditions (e.g., steep coastal inclines) and human activities (Ove Hoegh-Guldberg and Bruno 2010). Erosion of the seaward margin associated with sea-level rise and a possible increase of secondary productivity due to the greater availability of nutrients as a result of erosion further threaten mangrove forests (Alongi 2008).

Large losses are projected for countries in the region for a sea-level rise of 100 cm, which is this report's best estimate in a 4°C world warming scenario regionally by the 2080s (and globally by the 2090s). Sea-level rise is expected to play a significant role in the decline of coastal wetland, low unvegetated wetlands, mangroves, coastal forests, and salt marshes with a 100 cm sea-level rise (Mcleod, Hinkel, et al. 2010).[72] The study was conducted using the DIVA model for the six countries of the "Coral Triangle," which includes provinces in the Philippines, Indonesia, Malaysia, Timor-Leste, Papua New Guinea, and the Solomon Islands. In a 4°C world, total coastal wetland area is projected to decrease from 109,000 km^2 to 76,000 km^2 (about 30 percent) between 2010 and 2100.

At the level of administrative units, between 12 percent and 73 percent of coastal wetlands are projected to be lost at a 100 cm sea-level rise by the 2080s (compared to wetland area in 2010). Regions with a projected loss of more than 50 percent can be found in Timor-Leste, Indonesia (Jakarta Raya, Sulawesi

72 The projections for sea-level rise are 100cm by 2100, above 1995 levels.

Tengah, Sulawesi Tenggara, Sumatra Barat, Yogyakarta), Malaysia (Terengganu), and the Philippines (Cagayan Valley, Central Luzon, Central Visayas, Ilocos, Western Visayas), as well as parts of Papua New Guinea and the Solomon Islands. For the Philippines, a coastal wetland loss of about 51 percent by 2100 is projected (compared to 2010) (Mcleod, Hinkel, et al. 2010).

Blankespoor, Dasgupta, and Laplante (2012) apply the DIVA model to assess the economic implications of a 100 cm sea-level rise on coastal wetlands and estimate that the East Asia Pacific region may suffer the biggest loss in economic value from the impacts of such a rise. They find that the region could lose approximately $296.1–368.3 million per year in economic value (2000 U.S. dollars). Vietnam is also expected to lose 8,533 square kilometers of freshwater marsh (a 65-percent loss), and the Philippines is expected to lose 229 square kilometers of great lakes and wetlands by 2100 (or almost 100 percent of the current surface).

Projected Impacts on Coral Reefs

Coral reefs in South East Asia, which play a pivotal role in coastal rural livelihoods by providing affordable food and protection against waves, are exposed to ocean acidification and warming temperature as well as to increased human activities such as pollution and overfishing.

Coral Reefs in South East Asia

The *IPCC Fourth Assessment Report* found that coral reefs are vulnerable to increased sea-surface temperature and, as a result, to thermal stress. Increases of 1–3°C in sea-surface temperature are projected to result in more frequent bleaching events and widespread coral mortality unless thermal adaptation or acclimatization occurs. The scientific literature published since 2007, when the AR4 was completed, gives a clearer picture of these risks and also raises substantial concerns about the effects of ocean acidification on coral reef growth and viability.

Globally, coral reefs occupy about 10 percent of the tropical oceans and tend to occur in the warmer (+1.8°C) parts of lower sea-surface temperature variability in regions where sea-surface temperatures are within a 3.3°C range 80 percent of the time; this compares to temperatures of non-reef areas, which remain within a 7.0°C range for 80 percent of the time (Lough 2012). Coral reefs flourish in relatively alkaline waters. In the Asia-Pacific region, coral reefs occur between 25°N and 25°S in warm, light-penetrated waters (O. Hoegh-Guldberg 2013).

At the global level, healthy coral reef ecosystems provide habitat for over one million species (O. Hoegh-Guldberg 2013) and flourish in waters that would otherwise be unproductive due to low nutrient availability (Ove Hoegh-Guldberg 1999). The loss of coral reef communities is thus likely to result in diminished species richness, species extinctions, and the loss of species that are key to local ecosystems (N. A. J. Graham et al. 2006; K. M. Brander 2007). The IPCC AR4 found with high confidence that climate change is likely to adversely affect corals reefs, fisheries, and other marine-based resources. Research published since 2007 has strongly reinforced this message. This section examines projected changes and impacts due to climate change in the South East Asian region.

One of the highest concentrations of marine species globally occurs in the Coral Triangle. Coral reefs in South East Asia[73] have been estimated to cover 95,790 km²; within this region, reef estimates for the Philippines are approximately 26,000 km² and, for Vietnam, 1,100 km[74] (Nañola, Aliño, and Carpenter 2011). In addition to the climate-change-related risks posed to reefs, including ocean acidification and the increasing frequency and duration of ocean temperature anomalies, reefs are also at risk from such human activities as destructive fishing methods and coastal development resulting in increasing sediment outflow onto reefs (L. Burke, Selig, and Spalding 2002).

Projected Degradation and Loss due to Ocean Acidification and Increasing Temperature

Vulnerability to Ocean Acidification

Coral reefs have been found to be vulnerable to ocean acidification as a consequence of increasing atmospheric CO_2 concentrations. 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 of aragonite are below a value of 1.0, the water is corrosive to pure aragonite and unprotected aragonite shells (R. a Feely, Sabine, Hernandez-Ayon, Ianson, and Hales 2008). Due to anthropogenic CO_2 emissions, the levels at which waters become undersaturated with respect to aragonite have been observed to have shoaled when compared to pre-industrial levels (R. A. Feely et al. 2004).

Mumby et al. (2011) identify three critical thresholds which coral reefs may be at risk of crossing as atmospheric CO_2 concentrations increase: first, the degradation threshold, beyond which an ecosystem begins to degrade (for example, above 350 ppm, coral bleaching has been observed to begin occurring); second, thresholds of ecosystem state and process, which determine whether an ecosystem will exhibit natural recovery or will shift into a more damaged state; and, finally, the physiological threshold, whereby essential functions become severely impaired. These thresholds involve different processes, would have different repercussions,

73 In the study referred to (L. Burke et al. 2002), South East Asia encompasses Indonesia; the Philippines; Spratly and Paracel Islands; Japan; Thailand; Myanmar; Vietnam; China; Taiwan, China; Brunei Darussalam; Singapore; and Cambodia.

74 It should be noted that satellite measurements yield lower values (Nañola et al. 2011)

are associated with different levels of uncertainty, and are understood by scientists to varying extents. Mumby et al. (2011) stress that while all types of threshold seriously undermine the healthy functioning of the reef ecosystem, not all of them imply collapse.

Earlier work by Veron et al. (2009) indicates that a level of 350 ppm CO_2 could be a long-term viability limit for coral reefs, if multiple stressors such as high sea surface water temperature events, sea-level rise, and deterioration in seawater quality are included. This level of CO_2 concentration has already been exceeded in the last decade. Even under the lowest of the AR5 scenarios (corresponding to a 2°C world), which reaches a peak CO_2 concentration at around 450 ppm by mid-century before beginning a slow decline, a level of 350 ppm would not be achieved again for many centuries. At the peak CO_2 concentration for the lowest scenario, it has been estimated that global coral reef growth would slow down considerably, with significant impacts well before 450 ppm is reached. Impacts could include reduced growth, coral skeleton weakening, and increased temperature sensitivity (Cao and Caldeira 2008). At 550 ppm CO_2 concentration, which in a 4°C world warming scenario would be reached by around the 2050s, it has been projected that coral reefs will start to dissolve due to ocean acidification (Silverman et al. 2009).

Vulnerability to Warming Waters

Since the 1980s, elevated sea-surface temperatures have been increasingly linked with mass coral bleaching events in which the symbiotic algae (zooxanthellae) and their associated pigments are temporarily or permanently expelled (Glynn 1984; Goreau and Hayes 1994; Ove Hoegh-Guldberg 1999).

Coral mortality after bleaching events increases with the length and extent to which temperatures rise above regional summer maxima (Ove Hoegh-Guldberg 1999). Coral bleaching can be expected when a region's warm season maximum temperature is exceeded by 1°C for more than four weeks; bleaching becomes progressively worse at higher temperatures and/or longer periods during which the regional threshold temperature is exceeded (Goreau and Hayes 1994; Ove Hoegh-Guldberg and Bruno 2010). It is clear from model projections that, within a few decades, warming of tropical sea surface waters would exceed the historical thermal range and alter the physical environment of the coral reefs.

As expected, tropical oceans have been warming at a slower rate than globally (average of 0.08°C per decade over 1950–2011 in the tropics, or about 70 percent of the global average rate). The observed temperatures in the period 1981–2011 were 0.3–0.4°C above 1950–80 levels averaged over the tropical oceans (Lough 2012). Overall, 65 percent of the tropical oceans have warmed significantly while 34 percent have as yet shown no significant change. The observed absolute warming was greatest in the northwest and northeast tropical Pacific and the southwest tropical Atlantic. It is of substantial relevance to South East Asia that, when taking into account inter-annual variability, the strongest changes are observed in the near-equatorial Indian and western Pacific as well as the Atlantic Ocean.

Global warming-induced in exceedance of the temperature tolerance ranges within which coral reefs have evolved has been projected to produce substantial damages through thermal stress to the coral reefs. There is significant evidence that reefs at locations with little natural temperature variability (and thus historically few warm events) are particularly vulnerable to changes in marine chemistry and temperatures (Carilli, Donner, and Hartmann 2012). Environmental conditions and background climate conditions appear to further influence the upper thermal tolerance threshold temperature such that it varies across locations (Carilli et al. 2012). Taking this into account, Boylan and Kleypas (2008) suggest that for areas with low natural variability the threshold temperature for bleaching is better described (compared to the 1°C threshold) with the regionally based threshold twice the standard deviation of warm season sea-surface temperature anomalies. For tropical reef organisms, compromised physiological processes have been observed beyond temperatures of around 30–32°C (Lough 2012).

Significant increases above the historical range of sea-surface temperatures have been observed in the tropics. Lough (2012), for example, finds that coral reef locations with historical (1950–80) ranges of 27–28°C and 28–29°C experienced a shift in the 1981–2011 period toward a range of 29–30°C. The percentage of months within the upper (29–30°C) range increased significantly, up 3.1 percentage points per decade over the period 1950–2011. There was also a significant 0.4 percentage point per decade change in the number of months within the 31–32°C range, indicating that this estimated upper thermal tolerance threshold for tropical coral reefs could be exceeded if this trend continues.

For projections of the risks of global warming on coral reef bleaching, it is now standard to use indicators of thermal exposure; these include degree heating weeks (DHW) and degree heating months (DHM), which are defined as the product of exposure intensity (degrees Celsius above threshold) and duration (in weeks or months) (Meissner et al. 2012). Bleaching begins to occur when the cumulative DHW exceeds 4°C-weeks (1 month within a 12-week period) and severe when the DHW exceeds 8°C-weeks (or 2 months).

Combined Impacts of Ocean Acidification and Increasing Temperature

Meissner et al. (2012) project that a combination of reduced aragonite saturation levels (associated with the process of ocean acidification) and increasing sea-surface temperatures will expose reefs to more severe thermal stress, resulting in bleaching. Projections for a 2°C world show some recovery of both aragonite saturation and sea surface temperatures within the next 400 years. For this scenario, anomalies of mean tropical sea surface temperature do not exceed 1.9°C and zonal mean aragonite saturation remains above 3 between 30°N and 30°S. It should be noted that present-day open ocean aragonite saturation levels are between 3.28 and 4.06, and no coral reefs are found in environments with levels below 3.

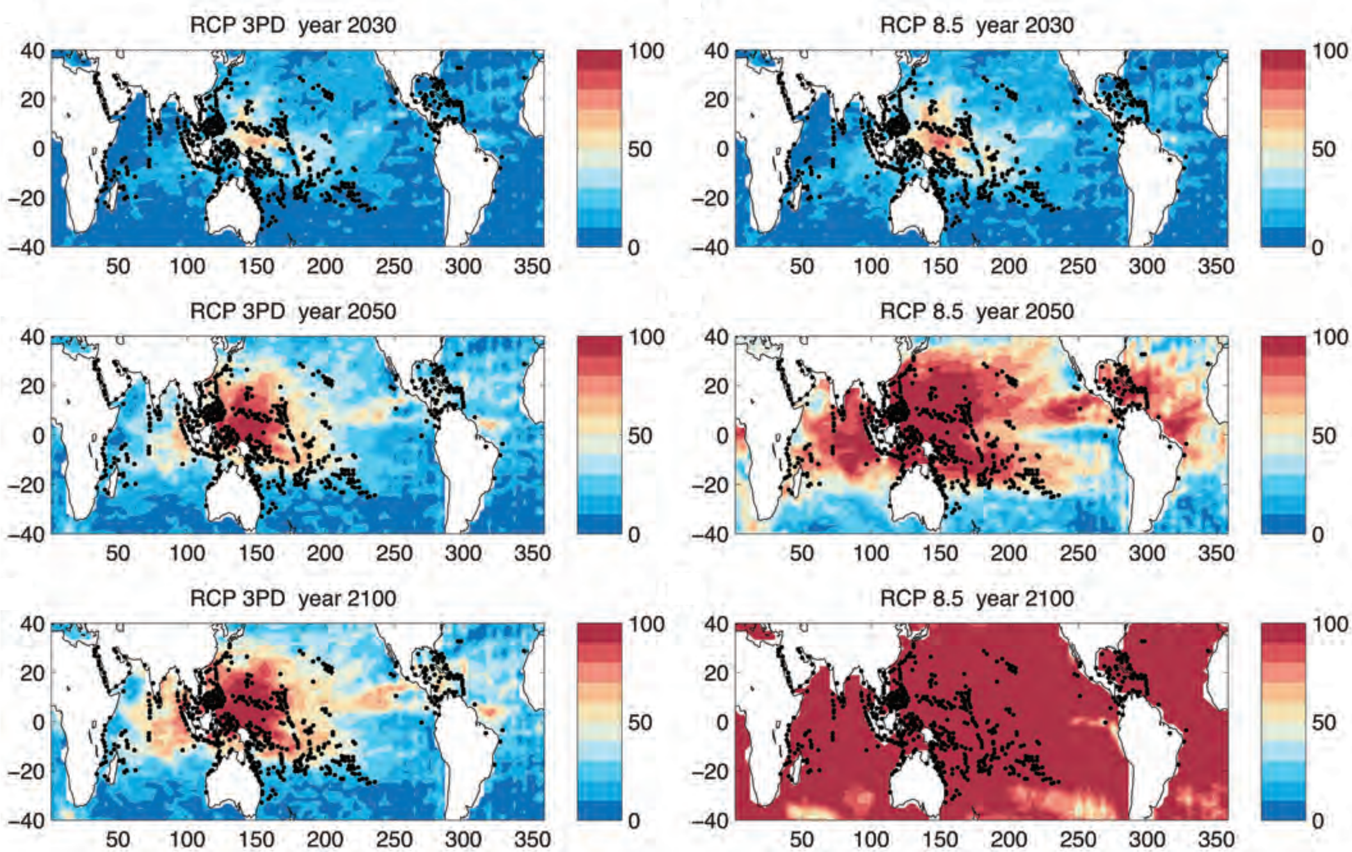
In a 3°C world and in a 4°C world, no recovery of either temperature or aragonite saturation occurs within the next 400 years. Furthermore, the zonal mean aragonite saturation at all latitudes falls below 3.3 as early as 2050 in a 3°C world. In a 4°C world, this level is reached as early as 2040; it reaches 3 by the 2050s, and continues a steady decline thereafter. In both a 3°C world and a 4°C world, open ocean surface seawater aragonite is projected to drop below thresholds by the end of the century (Meissner et al. 2012).

By the 2030s (approximately 1.2°C above pre-industrial levels), 66 percent of coral reef areas are projected to be thermally marginal, with CO_2 concentrations around 420 ppm. In the same timeframe in a 4°C warming scenario (about 1.5°C warming), about 85 percent of coral reef areas are projected to be thermally marginal for a CO_2 concentration of around 450 ppm by the 2030s (Meissner et al. 2012).

By the 2050s, with global mean warming of around 1.5°C under a low emissions (2°C warming by 2100) scenario and about 2°C under a high emissions (4°C warming by 2100) scenario, 98–100 percent of coral reefs are projected to be thermally marginal. In a 4°C warming scenario, in 2100 virtually all coral reefs will have been subject to a severe bleaching event every year (Meissner et al. 2012).

The western Pacific clearly stands out as a highly vulnerable area in all scenarios; even with 2°C warming, in 2100 there is a 60–100 percent probability of a bleaching event happening every year (see Figure 4.11). It is unlikely that coral reefs would survive such a regime. Under all concentration pathways (i.e., ranging from 2°C to above 4°C by the end of the century), virtually every coral reef in South East Asia would experience severe thermal stress by the year 2050 under warming levels of 1.5°C–2°C above pre-industrial levels (Meissner et al. 2012). Furthermore, by the 2030s, there is a 50-percent likelihood of bleaching events under a 1.2°C warming scenario and a 70-percent likelihood under a 1.5°C warming scenario (above pre-industrial levels).

Figure 4.11: Projected impact of climate change on coral systems in South East Asia



Probability of a severe bleaching event (DHW>8) occurring during a given year under scenario RCP2.6 (approximately 2°C, left) and RCP8.5 (approximately 4°C, right).

Source: Meissner et al. (2012).

Reprinted from Springer; Coral Reefs, 31(2), 2012, 309-319, Large-scale stress factors affecting coral reefs:open ocean sea surface temperature and surface seawater aragonite saturation over the next 400 years, Meissner et al., Figure 3, with kind permission from Springer Science and Business Media B.V. Further permission required for reuse.

The analysis of Frieler et al. (2012) produces quite similar results. By 1.5°C warming above pre-industrial levels, about 89 percent of coral reefs are projected to be experiencing severe bleaching (DHM 2 or greater); by 2°C warming, that number rises to around 100 percent. Highly optimistic assumptions on coral reef thermal adaptation potential would be required if even 66 percent of coral reef areas were to be preserved under a 2°C warming scenario; only 10 percent would be preserved without such optimistic interpretations (Frieler et al. 2012), which seems the more likely assumption. Indeed, a recent statistical meta-analysis of over 200 papers published so far on the effects of acidification on marine organisms suggests that increased temperatures enhance the sensitivity of marine species to acidification. This study further strengthens the evidence that acidification negatively impacts the abundance, survival, growth, and development of many calcifying marine organisms with corals, calcifying algae, and molluscs (e.g. shell fish) the most severely impacted (Kroeker et al. 2013).

At finer spatial resolution, and taking further stresses such as coastal pollution and overexploitation into account, Mcleod, Moffitt, et al. (2010) identify the eastern Philippines as the most threatened coral reef area of the Coral Triangle.

Human and Development Implications of Coral Reef Loss and Degradation

Implications for Coastal Protection

Coral reefs play a vital role in coastal protection. This is particularly so in the Philippines. Located in the typhoon belt and consisting of an archipelagic structure, the Philippines is naturally vulnerable to the impacts of projected sea-level rise and the synergistic effects of high-energy waves associated with typhoons (Villanoy et al. 2012).

Villanoy et al. (2012) simulate the role of reefs on coastal wave energy dissipation under sea-level rise (0.3 m and 1 m) and under storm events at two sites in the Philippines facing the Pacific Ocean. Employing a model to simulate wave propagation and prescribing a mean depth of 2 m for the reef, they show that for a sea-level rise scenario where wave height is increased by 1–200 cm, coral reefs continue to afford protection by dissipating wave energy (which reduces wave run-up on land). Under simulated sea-level rise and wave heights of 400 cm, however, the wave dissipating effects of the reefs, while still measurable, are significantly decreased. This shows that efficiency of coastal protection by coral reefs depends on the degree of sea-level rise.

It should be noted, however, that Villanoy et al. (2012) assume a healthy reef with 50–80 percent coral cover and suggest that some corals might grow fast enough to keep pace with projected sea-level rise. While they note that the fast-growing species might be more susceptible to coral bleaching due to warmer waters, they take neither this nor the impacts of ocean acidification into account. Thus, their assessment of the effectiveness of coral reefs for coastal protection may be too optimistic, as oceanic conditions in a 4°C world (which would roughly correspond to a 100 cm sea-level rise) are not considered here. Projections by Meissner et al. (2012) show that even under lower warming scenarios, all coral reefs in South East Asia as early as 2050 will have experienced severe bleaching events every year.

This site-specific modeling study does, however, confirm the importance of coral reefs for protection against wave run-up on land. Thus, natural protection against the impacts of sea-level rise due to climate change would itself be degraded due to the effects of climate change.

Implications for Fishing Communities and the Economic Consequences

Coral reefs are pivotal for the socioeconomic welfare of about 500 million people globally (Wilkinson 2008). South East Asia alone has 138 million people living on the coast and within 30 km of a coral reef (L. Burke, Reytar, Spalding, and Perry 2011)—defined as reef-associated populations. Coral reefs fisheries are mostly suitable for small-scale fishing activities, thanks to the easy accessibility of the coral reefs and the need for only minimal investments in capital and technology (Whittingham, Townsley, and Campbell 2003). Vietnam and the Philippines each have between 100,000 and 1 million reef fishers (excluding aquaculture activities) (L. Burke et al. 2011). Coastal and reef-associated communities are thus likely to suffer major social, economic, and nutritional impacts as a result of climate change (Sumaila and Cheung 2010).

It is important to note that under future stress, reefs may not cease to exist altogether but would become dominated by other species. These species might not, however, be suitable for human consumption (Ove Hoegh-Guldberg 2010). The present understanding of the mid- and long-term economic and social implications of coral reef degradation induced by warming sea temperatures and ocean acidification on reef fisheries is limited (S. K. Wilson et al. 2010). N. A. J. Graham et al. (2006) likewise note the lack of empirical data on the implications of coral bleaching for other components of reef ecosystems, including for the longer-term responses of species such as reef fish.

Nicholas A. J. Graham et al. (2008) and Nicholas A. J. Graham et al. (2011) assess the impacts of climate change on coral fish stock (Box 4.4). In these studies, climate-change-induced impacts on coral reefs were estimated based on the consequences of the 1998 coral bleaching event in the Indian Ocean. The authors find a clear correlation between coral bleaching events and the depletion of some coral fish species (the most vulnerable species to climate disturbance are the obligate and facultative corallivores). Climate change is, however, not the only stressor depleting reef fish stock. The unsustainable use of resources, due primarily to overfishing, also significantly contributes to declines in coral fish stocks (Newton, Côté, Pilling, Jennings, and Dulvy 2007).

Box 4.4: Fundamental Ecosystem Change

Fish may be affected by changes to the physiological conditions of species following coral loss and through the physical breakdown of the reef structure. For example, a severe El-Niño-related bleaching event in the Indian Ocean in 1998 caused a phase shift from a coral-dominated state to a rubble and algal-dominated state of low complexity, with a >90 percent total loss of live coral cover across the inner Seychelles. This coral loss resulted in declines in taxonomic distinctness in reef fish. Loss of physical structure due to bleaching is identified by N. A. J. Graham, et al. (2006) as the main driving force of changes in species richness. This case, while not attributed to climate change in their study, illustrates the nature of the risks to fish species.

As a consequence, species vulnerable to one threat (climate or fishing) is unlikely to be affected by the other. According to Nicholas A J Graham et al. (2011), this reduces the probabilities of strong synergistic effects of fishing and climate disturbances at the species level. Nevertheless, at the coral fish community level, biodiversity is expected to be severely affected as species that are less vulnerable to one stressor are prone to be affected by the other.

Edward H. Allison et al. (2005) developed a simplified econometric model to project the consequences of climate change on per capita fish consumption. The analysis takes into account four different factors to estimate future fish consumption: human population density, current fish consumption, national coral reef area, and an arbitrary range of values for the loss of coral reef (from 5–15 percent over the first 15 years of projections). They find that, in any loss scenario, per capita fish consumption is expected to decrease due to congruent factors: increased population, loss of coral reef at the national level, and the finite amount of fish production per unit of coral area. Expected decreases estimated by this simplified model show that per capita coral fish availability could drop by 25 percent in 2050 compared to 2000 levels. This conclusion should be interpreted with care, however, since the econometric model is extremely simplified. It does nonetheless further highlight the negative contribution of climate and human stressors to coral fish stocks and their availability in the future.

Primary Productivity and Pelagic Fisheries

Open ocean ecosystems provide food and income through fisheries revenues (Hoegh-Guldberg 2013), and capture fisheries remain essential in developing economies due to their affordability and easy accessibility by coastal populations (Food and Agriculture Organization of the United Nations 2012b).

According to the FAO *Fishery Country Profile*,[75] fishery exports in Vietnam in 2004 amounted to $2.36 billion; 90 percent of commercial landings came from offshore fisheries. Exports of overall fish and fishery products in the Philippines amounted to $525.4 million. Major exploited stocks in the Philippines include small pelagic fish, tuna and other large pelagic fish, demersal fish, and invertebrates. Furthermore, pelagic fisheries contribute directly to food security. According to the FAO, small pelagic fish are considered the main source of inexpensive animal protein for lower-income groups in the Philippines.[76]

Changes in ocean chemistry and water temperature are expected to impact fisheries off the coast by leading to decreases in primary productivity[77] and direct impacts on fish physiology, and by changing the conditions under which species have developed—resulting in typically poleward distribution shifts. In fact, these shifts have already been observed (Sumaila, Cheung, Lam, Pauly, and Herrick 2011).

One effect of increasing sea-surface temperatures is enhanced stratification of waters. This is associated with a decline in available macronutrients as waters do not mix and the mixed layer becomes more shallow. The resulting nutrient limitation is expected to lead to a decrease in primary productivity. Inter-comparing four climate models, Steinacher et al. (2010) investigate the potential impacts under approximately 4.6°C above pre-industrial levels by 2100 globally. They find global decreases in primary productivity between 2 and 20 percent by 2100 relative to pre-industrial levels for all four models. While the strength of the signal varies across models, all models agree on a downward trend for the western Pacific region.

Taking into account changes in sea-surface temperatures, primary productivity, salinity, and coastal upwelling zones, Cheung et al. (2010) project changes in species distribution and patterns of maximum catch potential by 2055. It should be noted that while distribution ranges of 1066 species were assessed within this model, changes were not calculated at the species level. Under a scenario of 2°C warming by the 2050s, the western Pacific displays a mixed picture. The changes range from a 50-percent decrease in maximum catch potential around the southern Philippines, to a 16-percent decrease in the waters of Vietnam, to a 6–16 percent increase in the maximum catch potential around the northern Philippines. It is important to note that the impacts of ocean hypoxia and acidification, as further consequences of climate change, are not yet accounted for in these projections. These effects are expected to decrease catch potentials by 20–30 percent in other regions (see

75 http://www.fao.org/fishery/countrysector/FI-CP_VN/en.

76 http://www.fao.org/fishery/countrysector/FI-CP_PH/en.

77 Primary productivity refers to photosynthetic production at the beginning of the food chain (mainly through algae).

also Chapter 3 on "Aquatic Ecosystems") and can be expected to have adverse consequences for South East Asian fisheries.

Oxygen availability has been found to decline in the 200–700 meter zone and is related to reduced water mixing due to enhanced stratification (Stramma, Schmidtko, Levin, and Johnson 2010). Furthermore, warming waters lead to elevated oxygen demand across marine taxa (Stramma, Johnson, Sprintall, and Mohrholz 2008). Hypoxia is known to negatively impact the performance of marine organisms, leading to additional potential impacts on fish species (Pörtner 2010). Accordingly, a later analysis by W. W. L. Cheung, Dunne, Sarmiento, and Pauly (2011) which built on Cheung et al. (2010) found that, for the northeast Atlantic ocean, acidification and a reduction of oxygen content lowered the estimated catch potentials by 20–30 percent relative to simulations not considering these factors. No such assessments are available yet in the literature for South East Asia. Fisheries in Papua New Guinea are also expected to be affected by the consequences of warmer sea temperatures increasing stratification of the upper water column. Under the A2 scenario (corresponding to a 4.4°C degree increase by 2100 above pre-industrial levels) and using the IPSL-CM4, Bell et al. (2013) estimate biomass changes in the Pacific Ocean and in Papua New Guinea. They find that skipjack tuna biomass along PNG's coasts is expected to decrease between 2005 and 2100. Taking only climate change into account, they estimate that tuna biomass will decrease by about 25 percent by 2100. Fishing activities further decrease tuna biomass in the area (by about 10 percent in 2035, 10 percent in 2050, and about 35 percent by 2100 compared to 2000–2010 average catches in the region).

Cheung et al. (2012) project a decrease of 14–24 percent in the average maximum body weight of fish at the global level by 2050. In the study, they analyze the impacts of warmer water temperatures and decreased oxygen levels on the growth and metabolic parameters of fishes. The authors used two climate models (GFDL ESM 2.1 and IPSL-CM4-LOOP) under the SRES scenario A2 (corresponding to a 1.8°C temperature increase by 2050 above pre-industrial levels). According to their projections, the fish of the Java Sea and the Gulf of Thailand are expected to be the most severely affected; in these seas, average maximum body size in 2050 may be reduced 50–100 percent compared to 2000.

On a species level, Lehodey et al. (2010) project changes in the distribution of bigeye tuna larvae and adults. In a 4°C world, conditions for larval spawning in the western Pacific are projected to deteriorate due to increasing temperatures. Larval spawning conditions in subtropical regions in turn are projected to improve. Overall adult bigeye tuna mortality is projected to increase, leading to a markedly negative trend in biomass by 2100.

The analysis above indicates a substantial risk to marine food production, at least regionally for a warming of around 2°C above pre-industrial levels and on a broader scale in a 4°C world.

Projected Impacts on Economic and Human Development

Climate change impacts in South East Asia are expected to affect economic activity and decrease the revenues and incomes associated with these activities. Similarly, human development and primarily health may also be affected by the consequences of climate change.

Projected Impacts on Economic Development

In the following section, three types of economic impacts are explored: decreased tourism revenues due to several factors (including sea-level rise), increased damages due to tropical cyclones, and business disruptions due to extreme weather events.

Combined Risks to the Tourism Industry

The impacts of sea-level rise, increased tropical cyclone intensity, coral bleaching and biodiversity loss can have adverse effects on the tourism industry by damaging infrastructure. In addition, tropical cyclones have a negative effect on tourists' choice of destination countries on the same scale as such deterrents as terrorist attacks and political crises (L. W. Turner, Vu, and Witt 2012).

A growing number of tourists visit South East Asia for its cultural richness, landscapes, beaches, and marine activities. The contribution of tourism to employment and economic wealth is similarly growing. About 25.5 million people in the region benefited from direct, indirect, and induced jobs created in the travel and tourism industry (World Travel and Tourism Council 2012a). Travel and tourism's total contribution to regional GDP was estimated at $237.4 billion (or 10.9 percent) in 2011; the direct contribution was estimated at $94.5 billion (or 4.4 percent) of regional GDP.[78]

In Vietnam, revenues from travel and tourism range from a direct contribution of 5.1 percent of 2011 GDP to a total contribution of 11.8 percent (World Travel and Tourism Council 2012b). In the Philippines, revenues from the travel and tourism industry ranged from 4.9 percent of 2011 GDP (direct contribution) to 19.2 percent (total contribution) (World Travel and Tourism Council 2012c).

The South East Asian region has been identified as one of the most vulnerable regions to the impacts of climate change on tourism. In a global study, Perch-Nielsen (2009) found that when sea-level rise, extreme weather events, and biodiversity losses are taken into account, Thailand, Indonesia, the Philippines, Myanmar, and Cambodia rank among the most vulnerable tourism destinations.[79]

78 Excluding Timor-Leste.

79 The assessment by Perch-Nielsen (2009) allows for adaptive capacity, exposure, and sensitivity in a 2°C warming scenario for the period 2041–70. Adaptive capacity includes GDP per capita, the number of Internet users, regulatory quality, and

It is projected that increased weather event intensity—especially of tropical cyclones—combined with sea-level rise will cause severe damage in the region; this is likely to have negative impacts on beach resorts and other tourism infrastructure (Mendelsohn et al. 2012; Neumann, Emanuel, Ravela, Ludwig, and Verly 2012).

Coastal erosion, which can be driven or exacerbated by sea-level rise (Bruun 1962), also poses a threat to recreational activities and tourism—and, consequently, to associated revenues (Phillips and Jones 2006). Studies conducted in other regions—for example, in Sri Lanka (Weerakkody 1997), Barbados (Dharmaratne and Brathwaite 1998), and Mauritius (Ragoonaden 1997)–provide further evidence that coastal erosion can be detrimental to tourism.

Damages to coral reefs following bleaching events have also been found to negatively affect tourism revenue. Doshi et al. (2012) estimate that the 2010 bleaching event off the coasts of Thailand, Indonesia, and Malaysia resulted in economic losses of $50–80 million. Similar studies in Tanzania and the Indian Ocean have also observed that coral bleaching events have a significant negative impact on non-market benefits derived from coral reefs (Andersson 2007; Ngazy, Jiddawi, and Cesar 2004). Doshi et al. (2012) further estimate that the cost of coral bleaching ranges from $85–300 per dive. On the other hand, divers' willingness to pay to support reef quality improvements and protection increases because of coral bleaching events (Ransom and Mangi 2010).

Tropical Cyclone Risks

Across all basins and climate scenarios, tropical cyclone intensity is projected to increase. Combined with economic and demographic growth, increased TC intensity is expected to generate severe damages to both populations and assets. However, TC frequency is expected to decrease, potentially reducing associated damages and losses. Risk associated with tropical cyclones is a function of three parameters: the frequency and intensity of the hazard, the exposure (number of people or assets), and the vulnerability. The following section assesses the existing knowledge of tropical cyclones damages, taking into account climate and economic development changes.

Projected Population Exposure

Peduzzi et al. (2012) show that, at the global level, mortality risks due to tropical cyclones is influenced by tropical cyclone intensity, the exposure to risk, levels of poverty, and governance quality. In their study, poverty is assessed using the Human Development Index and GDP per capita; governance is defined using the following indicators: voice and accountability, government efficiency, political stability, control of corruption, and the rule of law. The authors first estimate the current risks in countries based on the average number of people killed per year and the average number of people killed per million inhabitants. Via this approach, they find that Myanmar is the country with the highest mortality risk index in South East Asia[80] (risk defined as medium high).

At the global level, it is estimated that 90 percent of the tropical cyclone exposure will occur in Asia. This region is also expected to experience the highest increase in exposure to tropical cyclones. It is projected that annual exposure will increase by about 11 million people in Pacific Asia (defined as Asia 2 in the study) and by 2.5 million people in Indian Ocean Asia (Asia 1) between 2010–30.

Projected Damage Costs

Due to the consistent projections of higher maximum wind speeds, and higher rainfall precipitation (Knutson et al. 2010), it can be expected that tropical cyclone damage will increase during the 21st century. Direct economic damages on assets due to strong TCs could double by 2100 compared to the no-climate-change baseline for population and GDP growth (Mendelsohn, Emanuel, Chonabayashi, and Bakkensen 2012).[81] Mendelsohn et al. (2012) project damage for a set of four climate models from the 1981–2000 period to the 2081–2100 period under the IPCC A1B SRES emission scenario, corresponding to an average 3.9°C temperature increase above pre-industrial levels. Total damage costs are projected to increase by a third compared to the no-climate-change baseline for population and GDP growth. The projected costs of TC damage in South East Asia, however, are strongly dominated by Vietnam and the Philippines, which show a large variation in both sign and size of damage across models. Above-average increases in TC damage as a percentage of GDP are projected for East Asia.

Tropical Cyclone Damage to Agriculture in the Philippines

Agricultural production in the Philippines is less vulnerable to the consequences of sea-level rise than production in the Vietnamese, Thai, and Burmese deltas, as most Philippine agriculture does not take place in coastal and low-lying areas. Nonetheless,

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the GDP generated by the travel and tourism industry. Sensitivity accounts for the share of arrivals for leisure, recreation, and holidays, the number of people affected by meteorologically extreme events, the number of people additionally inundated once a year for a sea-level rise of 50 cm, the length of low-lying coastal zones with more than 10 persons/km^2, and the beach length to be nourished in order to maintain important tourist resort areas. Finally, exposure involves the change in modified tourism climatic index, the change in maximum 5-day precipitation total, the change in fraction of total precipitation due to events exceeding the 95th percentile of climatological distribution for wet day amounts, and the required adaptation of corals to increased thermal stress.

80 Philippines: 5; Vietnam: 5; Laos: 5; Thailand: 4.

81 The authors estimate Global World Product in 2100 assuming that least developed countries' economies grow at 2.7 percent per annum, that emerging countries' economies grow at 3.3 percent per annum, and that developed countries grow at 2.7 percent per annum. For the global population projections, the authors project a population of 9 billion people.

tropical cyclones affect rice and other agricultural production in the Philippines—and may even more severely impact them as a result of climate change. The Philippines is located in the typhoon belt; on average, seven or eight tropical cyclones make landfall each year (Yumul et al. 2011). In recent years, tropical cyclones have generated significant damage; the agricultural sector suffered the most losses. For example, category 5 cyclone Bopha generated $646 million in damage to the agricultural sector in December 2012. Due to the impacts of Bopha, the Philippines Banana Growers and Exporters Association reported that about 25 percent of the banana production was devastated and that restoring destroyed farms would cost approximately $122 million (AON Benfield 2012). In the aftermath of category 4 cyclone Imbudo, local farmers in the Isabela Province reported crop losses as a proportion of annual farm household income at 64 percent for corn, 24 percent for bananas, and 27 percent for rice (Huigen and Jens 2006). At the country level, PHP 1.2 billion of damage occurred (about $29 million).

Additional Economic Impacts Due to Business Disruption

Extreme weather events and sea-level rise induced impacts are expected to have two types of economic implications: direct asset losses via damage to equipment and infrastructure and indirect business and economic disruptions affecting business activities and supply chains (Rose 2009).

While the consequences of past events imply that disruption to economic activity is a major potential source of losses incurred by climate impacts, the current understanding of business disruption in developing countries is still very limited. Indirect impacts of disasters include, among other things, off-site business interruption, reduced property values, and stock market effects (Asgary et al. 2012; Rose 2009). Business disruption is principally due to interruptions, changes, and delays in services provided by public and private electricity and water utilities and transport infrastructure (Sussman and Freed 2008). Coastal flooding and tropical cyclones can cause business disruption in developed and developing countries alike, as witnessed in the case of Hurricane Katrina in 2005. These business and economic disruptions generate a major portion of the total commercial insurance losses (Ross, Mills, and Hecht 2007). In the case of Hurricane Katrina, for example, losses due to business interruption, at $10 billion, were estimated to be as high as direct losses. In South East Asia, the 2011 Thai floods generated $32 billion in business interruption and other losses in the manufacturing sector (World Bank and GFDRR 2011).

The consequences of past events indicate that economic losses due to flooding reach beyond the direct point of impact. Future indirect responses to flooding, however, have not yet been projected for the region.

Box 4.5: Business Disruption due to River Flooding

River flooding is another climate-driven risk in low-lying delta regions. Recent observations of the consequence of extreme rainfall events, such as those that led to the 2011 Thailand floods, indicate that river flooding can be associated with significant loss of life and large total economic losses due to business interruption. Damages in the 2011 floods were estimate at $45.7 billion (equivalent to 13.2 percent of GDP); most of the losses were clustered in the Bangkok region (World Bank and GFDRR 2011). Flood damage in this case was 40 times higher than in earlier extreme floods and had substantial secondary effects on global industrial supply systems (Centre for Research on the Epidemiology of Disasters 2013). This report notes only past vulnerability and does not examine the possibility of increased exposure to river flooding in the future.

Projected Human Impacts

The impacts outlined in the above sections are expected to have repercussions on human health and on livelihoods; these impacts will be determined by the socioeconomic contexts in which they occur. The following provides a sketch of some of the key issues in South East Asia.

Projected Health Impacts and Excessive Mortality

South East Asia has been identified as a hotspot for diseases that are projected to pose an increasing risk under climate change. These include water- and vector-borne diseases and diarrheal illnesses (Coker, Hunter, Rudge, Liverani, and Hanvoravongchai 2011). Flooding compounds the risk of these diseases. Flooding is also associated with immediate risks, including drowning and the disruption of sanitation and health services as a result of damages to infrastructure (Schatz 2008).

Drowning is the main cause of immediate death from floods (Jonkman and Kelman 2005). Floodwaters can also damage the sewage systems and contribute to local freshwater and food supply contamination. Faecal contamination due to sewage system failure, which can also affect livestock and crops, was observed in 1999 following Hurricane Floyd in the United States (Casteel, Sobsey, and Mueller 2006).

The transmission of diarrheal diseases is influenced by a number of climatic variables, including temperature, rainfall, relative humidity, and air pressure, all of which affect pathogens in different ways (Kolstad and Johansson 2011). A factor driving the transmission of diarrheal diseases in South East Asia is water scarcity during droughts, which often leads to poor sanitation, in combination with climate-change-induced impacts such as droughts, floods, and increased storminess (Coker et al. 2011). In a 4°C warming scenario, the relative risk of diarrhea is expected to increase 5–11 percent for the period 2010–39 and 13–31 percent for the period 2070–99 in South East Asia relative to 1961–1990 (Kolstad and Johansson 2011).

Moreover, vector-borne diseases, such as malaria and dengue fever, may also increase due to floods (Watson, Gayer, and Connolly 2007). Increased sea-surface temperature and sea-surface height has been observed to positively correlate with subsequent outbreaks of cholera in developing countries (Colwell 2002).

Heat extremes can also have significant impacts on human health. The elderly and women are considered to be the most vulnerable to heat extremes. South East Asia's populations are rapidly aging; in Vietnam, for example, the percentage of people aged 60 and over is projected to increase 22 percent between 2011–50, to account for a share of 31 percent of the total population in 2050 (United Nations Population Division 2011). These increases in the proportion of older people will place larger numbers of people at higher risk of the effects of heat extremes.

While rural populations are also exposed to climate-related risks, the conditions that characterize densely populated cities make urban dwellers particularly vulnerable. This is especially true of those who live in informal settlements (World Health Organization 2009).

Migration

Human migration can be seen as a form of adaptation and an appropriate response to a variety of local environmental pressures (Tacoli 2009), and a more comprehensive discussion of drivers and potential consequences of migration is provided in Chapter 3 on "Population Movement". While migration is a complex, multi-causal phenomenon, populations in South East Asia are particularly exposed to certain risk factors to which migration may constitute a human response.

Tropical cyclones have led to significant temporary population displacements in the aftermath of landfall. The tropical cyclone Washi, which struck the island of Mindanao in the Philippines in 2011, caused 300,000 people to be displaced (Government of the Philippines 2012) (see also Box 4.6).

South East Asian deltaic populations are expected to be the most severely affected by rising sea levels and storm surges (Marks 2011; Warner 2010; World Bank 2010b). In Vietnam alone, if the sea level rises up to 100 cm, close to five million people may be displaced due to permanent flooding and other climate-change-related impacts resulting in the submergence of deltaic and coastal areas (Carew-Reid 2008). However, there is large uncertainty as to the number of people expected to be affected by permanent migrations and forced relocations due to uncertainties in the projected physical impacts. The impacts of socioeconomic conditions add a further unknown to the projections.

Box 4.6: Planned Resettlement

As part of a flood management and environmental sanitation strategy, Vietnam's Department of Agriculture and Rural Development has undertaken the relocation of particularly vulnerable communities along river banks (Dun 2009). Although these relocations are often within a radius of 1–2 km, the potential disruption of social networks poses a risk to people´s livelihoods (Warner 2010). As the impacts of sea-level rise and tropical cyclones reduce adaptation options, the frequency of internal, temporary, and permanent migrations may increase (Warner 2010). Having lost their fisheries and agriculture-based livelihoods, people have in the past chosen to relocate to urban areas. A migrant to Phnom Penh from the Mekong River Delta explained, "*Flooding occurs every year at my former living place. I could not grow and harvest crops. Life therefore was very miserable. Besides, my family did not know what else we could do other than grow rice and fish. Flooding sometimes threatened our lives. So we came here to find another livelihood*" (Dun 2009: 17)

Conclusion

The key impacts that are expected to affect South East Asia at different levels of warming and sea level rise are summarized in Table 4.9.

Due to a combination of the risk factors driven by sea-level rise, increased heat extremes, and more intense tropical cyclones, critical South East Asian rice production in low lying coastal and deltaic areas is projected to be at increasing risk. Coastal livelihoods dependent on marine ecosystems are also highly vulnerable to the adverse impacts of climate change. Coral reefs, in particular, are extremely sensitive to ocean warming and acidification. Under 1.2°C warming, there is a high risk of annual bleaching events occurring (50-percent probability) in the region as early as 2030. Under 4°C warming by 2100, the likelihood is 100 percent. There are strong indications that this could have devastating impacts on tourism revenue and reef-based fisheries already under stress from overfishing. The coastal protection provided by corals reefs is also expected to suffer. In addition, warming seas and ocean acidification are projected to lead to substantial reductions in fish catch potential in the marine regions around South East Asia.

The livelihood alternative offered by aquaculture in coastal and deltaic regions would also come under threat from the impacts of sea-level rises projected to increase by up to 75 cm in a 2°C world and 105 cm in a 4°C world. Salinity intrusion associated with sea-level rise would affect freshwater and brackish aquaculture farms. In addition, increases in the water temperature may have adverse effects on regionally important farmed species (tiger shrimp and stripped catfish) as surface waters warm. Increasingly intense tropical cyclones would also impact aquaculture farming.

Migration to urban areas as a response to diminishing livelihoods in coastal and deltaic areas is already occurring. While this response may offer opportunities not available in rural areas, cities are associated with a high vulnerability to the impacts of climate change. The urban poor, who constitute large proportions of city populations in the region, would be particularly hard hit. Floods associated with sea-level rise and storm surges carry significant risks in informal settlements, where damages to sanitation and water facilities are accompanied by health threats. The high population density in such areas compounds these risks.

South East Asia as a region is characterized by a high exposure to both slow-onset impacts associated with sea-level rise, ocean warming, and acidification, and sudden-onset impacts associated with tropical cyclones. The corrosive effects of the slow-onset impacts potentially undermine resilience and increase vulnerability in the face of devastating extreme weather events. This complex vulnerability is set to increase as the world warms toward 4°C.

Table 4.9: Impacts in South East Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Regional Warming		South China Sea warmed at average rate of 0.3–0.4°C per decade since the 1960s.[2] Vietnam warmed at a rate of about 0.3°C per decade since 1971,[3] more than twice the global average rate for 1956–2005 of about 0.13°C per decade[4]		Summer warming[5] about 1.5°C[6] above the 1951–1980 baseline by the 2040s. Strongest warming expected in North Vietnam and Laos.[7] Warm nights (beyond 90th percentile in present-day climate) are projected to become the new normal[8]		Summer temperatures increase by 4.5°C.[9] Strongest warming expected in North Vietnam and Laos (5.0°C). Almost all nights (~95 percent) beyond present-day 90th percentile[10]
Heat Extremes	**Unusual Heat Extremes**	Virtually absent	About 50–60 percent of land boreal summer months (June, July August) (JJA)	About 60–70 percent of land boreal summer months (JJA)	About 85 percent of land boreal summer months (JJA)	>90 percent of land boreal summer months (JJA)
	Unprecedented Heat Extremes	Absent	About 25–30 percent of land boreal summer months (JJA)	30–40 percent of land area during boreal summer months Strongest increase Indonesia and southern Philippine islands with roughly half of summer months experiencing unprecedented heat[11]	About 70 percent of land boreal summer months (JJA)	>80 percent of land area during boreal summer months Indonesia and southern Philippine islands are projected to see the strongest increase, with all summer months experiencing unprecedented heat extremes[12]
Precipitation	**Region**			Slight increase during dry season (DJF)		Large model uncertainty regarding changes in wet season rainfall, ranging from a decrease of 5 percent to an increase of 10 percent[13]
	Extremes			Median >10 percent increase of extreme wet day precipitation share of the total annual precipitation.[14] Both minimum and maximum precipitation extremes are amplified[10]		Median >50 percent increase in extreme wet day precipitation share of the total annual precipitation[10] Both minimum and maximum precipitation extremes are amplified[10]
	Dry Days			Marginal increase in maximum number of consecutive dry days (as a measure for drought)[15]		About 5 percent increase in maximum number of consecutive dry days[16] [10]

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Table 4.9: Impacts in South East Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Drought					Increased drought (uncertain) for parts of Indonesia, Vietnam, and New Guinea[17] because of increase in precipitation is not enough to offset increase in evaporation due to strong heating	
Tropical Cyclones	**Tropical Cyclone (frequency)**		High resolution models show an overall decrease in TC frequency[18]; strongest agreement on decrease in frequency is found for the South China Sea[19]	High-resolution models show an overall decrease in TC frequency[18]; strongest agreement on decrease in frequency is found for the South China Sea.[19] Uncertainty remains: For the western North Pacific, other methods that project cyclogenesis indicate an increase in potential TC events by 10 percent[20]	High-resolution models show an overall decrease in TC frequency[18]; strongest agreement on decrease in frequency is found for the South China Sea.[19] Uncertainty remains: For the western North Pacific, other methods that project cyclogenesis indicate an increase in potential TC events by 20 percent[21]	High-resolution models show an overall decrease in TC frequency[18,21]; strongest agreement on decrease in frequency is found for the South China Sea.[19] Decrease in frequency of TCs making landfall of 35 percent for South East Asia and 10 percent for the Philippines.[22] Uncertainty remains: For the western North Pacific, other methods that project cyclogenesis indicate an increase in potential TC events by 20 percent[23]
	Tropical Cyclone (intensity)	Category 4 tropical cyclone Nargis (2008) inundated an area up to 6m above sea level in the Irrawaddy River Delta in Myanmar in 2008. A total of 2.4 million people were affected, including 800,000 people temporarily displaced, a death toll of 84,000, and 54,000 missing. Nargis also severely affected the agricultural sector. In 2011, tropical cyclone Washi, struck the island of Mindanao in the Philippines, caused 300,000 people to be displaced[24]		Global increase in storm-centered rainfall over the 21st century by between 3–37 percent[25]—also in the western North Pacific[26]	Frequency of strongest category 5 cyclones projected to increase with mean maximum surface wind speed increases of 7–18 percent. Total increased TC intensity of 1–7 percent for coastal regions, after taking into account an overall decrease in TC frequencies[27]	Maximum wind velocity at the coast is projected to increase by about 6 percent for mainland South East Asia and about 9 percent for the Philippines[22]
Sea Level Rise (above present)		About 20cm to 2010	30cm–2040s, 50cm–2060s 75cm (65–85 cm) by 2080–2100[28]	30cm–2040s, 50cm–2060s 75cm (65–85 cm) by 2080–2100	30cm–2040s, 50cm–2060 90cm (75–105 cm) by 2080–2100	30cm–2040s, 50cm–2060 110 cm (85–130 cm) by 2080–2100, lower by 5 cm around Bangkok

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Table 4.9: Impacts in South East Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Sea-level Rise Impacts	**Coastal Erosion (loss of land)**	For the south Hai Thinh commune in the Vietnamese Red River delta, about 34 percent (12 percent) of the increase of erosion rate between 1965 and 1995 (1995 and 2005) has been attributed to the direct effect of sea-level rise[29]				A significant increase in coastal erosion for the Mekong Delta[30]
	Population Exposure	20 million people in South-East Asian cities exposed to coastal flooding in 2005[31]				8.5 million more people are projected to be exposed to coastal flooding by 2100[32] for global sea-level rise of 1m, up to 22 million if a very high urbanization rate assumed.[33] In Vietnam, close to 5 million people may be displaced[34]
	City Exposure		Bangkok – For a 14cm sea-level rise in 2025, 43 percent of the city area would be flooded.[35] Manila – For a 0.29m in 2050, a 100-year return-period flood could cause damages of up to 24 percent of the city's GDP by 2050[36]; a 30-year return-period flood could generate damages of approximately 15 percent of the city's GDP		Bangkok – For a 88cm sea level rise in 2100, up to 69 percent of Bangkok area would be flooded in 2100 respectively[37]	Ho Chi Minh City – up to 60 percent of the built-up area would be exposed[38] to a 1m sea-level rise

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Table 4.9: Impacts in South East Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Salinity Intrusion		In the Mekong River Delta in 2005, Long An province's sugar cane production diminished by 5–10 percent; significant rice production in Duc Hoa district was also destroyed[39]	Low to moderate risk of saltwater intrusion into coastal groundwater resources for a 40cm sea-level rise.[40] In Mekong River Delta, with a 30cm sea-level rise the total area affected of 1.3–1.7 million ha[41]. Loss of about 4.7 percent of rice paddies in the province due to inundation and possible agricultural loss of a larger area of 294,000 hectares (about 7.2 percent of the Mekong River Delta province) due to salinity intrusion.[42]			Mahakam river region in Indonesia – increase in land area affected by 7–12 percent[43]
Ecosystem Impacts	**Coral Reefs**		At around 1.5°C warming above pre-industrial levels, about 89 percent of coral reefs are projected to experience severe bleaching.[44] By the 2030s, bleaching events approach 50 percent likelihood levels under 1.2°C warming.[45]	Up to 100 percent of coral reefs are projected to experience severe bleaching.[44] By the 2030s, bleaching events approach 50 percent likelihood levels under 1.2°C warming.[45] By the 2050s, with global mean warming of about 2°C, between 98–100 percent of coral reefs are projected to be thermally marginal.[45]	Under all concentration pathways (i.e., ranging from 2°C to above 4°C by the end of the century), virtually every coral reef in South East Asia would experience severe thermal stress by year 2050 under warming levels of 1.5°C–2°C above pre-industrial levels.[45] By the 2030s, bleaching events approach 70 percent likelihood levels under 1.5°C warming.[45]	Under 4°C warming, in 2100 virtually all coral reefs would be subject to severe bleaching events annually.[45] Under all concentration pathways (i.e., ranging from 2°C to above 4°C by the end of the century), virtually every coral reef in South East Asia would experience severe thermal stress by year 2050 under warming levels of 1.5°C–2°C above pre-industrial levels.[45] By the 2030s, bleaching events approach 70 percent likelihood levels under 1.5°C warming.[45]
	Coastal Wetlands					Coastal wetland area decreases from 109,000 km^2 to 76,000 km^2 (about 30 percent) between 2010 and 2100.[46] Vietnam – Loss of 8,533 square kilometres of freshwater marsh (65 percent loss). Philippines – Loss of 229 square kilometres (about 100 percent of the current surface) of lakes and wetlands by 2100.[47]

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Table 4.9: Impacts in South East Asia

Risk/Impact	Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Aquaculture	Between 1996 and 2011, fishing output in Vietnam was multiplied by 13 and its share of GDP from fishing and aquaculture increased from 5.9–8.1 percent[48]	Estimations of the costs of adapting[49] aquaculture in SEA range from $130 million per year for the period 2010–2050 to $190.7 million per year for the period 2010–2020.[50] In their study, Kam et al.[51] identify coastal flooding and salinity intrusion driven by sea-level rise as the main threats to aquaculture	Estimations of the costs of adapting aquaculture in SEA range from $130 million per year for the period 2010–2050[52] to $190.7 million per year for the period 2010–2020[53]		
Marine Fisheries	According to the FAO *Fishery Country Profile*,[54] fishery exports in Vietnam in 2004 amounted to $2.36 billion and 90 percent of commercial landings came from offshore fisheries. Exports of overall fish and fishery products in the Philippines amounted to $525.4 million		A 50 percent decrease in maximum catch potential around the southern Philippines and a 16 percent decrease in the waters of Vietnam to 6–16 percent increases around the northern Philippines[55]		Markedly negative trend in bigeye tuna[56]
Poverty		The relative risk of diarrhea is expected to increase 5–11 percent for the period 2010–2039 in South East Asia relative to 1961–1990[57]	The relative risk of diarrhea is expected to increase 5–11 percent for the period 2010–2039 in South East Asia relative to 1961–1990	The relative risk of diarrhea is expected to increase 5–11 percent for the period 2010–2039 and 13–31 percent for the period 2070–2099 in South East Asia relative to 1961–1990	
Tourism			Thailand, Indonesia, the Philippines, Myanmar, and Cambodia rank among the most vulnerable tourism destinations when sea-level rise, extreme weather events, and biodiversity losses are taken into account[58]		

Notes to Table 4.9

[1] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario, not in mitigation scenarios limiting warming to these levels, or below, since in that case the year of exceeding would always be 2100, or not at all.
[2] Tangang, Juneng, & Ahmad (2006).
[3] (Nguyen, Renwick, and McGregor (2013).
[4] Trenberth et al. (2007).
[5] The expected future warming is large compared to the local year-to-year natural variability. In a 2°C world, this shift is substantially smaller but still about 3–4 standard deviations.
[6] Model spread from 1.0°C to 2.0°C.
[7] Multimodel mean projecting up to 2°C under 2°C warming by 2071–2099.
[8] Occurrence probability around 60 (Sillmann & Kharin 2013).
[9] CMIP5 model range from 3.5°C to 6°C by 2100. The expected future warming is large compared to the local year-to-year natural variability. In a 4°C world, the monthly temperature distribution of almost all land areas in South East Asia shifts by 6 standard deviations or more toward warmer values.
[10] Sillmann and Kharin (2013), RCP8.5.
[11] Beyond 5-sigma under 2°C warming by 2071–2099.
[12] Beyond 5-sigma under 4°C warming by 2071–2099.
[13] Jourdain, Gupta, Taschetto, et al (2013).
[14] Sillmann and Kharin (2013).
[15] Sillmann and Kharin (2013), RCP2.6.
[16] Sillmann and Kharin (2013), RCP8.5.
[17] Dai (2011); (Dai (2012) using the RCP4.5 scenario.
[18] Held and Zhao (2011); Murakami, Wang, et al. (2012).
[19] Held and Zhao, (2011); Murakami, Sugi, and Kitoh (2012); Yokoi and Takayabu (2009)
[20] Caron and Jones (2007)the main large-scale climatic fields controlling tropical cyclone (TC.
[21] Caron and Jones (2007)the main large-scale climatic fields controlling tropical cyclone (TC.
[22] Murakami, Wang, and Kitoh (2011).
[23] Caron and Jones (2007)the main large-scale climatic fields controlling tropical cyclone (TC.
[24] Government of the Philippines (2012).
[25] Knutson et al. (2010).
[26] Rate of increase depends on the specific climate model used (Emanuel, Sundararajan, and Williams 2008).
[27] Murakami, Wang, et al. (2012). Future (2075–99) projections SRES A1B scenario.
[28] For a scenario in which warming peaks above 1.5°C around the 2050s and drops below 1.5°C by 2100. Due to slow response of oceans and ice sheets, the sea-level response is similar to a 2°C scenario during the 21st century, but deviates from it after 2100.
[29] (Duc, Nhuan, & Ngoi, 2012)
[30] 1m sea-level rise by 2100 (Mackay and Russell 2011).
[31] Brecht et al. (2012). In this study, the urban population fraction is held constant over the 21st century.
[32] Brecht et al. (2012). In this study, the urban population fraction is held constant over the 21st century.
[33] Hanson et al. (2011).
[34] Due to permanent floods and other climate-change-related impacts conducting [leading?] to deltaic and coastal areas submergence (Carew-Reid 2008).
[35] Dutta (2011).
[36] Muto et al. (2010).
[37] Dutta (2011).
[38] Storch and Downes (2011). In the absence of adaptation, the planned urban development for the year 2025 contributes to increase Ho Chi Minh City's exposure to sea-level rise by 17 percent.
[39] MoNRE (2010) states, "Sea-level rise, impacts of high tide, and low discharge in dry season contribute to deeper salinity intrusion. In 2005, deep intrusion (and more early than normal), high salinity, and long-lasting salinization occurred frequently in Mekong Delta provinces."
[40] Ranjan, Kazama, Sawamoto, and Sana (2009) assume a global sea-level rise of about 40cm above 2000 levels by 2100.
[41] World Bank (2010b).
[42] Without adaptation measures, rice production may in consequence decline by approximately 2.6 million tons per year, assuming 2010 rice productivity. This would represent a direct economic loss in export revenue of $1,22 billion, based on 2011 prices (World Bank 2010b).
[43] Under 4°C warming and 100m sea-level rise by 2100 (Mcleod et al. 2010).
[44] Frieler et al. (2012).
[45] Meissner et al. (2012).
[46] 100m sea-level rise (Mcleod et al. 2010).
[47] Blankespoor, Dasgupta, and Laplante (2012). The region could lose approximately $296.1–368.3 million per year in economic value (2000 U.S. dollars).
[48] (General Statistics Office of Vietnam 2012)
[49] Raising pond dikes and water pumping.
[50] World Bank (2010b) projections were calculated from a set 21 global models in the multimodel ensemble approach from 1980–99 and 2080–99 under the IPCC A1B scenario, corresponding to a 2.8°C temperature increase globally (3.3°C above pre-industrial levels).
[51] Kam, Badjeck, Teh, Teh, and Tran (2012).
[52] (World Bank, 2010b)For the World Bank study, projections were calculated from a set 21 global models in the multi-model ensemble approach from 1980–99 and 2080–99 under the IPCC A1B scenario, corresponding to a 2.8°C temperature increase globally (3.3°C above pre-industrial levels).
[53] Kam, Badjeck, Teh, Teh, and Tran (2012).
[54] http://www.fao.org/fishery/countrysector/FI-CP_VN/en.
[55] Maximum catch potential (Cheung et al. 2010).
[56] Lehodey et al. (2010). In a 4°C world, conditions for larval spawning in the western Pacific are projected to have deteriorated due to increasing temperatures to the benefit of subtropical regions. Overall adult mortality is projected to increase, leading to a markedly negative trend in biomass by 2100.
[57] Kolstad and Johansson (2011) derived a releationship between diarrhea and warming based on earlier studies (Scenario A1B).
[58] Perch-Nielsen (2009). Assessment allows for adaptive capacity, exposure, and sensitivity in a 2°C warming and 50cm SLR scenario for the period 2041–2070.

Chapter 5

South Asia: Extremes of Water Scarcity and Excess

REGIONAL SUMMARY

In this report, South Asia refers to a region comprising seven countries[82] with a growing population of about 1.6 billion people in 2010, which is projected to rise to over 2.2 billion by 2050. At 4°C global warming, sea level is projected to rise over 100 cm by the 2090s, monsoon rainfall to become more variable with greater frequency of devastating floods and droughts. Glacier melting and snow cover loss could be severe, and unusual heat extremes in the summer months (June, July, and August) are projected to affect 70 percent of the land area. Furthermore, agricultural production is likely to suffer from the combined effects of unstable water supply, the impacts of sea-level rise, and rising temperatures. The region has seen robust economic growth in recent years, yet poverty remains widespread and the combination of these climate impacts could severely affect the rural economy and agriculture. Dense urban populations, meanwhile, would be especially vulnerable to heat extremes, flooding, and disease.

Current Climate Trends and Projected Climate Change to 2100

South Asia has a unique and diverse geography dominated in many ways by the highest mountain range on Earth, the Himalayan mountain range and Tibetan Plateau, giving rise to the great river systems of the Indus, Ganges, and Brahmaputra. The climate of the region is dominated by the monsoon: The largest fraction of precipitation over South Asia occurs during the summer monsoon season. Eighty percent of India's rainfall, for example, occurs in this period. The timely arrival of the summer monsoon, and its regularity, are critical for the rural economy and agriculture in South Asia.

Under future climate change, the frequency of years with above normal monsoon rainfall and of years with extremely deficient rainfall is expected to increase. The Ganges, Indus, and Brahmaputra—are vulnerable to the effects of climate change due to the melting of glaciers and loss of snow cover. The result

[82] Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka. This follows the SREX regional definition and hence does not include Afghanistan. Some of the studies reviewed in the report however include Afghanistan, and less frequently Iran or Turkey, in their assessment for South Asia.

is a significant risk to stable and reliable water resources for the region, with increases in peak flows associated with the risk of flooding and dry season flow reductions threatening agriculture.

In the past few decades a warming trend has begun to emerge over South Asia, particularly in India, which appears to be consistent with the signal expected from human induced climate change. Recent observations of total rainfall amounts during the monsoon period indicate a decline in rainfall, likely due to the effects of anthropogenic aerosols, particularly black carbon. In addition to these patterns there are observed increases in the frequency of the most extreme precipitation events, as well as increases in the frequency of short drought periods.

Rainfall

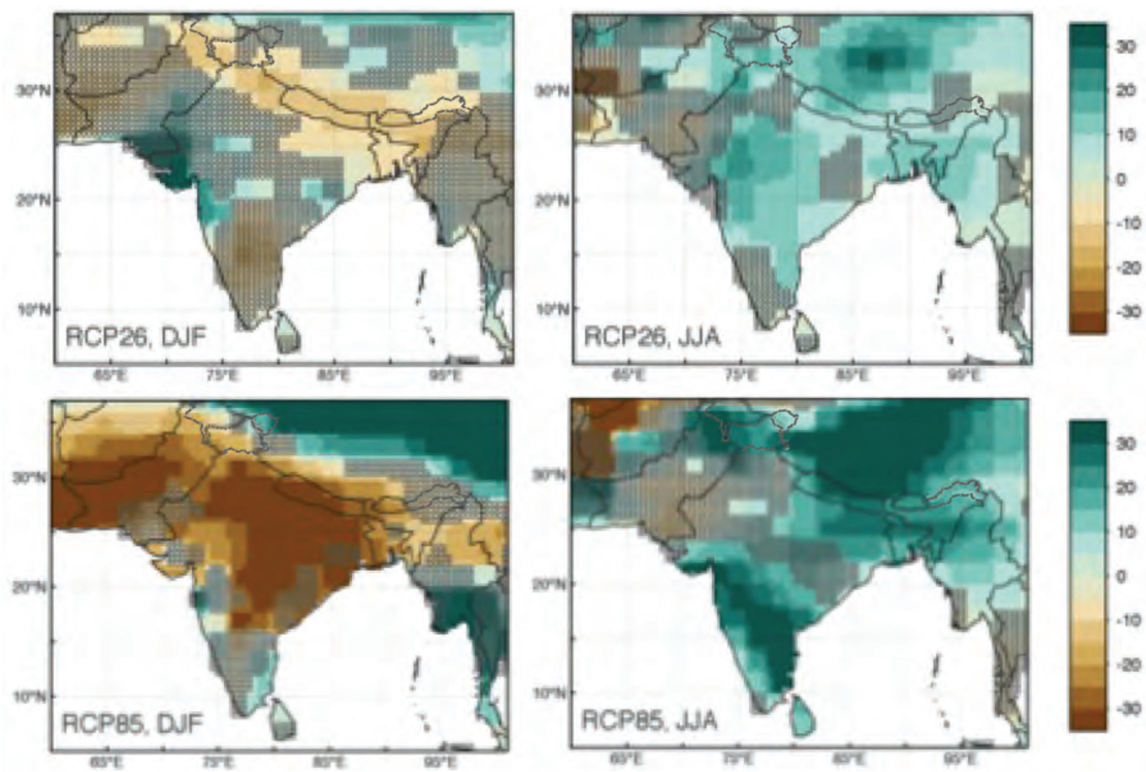
During recent decades, increases in the frequency of the most extreme precipitation events have been observed. Annual precipitation is projected to increase by up to 30 percent in a 4°C world. The seasonal distribution of precipitation is expected to become amplified, with a decrease of up to 30 percent during the dry season and a 30 percent increase during the wet season.

Temperature

In a 4°C world, South Asian summer temperatures are projected to increase by 3°C to nearly 6°C by 2100, with the warming most pronounced in Pakistan. The pattern remains the same in a 2°C world, with warming reaching 2°C in the northwestern parts of the region and 1°C to 2°C in the remaining regions. By the time 1.5°C warming is reached, heat extremes that are unusual or virtually absent in today´s climate in the region are projected to cover 15 percent of land areas in summer.

Under 2°C warming, unusual extreme heat over 20 percent of the land area is projected for Northern Hemisphere summer months, with unprecedented heat extremes affecting about 5 percent of the land area, principally in the south. Under 4°C warming, the west coast and southern India, as well as Bhutan and northern Bangladesh, are projected to shift to new, high-temperature climatic regimes. Unusual heat is projected for 60–80 percent of the Northern Hemisphere summer months in most parts of the region. Some regions are projected to experience unprecedented heat during more than half of the summer months, including Sri Lanka and Bhutan. In the longer term, the exposure of South Asia

Figure 5.1: South Asia Multi-model mean of the percentage change dry-season (DJF, left) and wet-season (JJA, right) precipitation for RCP2.6 (2°C world; top) and RCP8.5 (4°C world; bottom) for South Asia by 2071–2099 relative to 1951–1980



Hatched areas indicate uncertainty regions with 2 out of 5 models disagreeing on the direction of change compared to the remaining 3 models.

Table 5.1: Summary of climate impacts and risks in South Asia[a]

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C[b] (2030s[c])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C (2080s)
Regional warming		2011 Indian temperature 9th warmest on record. 2009 warmest at 0.9°C above 1961–90 average		Warm spells lengthen to 20–45 days. Warm nights occur at frequency of 40 percent		Warm spells lengthen to 150–200 days. Warm nights occur at frequency of 85 percent
Heat extremes (in the Northern Hemisphere summer)[d]	Unusual heat extremes	Virtually absent	15 percent of land	20 percent of land	>50 percent of land	>70 percent of land In south almost all summer months unusually hot
	Unprecedented heat extremes	Absent	Virtually absent	<5 percent of land	20 percent of land	>40 percent of land
Precipitation (including the monsoon)		Decline in South Asian monsoon rainfall since the 1950s but increases in frequency of most extreme precipitation events	Change in rainfall uncertain	Change in rainfall uncertain; 20 percent increase of extreme wet day precipitation share of the total annual precipitation[e]	About 5 percent increase in summer (wet season) rainfall	About 10 percent increase in summer (wet season) rainfall. Intra seasonal variability of monsoon rainfall increased, by about 15 percent. 75 percent increase of extreme wet day precipitation share of total annual precipitation[f]
Drought		Increased frequency short droughts			Increased drought over north-western parts of the region, particularly Pakistan	Increased length of dry spells measured by consecutive dry days in eastern India and Bangladesh
Sea-level rise above current:		About 20 cm to 2010	30cm–2040s 50cm–2070 70 cm by 2080–2100	30cm–2040s 50cm–2070 70cm by 2080–2100	30cm–2040s 50cm–2060 90cm by 2080–2100	30cm–2040s 50cm–2060 105cm by 2080–2100, Maldives 10cm higher

[a] A more comprehensive table of impacts and risks for SEA is presented at the end of Chapter 5.
[b] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario exceeding 4°C by the 2080s.
[c] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario exceeding 4°C by the 2080s.
[d] Mean across climate model projections is given. Illustrative uncertainty range across the models (minimum to maximum) for 4°C warming are 70–100 percent for unusual extremes, and 30–100 percent for unprecedented extremes. The maximum frequency of heat extreme occurrence in both cases is close to 100 percent, as indicator values saturate at this level.
[e] 50 percent uncertainty range 8–12 percent.
[f] 50 percent uncertainty range 65–85 percent.

to an increase in these extremes could be substantially limited by holding warming below 2°C.

Likely Physical and Biophysical Impacts as a Function of Projected Climate Change

The projected changes in rainfall, temperature, and extreme event frequency and/or intensity would have both direct and indirect impacts on monsoon activity, droughts, glacial loss, snow levels, river flow, ground water resources, and sea-level rise.

Monsoon

While most modeling studies project increases in average annual monsoonal precipitation over decadal timescales, they also project significant increases in inter-annual and intra-seasonal variability.

For global mean warming approaching 4°C, a 10 percent increase in annual mean monsoon intensity and a 15 percent increase in year-to-year variability of Indian summer monsoon precipitation is projected compared to normal levels during the first half of the 20th century. Taken together, these changes imply that an extreme wet monsoon that currently has a chance of occurring only once in 100 years is projected to occur every 10 years by the end of the century.

A series of unusually intense monsoonal rainfall events in the mountainous catchment of the Indus River was one of the main physical drivers of the devastating Pakistan floods of 2010, which resulted in more than 1,900 casualties and affected more than 20 million people. Farms and key infrastructure, such as bridges, were washed away in the predominantly rural areas affected. The rainfall event itself was only the start of a chain of events that led to prolonged and wide-scale flooding downstream, with many other factors due to human activity. Irrigation dams, barrages, river embankments, and diversions in the inland basins of rivers can seriously exacerbate the risk of flooding downstream from extreme rainfall events higher up in river catchments.

Large uncertainty remains about the behavior of the Indian summer monsoon under global warming. An abrupt change in the monsoon, for example, toward a drier, lower rainfall state, could precipitate a major crisis in South Asia, as evidenced by the anomalous monsoon of 2002, which caused the most serious drought in recent times (with rainfall about 209 percent below the long-term normal and food grain production reductions of about 10–15 percent compared to the average of the preceding decade). Physically plausible mechanisms have been proposed for such a switch, and changes in the tropical atmosphere that could precipitate a transition of the monsoon to a drier state are projected in the present generation of climate models.

Droughts

The projected increase in seasonality of precipitation is associated with an increase in the number of dry days and droughts with adverse consequences for human lives. Droughts are expected to pose an increasing risk in parts of the region, particularly Pakistan, while increasing wetness is projected for southern India. The direction of change is uncertain for northern India. Of the ten most severe drought disasters globally in the last century, measured in terms of the number of people affected, six were in India, affecting up to 300 million people. For example, the Indian droughts of 1987 and 2002/2003 affected more than 50 percent of the crop area in the country and, in 2002, food grain production declined by 29 million tons compared to the previous year. It is estimated that in the states of Jharkhand, Orissa, and Chhattisgarh, major droughts, which occur approximately every five years, negatively impact around 40 percent of agricultural production.

Glacial Loss, Snow Cover Reductions, and River Flow

Over the past century most of the Himalayan glaciers have been retreating. Currently, 750 million people depend on the glacier-fed Indus and Brahmaputra river basins for freshwater resources, and reductions in water availability could significantly reduce the amount of food that can be produced within the river basins. These rivers depend heavily on snow and glacial melt water, which makes them highly susceptible to climate-change-induced glacier and snowmelt. Warming projections of about 2.5°C above pre-industrial levels by the 2050s indicate the risk of substantial reductions in the flow of the Indus and Brahmaputra in summer and late spring, after a period with increased flow. The availability of water for irrigation is very much contingent on these water resources, particularly during the dry seasons.

- An increased river flow in spring is projected due to stronger glacial melt and snowmelt, with less runoff available prior to monsoon onset in late spring and summer.
- For the Indus River Delta, high flow is projected to increase by about 75 percent for warming above 2°C. Higher peak river flows expose a growing number of people inhabiting the densely populated river deltas of the regions to the combined risks of flooding, sea-level rise, and increasing tropical cyclone intensity.

Groundwater Resources

Groundwater resources, which are mainly recharged by precipitation and surface-water, are also expected to be impacted by climate change. South Asia, especially India and Pakistan, are highly sensitive to decreases in groundwater recharge as these countries are already suffering from water scarcity and largely depend on a supply of groundwater for irrigation. In India, for example, 60 percent of irrigation depends on groundwater, while about 15 percent of the country's groundwater tables are overexploited, including the Indus basin. Groundwater resources are particularly important to mitigate droughts and related impacts on agriculture and food security. With increased periods of low water availability and dry spells projected, it is likely that groundwater resources will become even more important for agriculture, leading to greater pressure on resources. Projected increases in the variability and seasonality of monsoon rainfall may affect groundwater recharge during the wet season and lead to increased exploitation during the dry season.

Sea-level Rise

With South Asian coastlines being located close to the equator, projections of local sea-level rise show a greater increase compared to higher latitudes. Sea-level rise is projected to be approximately 100–115 cm by the 2090s in a 4°C world, and 60–80 cm in a 2°C world, by the end of the 21st century relative to 1986–2005, with the highest values (up to 10 cm more) expected for the Maldives. This is generally around 5–10 percent higher than the global mean, and a 50 cm sea-level rise would likely occur by 2060.

Sector-based and Thematic Impacts

Water Resources are already at risk in the densely populated countries of South Asia, according to most studies that assess this risk. One study indicates that for a warming of about 3°C above pre-industrial levels by the 2080s, it is very likely that per capita water availability will decrease by more than 10 percent due to a combination of population increase and climate change in South Asia. Even for 1.5–2°C warming, major investments in water storage capacity would be needed in order to utilize the potential benefits of increased seasonal runoff and compensate for lower dry seasons flows, to allow improved water availability throughout the year.

The quality of freshwater is also expected to suffer from potential climate impacts. Sea-level rise and storm surges in coastal and deltaic regions would lead to saltwater intrusion degrading groundwater quality. Contamination of drinking water by saltwater intrusion may cause an increasing number of diarrhea cases. Cholera outbreaks may also become more frequent as the bacterium that causes cholera, *vibrio cholerae*, survives longer in saline water. About 20 million people in the coastal areas of Bangladesh are already affected by salinity in their drinking water.

Crop Yields are vulnerable to a host of climate-related factors in the region, including seasonal water scarcity, rising temperatures, and salinity intrusion due to sea-level rise. Rising temperatures and changes in rainfall patterns have contributed to reduced relative yields of rice, the most important crop in Asia, especially in rainfed areas. Cultivated crops have been observed to also be sensitive to rising temperatures. One study finds that compared to calculations of potential yields without historic trends of temperature changes since the 1980s, rice and wheat yields have declined by approximately 8 percent for every 1°C increase in average growing-season temperatures. Another study found that the combination of warmer nights and lower precipitation at the end of the growing season has caused a significant loss of rice production in India: yields could have been almost 6-percent higher without the historic change in climatic conditions.

While overall yields have increased over the last several decades, in the last decade worrying signs have emerged of crop yield stagnation on substantial areas of Indian cropland. The projected increase in extreme heat affecting 10 percent of total land area by 2020 and 15 percent by 2030 poses a high risk to crop yields. Crop yields are projected to decrease significantly for warming in the 1.5–2.0°C range; if there is a strong CO_2 fertilization effect, however, the negative effects of warming might be offset in part by low-cost adaptation measures. Above about 2°C warming above pre-industrial levels, crop yields are projected to decrease around 10–30 percent for warming of 3–4.5°C, with the largest reductions in the cases where the CO_2 fertilization effect is weak.

Total Crop Production without climate change is projected to increase significantly (by 60 percent) in the region and be under increased price pressure and a trend factor expressing technological improvements, research and development, extension of markets, and infrastructure. Under 2°C warming by the 2050s, the increase may be reduced by at least 12 percent, requiring more than twice the imports to meet per capita demand than is required without climate change. As a result, per-capita calorie availability is projected to decrease significantly. Decreasing food availability can lead to significant health problems in affected populations, including childhood stunting, which is projected to increase by 35 percent by 2050 compared to a scenario without climate change.

Energy Security is expected to come under increasing pressure from climate-related impacts to water resources. The two dominant forms of power generation in the region are hydropower and thermal power generation (e.g., fossil fuel, nuclear, and concentrated solar power), both of which can be undermined by inadequate water supplies. Thermal power generation may also be affected through pressure placed on cooling systems by increases in air and water temperatures.

Integrated Synthesis of Climate Change Impacts in the South Asia Region

Water resource dynamics: Many of the climate risks and impacts that pose potential threats to populations in the South Asia region can be linked back to changes to the water cycle—extreme rainfall, droughts, and declining snow fall and glacial loss in the Himalayas leading to changes in river flow—combined in the coastal regions with the consequences of sea-level rise and increased tropical cyclone intensity. Increasing seasonality of precipitation as a loss of snow cover is likely to lead to greater levels of flooding, and higher risks of dry periods and droughts. Exacerbating these risks are increases in extreme temperatures, which are already observed to adversely affect crop yields. Should these trends and patterns continue, substantial yield reductions can be expected in the near and midterm. Changes in projected rainfall amounts and geographical distribution are likely to have profound impacts on agriculture, energy, and flood risk.

The region is highly vulnerable even at warming of less than 2°C given the significant areas affected by droughts and flooding at present temperatures. In addition, the projected risks to crop yields and water resources, and sea-level rise reaching 70 cm by the 2070s, are likely to affect large populations.

Deltaic Regions and Coastal Cities are particularly exposed to cascading risks resulting from a combination of climatic changes, including increased temperature, increased river flooding, rising sea levels, and increasingly intense tropical cyclones and their consequences. Deaths in India and Bangladesh currently account for 86 percent of global mortalities from cyclones even though only 15 percent of all tropical cyclones affect this region.

- ***Bangladesh*** emerges as an impact hotspot with increasing and compounding challenges occurring in the same timeframe from extreme river floods, more intense tropical cyclones, rising sea levels, extraordinarily high temperatures, and declining crop yields. Increased river flooding combined with tropical cyclone surges poses a high risk of inundation in areas with the largest shares of poor populations. A 27 cm sea-level rise, projected for the 2040s, in combination with storm surges from an average 10-year return period cyclone, such as Cyclone Sidr, could inundate an area more than 80-percent larger than the area inundated at present by a similar event.
- ***Kolkata*** and ***Mumbai*** are highly vulnerable to the impacts of sea-level rise, tropical cyclones, and riverine flooding. Floods and droughts are associated with health impacts, including diarrheal diseases, which at present are a major cause of child mortality in Asia and the Pacific.

Climate change shocks to seasonal water availability would confront populations with ongoing and multiple challenges to accessing safe drinking water, sufficient water for irrigation, and adequate cooling capacity for thermal power production.

Irrespective of future emission paths, in the next 20 years a several-fold increase in the frequency of unusually hot and extreme summer months can be expected from warming already underway. A substantial increase in excess mortality is expected to be associated with such heat extremes and has been observed in the past.

Increasing risks and impacts from extreme river floods, more intense tropical cyclones, rising sea levels, and extraordinarily high temperatures are projected. Population displacement, which already periodically occurs in flood-prone areas, is likely to continue to result from severe flooding and other extreme events. Agricultural production is likely to suffer from the combined effects of rising temperatures, impacts on seasonal water availability, and the impacts of sea-level rise.

Future economic development and growth will contribute to reducing the vulnerability of South Asia's large and poor populations. Climate change projections indicate, however, that high levels of vulnerability are projected and their societal implications indicate that high levels of vulnerability are likely to remain and persist. Warming is projected to significantly slow the expected reduction in poverty levels. Many of the climate change impacts in the region pose a significant challenge to development, even with relatively modest warming of 1.5–2°C. Major investments in infrastructure, flood defense, and development of high temperature and drought resistant crop cultivars, and major improvements in such sustainability practices as groundwater extraction, would be needed to cope with the projected impacts under this level of warming.

Introduction

This report defines the South Asian region as Bangladesh, Bhutan, India, Nepal, the Maldives, Pakistan, and Sri Lanka. For the projections of temperature and precipitation changes, heat extremes, and sea-level rise presented here, South Asia is defined as ranging from 61.25 to 99.25°E and 2.25 to 30.25°N.[83]

Although economic growth in South Asia has been robust in recent years, poverty remains widespread and the world's largest concentration of poor people reside in the region. The unique geography of the region plays a significant part in shaping the livelihoods of South Asians. Agriculture and the rural economy are largely dependent on the timely arrival of the Asian summer monsoon. The Hindu Kush and Himalaya mountains to the north contain the reach of the monsoon, thereby confining its effects to the subcontinent and giving rise to the great river systems of the Indus and Ganges-Brahmaputra.

The populations of South Asia are already vulnerable to shocks in the hydrological regime. Poverty in the Bay of Bengal region, for example, is already attributed in part to such environmental factors as tropical cyclones and seasonal flooding. Warming toward 4°C, which is expected to magnify these and other stressors, would amplify the challenge of poverty reduction in South Asia (Box 5.1). These risk factors include:

- Increases in temperatures and extremes of heat
- Changes in the monsoon pattern
- Increased intensity of extreme weather events, including flooding and tropical cyclones
- Sea-level rise

These physical impacts and their effects on a number of sectors, including agriculture, water resources, and human health, will be reviewed in this analysis. Not all potential risks and affected sectors are covered here as some (e.g., ecosystem services) fall outside the scope of this report.

Regional Patterns of Climate Change

A warming trend has begun to emerge over South Asia in the last few decades, particularly in India, and appears to be consistent

83 Impact assessments pertaining to water resources, droughts and health impacts include Afghanistan.

Box 5.1: Observed Vulnerabilities

Observed Vulnerability – Floods

The 2010 flash flood in Pakistan is an example of an extreme event of unprecedented severity and illustrates the challenges South Asia faces (UNISDR 2011). Unusually intense monsoonal rainfall in the mountainous catchment of the Indus River was one of the main physical drivers of the devastating flood (P. Webster, Toma, and Kim 2011). The flood caused more than 1,900 casualties, affected more than 20 million people, and resulted in $9.5 billion in economic damages—the highest number of people affected and the largest price tag ever for a natural disaster in Pakistan (EM-DAT 2013, based on data from 1900–2013). Homes, farms, and such key infrastructure as bridges were washed away in the predominantly rural area affected (UNISDR 2011).

Observed Vulnerability – Droughts

Losses induced by past droughts highlight current South Asian vulnerability to droughts. Of the 10 most severe drought disasters globally in the last century, measured in terms of the number of people affected, six took place in India; these affected up to 300 million people (in 1987 and 2002; 1900–2013 data based on EM-DAT 2013). In India, the droughts of 1987 and 2002–2003 affected more than 50 percent of the crop area in the country (Wassmann, Jagadish, Sumfleth, et al. 2009); in 2002, food grain production declined by 29 million tons compared to the previous year (UNISDR 2011). Major droughts in the states of Jharkhand, Orissa, and Chhattisgarh, which occur approximately every five years, are estimated to affect around 40 percent of rice production, an $800 million loss in value (Wassmann, Jagadish, Sumfleth, et al. 2009).

with the signal expected from human-induced climate change (Kumar et al 2010).

Recent observations of total rainfall amounts during the monsoon period indicate a decline in the last few decades. While some earlier studies find no clear trend in the all-India mean monsoon rainfall (Guhathakurta and Rajeevan 2008; R. Kripalani, Kulkarni, Sabade, and Khandekar 2003),[84] more recent studies indicate a decline of as much as 10 percent in South Asian monsoon rainfall since the 1950s (Bollasina, Ming, and Ramaswamy 2011; Srivastava, Naresh Kumar, and Aggarwal 2010; A. G. Turner and Annamalai 2012; Wang, Liu, Kim, Webster, and Yim 2011).[85] The data also note a downward trend in rainfall during monsoon and post-monsoon seasons in the basins of the Brahmaputra and Barak rivers in the state of Assam in Northeast India for the time period 1901–2010; this trend is most pronounced in the last 30 years (Deka, Mahanta, Pathak, Nath, and Das 2012). While the observed decline is inconsistent with the projected effects of global warming, there are indications that the decline could be due at least in part to the effects of black carbon and other anthropogenic aerosols (A. G. Turner and Annamalai 2012).

Within this overall picture, important changes have been observed in the structure and processes of precipitation events in the monsoon region. Most rainfall during the monsoon period comes from moderate to heavy rainfall events, yet recent studies indicate a decline in the frequency of these events from the 1950s to the present (P. K. Gautam 2012;[86] R. Krishnan et al. 2012), consistent with observations of changes in monsoon physics.[87] These trends are in accordance with very high resolution modeling (20 km resolution) of the future effects of greenhouse gases and aerosols on the Indian monsoon (R. Krishnan et al. 2012).

In addition to these patterns, there are observed increases in the frequency of the most extreme precipitation events (R. Gautam, Hsu, Lau, and Kafatos 2009; P. K. Gautam, 2012) and in the frequency of short drought periods (Deka et al. 2012). Deka et al. (2012) attribute this to a superposition of the effects of global warming on the normal monsoon system. They argue that these changes "indicate a greater degree of likelihood of heavy floods as well as short spell droughts. This is bound to pose major challenges to agriculture, water, and allied sectors in the near future." Over northern India, the 20th century has witnessed a trend toward increasingly frequent extreme rain events attributed to a warming atmosphere (N. Singh and Sontakke 2002; B. N. Goswami, Venugopal, Sengupta, Madhusoodanan, and Xavier 2006; Ajayamohan and Rao 2008).

Extreme rainfall events over India show wide spatial variability, with more extreme events occurring over the west coast and central and northeast India (Pattanaik and Rajeevan 2009). The frequency and intensity of extreme rainfall events over central India show a rising trend under global warming, whereas the frequency of moderate events show a significant decreasing trend (B. N. Goswami, Venugopal, Sengupta, Madhusoodanan, and Xavier 2006).

84 Even though there is no overall rainfall trend in in India, several smaller regions within the country show significant increasing and decreasing trends (Guhathakurta and Rajeevan 2008; K. R. Kumar, Pant, Parthasarathy, and Sontakke 1992).

85 Although most studies agree on the existence of this decrease, its magnitude and significance are highly dependent on the sub-region on which the analysis is performed and the dataset that is chosen (A. G. Turner and Annamalai 2012).

86 Gridded observational data for Central India show a decrease in moderate (5–100 mm/day) rainfall events.

87 APHRODITE observational dataset shows that the frequency of moderate-to-heavy rainfall events (i.e., local rainfall amounts between the 75th and 95th percentile) during the summer monsoon season has decreased between 1951–2010. For the same time period, parallel changes in the rising branch of the meridional overturning circulation of the South Asian Monsoon from NCEP reanalysis data are observed with a decrease in the variability of the inter-annual vertical velocity.

Projected Temperature Changes

A 2°C world shows substantially lower average warming over the South Asian land area than would occur in a 4°C world. Figure 5.2 shows the projected boreal summer the months of June, July, and August (JJA) warming over the Indian subcontinent for RCP2.6 and RCP8.5 scenarios. Summer warming in India is somewhat less strong than that averaged over the total global land area, with temperatures peaking at about 1.5°C above the 1951–80 baseline by 2050 under RCP2.6. Under RCP8.5, warming increases until the end of the century and monthly Indian summer temperatures reach about 5°C above the 1951–80 baseline by 2100 in the multimodel mean. Geographically, the warming occurs uniformly, though inland regions warm somewhat more in absolute terms (see Figure 5.3). Relative to the local year-to-year natural variability, the pattern is reversed—with coastal regions

Figure 5.2: Temperature projections for South Asian land area for the multi-model mean (thick line) and individual models (thin lines) under scenarios RCP2.6 and RCP8.5 for the months of JJA

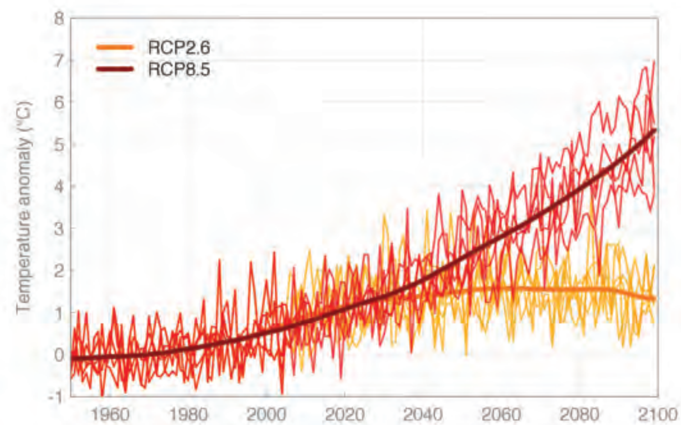
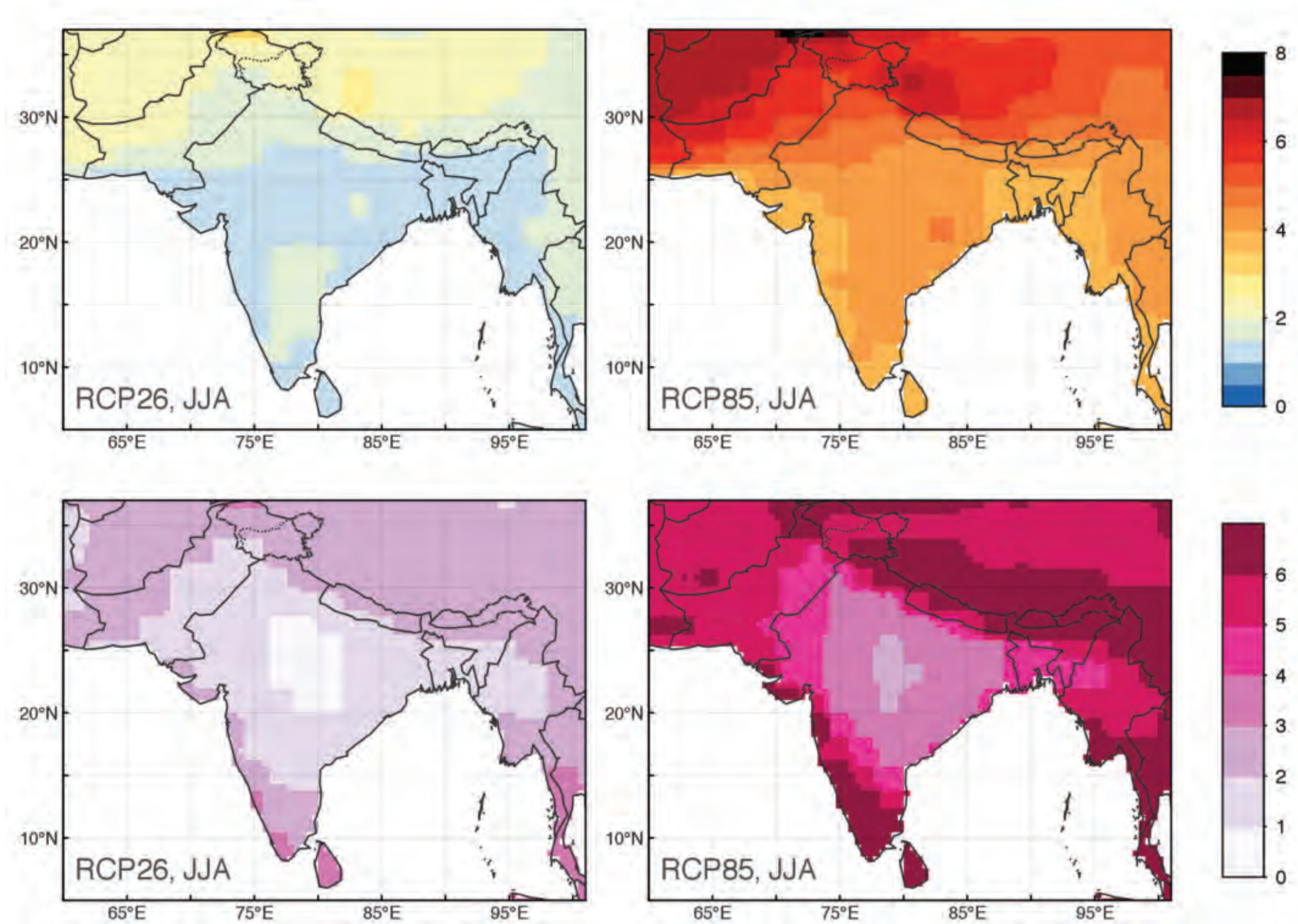


Figure 5.3: Multi-model mean temperature anomaly for RCP2.6 (left) and RCP8.5 (right) for the months of JJA for South Asia. Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–99 relative to 1951–80, and normalized by the local standard deviation (bottom row)



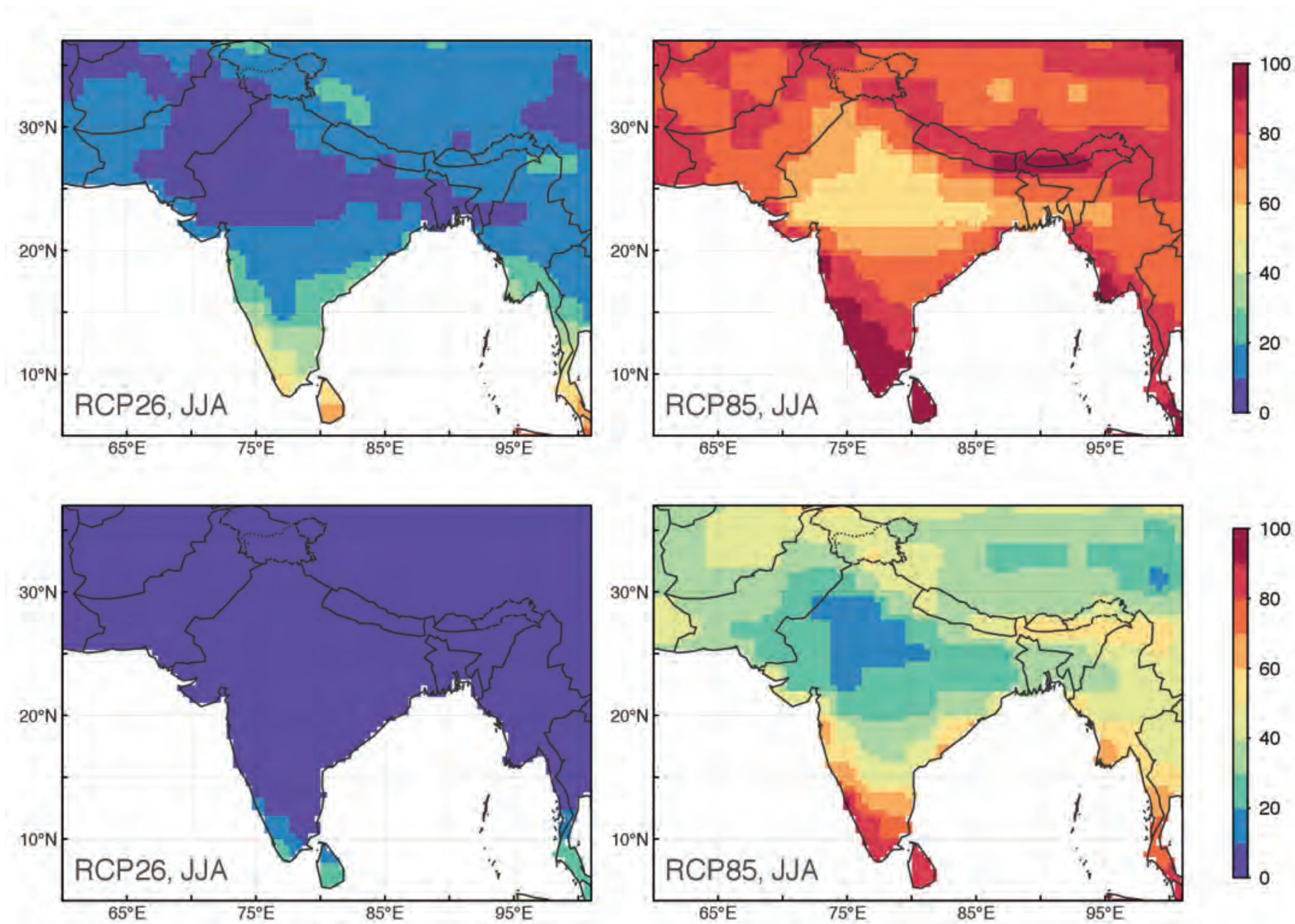
warming more, especially in the southwest (see Figure 5.3). In a 4°C world, the west coast and southern India, as well as Bhutan and northern Bangladesh, shift to new climatic regimes, with the monthly temperature distribution moving 5–6 standard deviations toward warmer values.

These projections are consistent with other assessments based on CMIP3 models. For example, Kumar et al. (2010) project a local warming in India of 2°C by mid-century and 3.5°C above the 1961–90 mean by the end of the 21st century. These local estimates come with considerable uncertainty; there is high confidence, however, that temperature increases will be above any levels experienced in the past 100 years. Using the UK Met Office regional climate model PRECIS, under the SRES-A2 scenario (leading to approximately 4.1°C above pre-industrial levels), Kumar et al. (2010) find local temperature increases exceeding 4°C for northern India.

Projected Changes in Heat Extremes

In a 4°C world, the ISI-MIP multimodel mean shows a strong increase in the frequency of boreal summer months hotter than 5-sigma over the Indian subcontinent, especially in the south and along the coast as well as for Bhutan and parts of Nepal (Figures 5.4 and 5.5). By 2100, there is an approximately 60-percent chance that a summer month will be hotter than 5-sigma (multimodel mean; Figure 5.5), very close to the global average percentage. The limited surface area used for averaging implies that there is larger uncertainty over the timing and magnitude of the increase in frequency of extremely hot months over South Asia compared to that of the global mean. By the end of the 21st century, most summer months in the north of the region (> 50 percent) and almost all summer months in the south (> 90 percent) would be hotter than 3-sigma under RCP8.5 (Figure 5.4).

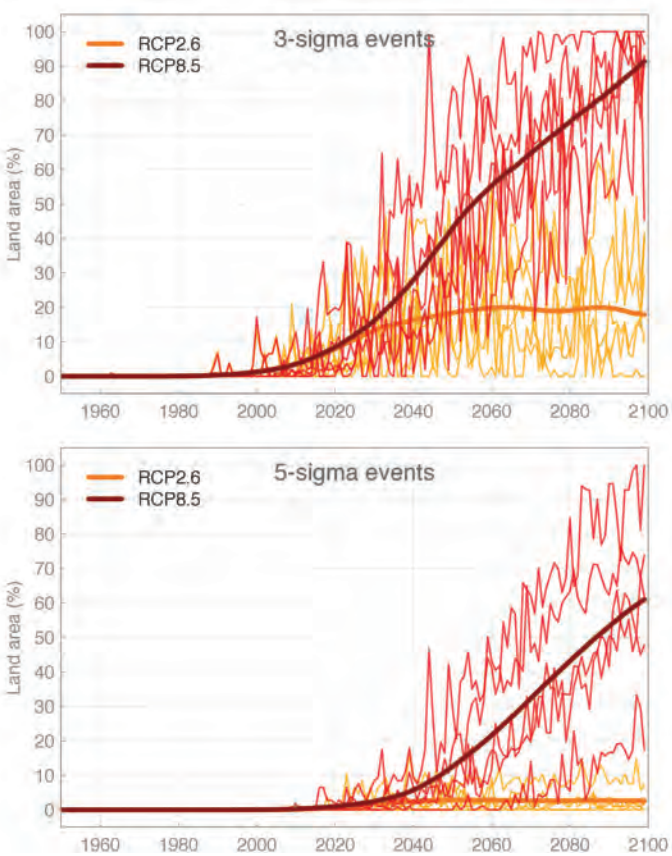
Figure 5.4: Multi-model mean of the percentage of boreal summer months (JJA) in the time period 2071–99 with temperatures greater than 3-sigma (top row) and 5-sigma (bottom row) for scenarios RCP2.6 (left) and RCP8.5 (right) over South Asia



In a 2°C world, most of the high-impact heat extremes projected by RCP8.5 for the end of the century would be avoided. Extremes beyond 5-sigma would still be virtually absent, except for the southernmost tip of India and Sri Lanka (Figure 5.4). The less extreme months (i.e., beyond 3-sigma), however, would increase substantially and cover about 20 percent of the surface area of the Indian subcontinent (Figure 5.5). The increase in frequency of these events would occur in the near term and level off by mid-century. Thus, irrespective of the future emission scenario, the frequency of extreme summer months beyond 3-sigma in the near term would increase several fold. By the second half of the 21st century, mitigation would have a strong effect on the number and intensity of extremes.

For the Indian subcontinent, the multimodel mean of all CMIP5 models projects that warm spells, with consecutive days beyond the 90th percentile, will lengthen to 150–200 days under RCP8.5, but only to 30–45 days under RCP2.6 (Sillmann 2013). By the end of the century, warm nights are expected to occur at a frequency of 85 percent under RCP8.5 and 40 percent under RCP2.6.

Figure 5.5: Multi-model mean (thick line) and individual models (thin lines) of the percentage of South Asian land area warmer than 3-sigma (top) and 5-sigma (bottom) during boreal summer months (JJA) for scenarios RCP2.6 and RCP8.5



Precipitation Projections

A warmer atmosphere carries significantly more water than a cooler one based on thermodynamic considerations. After taking into account energy balance considerations, climate models project an increase in global mean precipitation of about 2 percent per degree of warming.[88]

Model projections in general show an increase in the Indian monsoon rainfall under future emission scenarios of greenhouse gases and aerosols. The latest generation of models (CMIP5) confirms this picture, projecting overall increases of approximately 2.3 percent per degree of warming for summer monsoon rainfall (Menon, Levermann, Schewe, Lehmann, and Frieler 2013). The increase in precipitation simulated by the models is attributed to an increase in moisture availability in a warmer world; it is, somewhat paradoxically, found to be accompanied by a weakening of the monsoonal circulation (Bollasina et al., 2011; R. Krishnan et al. 2012; A. G. Turner and Annamalai 2012), which is explained by energy balance considerations (M. R. Allen and Ingram 2002). Some CMIP5 models show an increase in mean monsoon rainfall of 5–20 percent at the end of the 21st century under a high warming scenario (RCP8.5) compared to the pre-industrial period (N. C. Jourdain, Gupta, Taschetto, et al 2013). This newer generation of models indicates reduced uncertainty compared to CMIP3; however, significant uncertainty remains.[89]

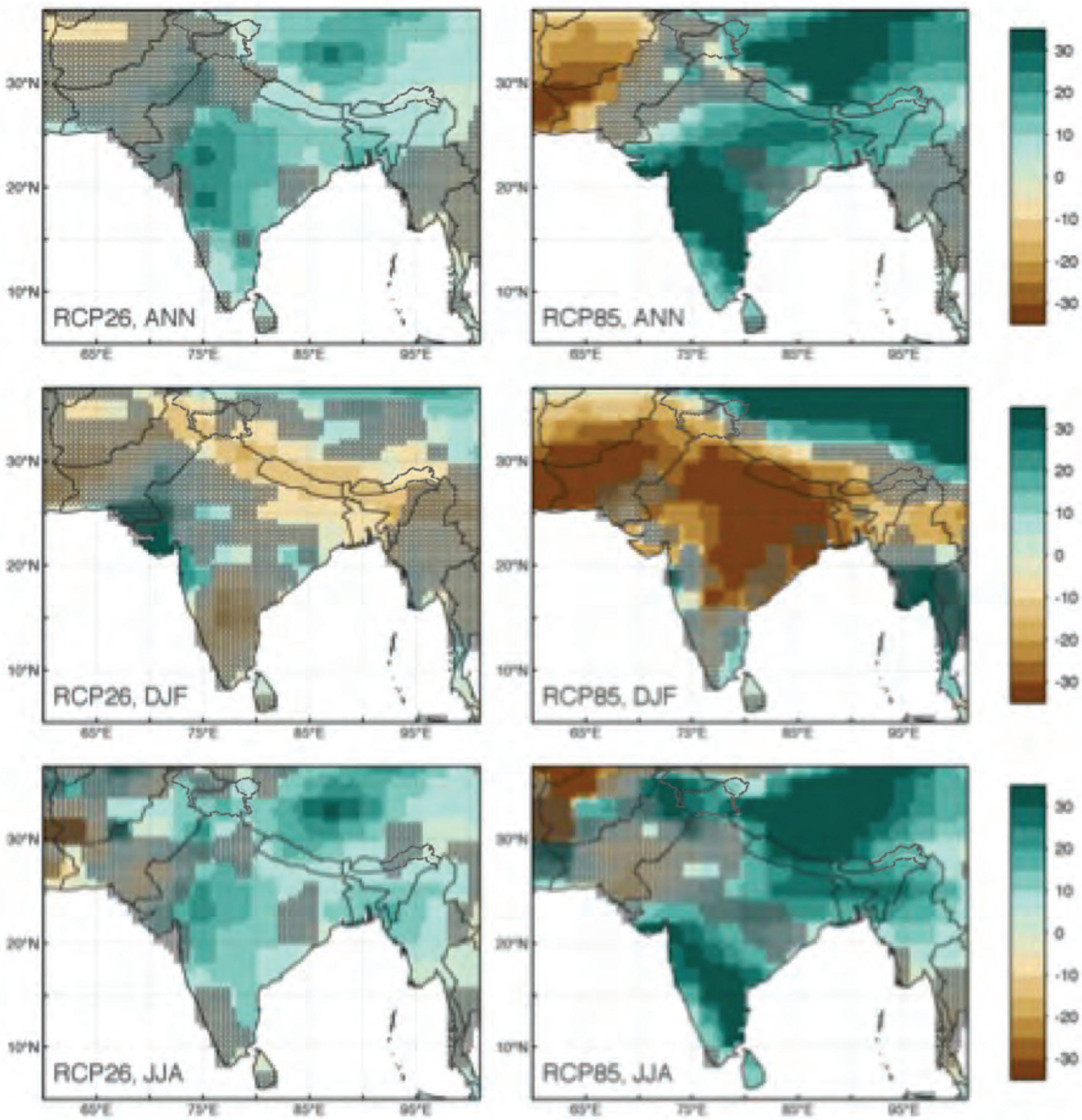
In the 5 GCMs (ISI-MIP models) analyzed for this report, annual mean precipitation increases under both emissions of greenhouse gases and aerosols in the RCP2.6 and RCP8.5 scenarios over most areas of the region. The notable exception is western Pakistan (Figure 5.6). The percentage increase in precipitation is enhanced under RCP8.5, and the region stretching from the northwest coast to the South East coast of peninsular India will experience the highest percentage (~30 percent) increase in annual mean rainfall.

It should be noted that the uncertain regions (hatched areas) with inter-model disagreement on the direction of percentage change in precipitation are reduced under the highest concentration RCP8.5 scenario. The percentage change in summer (JJA)

88 In contrast to the processes behind temperature responses to increased greenhouse gas emissions, which are fairly well understood, projecting the hydrological cycle poses inherent difficulties because of the higher complexity of the physical processes and the scarcity of long-term, high-resolution rainfall observations (M. R. Allen and Ingram 2002).

89 The projected precipitation from a subset of CMIP-3 models was an overall increase—but with a range of trends, including negative, in monsoon rainfall by 2100 (Turner and Annamalai 2012). The set of four GCMs used by the authors is able to simulate the observed seasonality and intra-annual variability of rainfall as well as the ENSO-ISM teleconnection; it showed substantial decadal variability. This is similar to that observed for the All India Rainfall (AIR) time series. The model ensembles did not replicate phasing, mean, or standard deviation of the AIR curve, however, from which the authors conclude that the decadal-scale variability is largely due to internal variability of the coupled atmosphere-ocean system. The models themselves do not show consistent changes.

Figure 5.6: Multi-model mean of the percentage change in annual (top), dry-season (DJF, middle) and wet-season (JJA, bottom) precipitation for RCP2.6 (left) and RCP8.5 (right) for South Asia by 2071–99 relative to 1951–80



Hatched areas indicate uncertainty regions, with 2 out of 5 models disagreeing on the direction of change compared to the remaining 3 models.

precipitation (i.e., during the wet season) resembles that of the change in annual precipitation. The winter (the months of December, January, February (DJF)) precipitation (Figure 5.6) shows a relative decrease in Pakistan and the central and northern regions of India, whereas the rest of the regions show inter-model uncertainty in the direction of change under the RCP8.5 scenario. This is in agreement with previous studies based on the IPCC AR4 (CMIP3) models (e.g., Chou, Tu, and Tan 2007) which suggest that the wet season gets wetter and the dry season gets drier. Under RCP2.6, the direction of the percentage change in winter rainfall shows large inter-model uncertainty over almost all regions of India.

Increased Variability in the Monsoon System

The largest fraction of precipitation over South Asia occurs during the monsoon season. For example, approximately 80 percent of the rainfall over India occurs during the summer monsoon

(June–September), providing the required amount of water for both rainfed crops and for the irrigated crops which largely depend on surface or groundwater reserves replenished by the monsoon rains (Mall, Singh, Gupta, Srinivasan, and Rathore 2006). The timing of monsoon rainfall is very important for agriculture and water supply, and variability in the monsoon system increases South Asia's risk of flooding and droughts. A decrease in seasonal water availability, together with population increases, may have severe effects on water and food security in this densely populated region (K. K. Kumar et al. 2010).

IPCC AR4 found projected increases in the variability of the monsoon and the seasonality of precipitation; these findings are reinforced by the new CMIP5 model projections. These changes in monsoon variability are expected to pose major challenges that increase with rising levels of warming to human systems that depend on precipitation and river runoff as major sources of freshwater (Box 5.2).

The total amount of rainfall, the length of the monsoon season, and the distribution of rainfall within the season determine the outcome of the monsoon season for the human population dependent on it. For example, the number of rainy days and the intensity of rainfall are key factors (K. K. Kumar et al. 2010). Along with the projected total increase in summer monsoon rainfall, an increase in intra-seasonal variability of approximately 10 percent for a near –4°C world (3.8°C warming in RCP 8.5 for the period 2050–2100) is projected, based on CMIP5 GCMs (Menon, Levermann, and Schewe 2013). The intra-seasonal variability in precipitation, which may lead to floods, can be one of the greatest sources of risk to agriculture and other human activities in South Asia. Sillmann and Kharin (2013a) project, also based on CMIP5 GCMs, that the total annual precipitation on wet days increases significantly over South Asian regions under both high- and low-emission scenarios.

While most modeling studies project average annual mean increased monsoonal precipitation on decadal timescales, they also project significant increases in inter-annual and intra-seasonal variability (Endo, Kitoh, Ose, Mizuta, and Kusunoki 2012; May, 2010; Sabade, Kulkarni, and Kripalani 2010; A. G. Turner and Annamalai 2012; K. K. Kumar et al. 2010):

- The frequency of years with above-normal monsoon rainfall and of years with extremely deficient rainfall is projected to increase in the future (R. H. Kripalani, Oh, Kulkarni, Sabade, and Chaudhari 2007; Endo et al. 2012).
- An increase in the seasonality of rainfall, with more rainfall during the wet season (Fung, Lopez, and New 2011; A. G. Turner and Annamalai 2012), and an increase in the number of dry days (Gornall et al. 2010) and droughts (Aiguo Dai, 2012; D.-W. Kim and Byun 2009).
- An increase in the number of extreme precipitation events (Endo et al. 2012; K. K. Kumar et al. 2010).

Although uncertainty in the effects of global warming on total wet-season rainfall is considerable in the region (see hatched areas in Figure 5.6 JJA), there are particularly large uncertainties in GCM projections of spatial distribution and magnitude of the heaviest extremes of monsoon rainfall (A. G. Turner and Annamalai 2012). The models assessed by Kumar et al. (2010)[90] in general show an increase in the maximum amount of seasonal rainfall for the multimodel ensemble mean around June, July, and August.

There are also a number of simulations assessed in the study by K. K. Kumar et al. (2010) that actually project less rainfall for JJA by 2100. The relative rainfall increase with

Box 5.2: Indian Monsoon: Potential "Tipping Element"

Several mechanisms in the climate system have been identified that when forced by human-induced global warming can lead to relatively rapid, large-scale state shifts, which can lead to non-linear impacts for human systems.[a] Such a "tipping element" of very high relevance for South Asia is a potential abrupt change in the monsoon (Schewe and Levermann 2012) caused by global warming, toward a much drier, lower rainfall state. The emergence of major droughts caused by this would likely precipitate a major crisis in South Asia. Physically plausible mechanisms have been proposed for such a switch and the geological record for the Holocene and last glacial period shows that rainfall in India and China has undergone strong and abrupt changes in the past (Levermann, Schewe, Petoukhov, and Held 2009). Changes in the tropical atmosphere that could precipitate a transition of the monsoon to a drier state are projected in the present generation of climate models and is associated with changes in the El Niño/La Niña-Southern Oscillation (ENSO) (Schewe and Levermann 2012). At this stage such a risk remains speculative—but it clearly demands further research given the significant consequences of such an event. Major droughts in South Asia are associated with large-scale hardship and loss of food production. In India, for example, the droughts in 1987 and 2002/2003 affected more than 50 percent of the crop area in the country and caused major declines in crop production.

[a] Examples of such "tipping elements" are passing of thresholds to irreversible mass loss of the Greenland ice sheet and a dieback of the Amazon rainforest (Lenton, 2011).

[90] Temperature and rainfall characteristics in past and future monsoonal climate are analyzed based on an observational-based, all-India summer monsoon rainfall dataset and the projections made by 22 CMIP3 GCMs. For the baseline runs from 1861–1999, observational and reanalysis data were used to force the models, with the projection period from 2000–2100 for which the SRES A1B scenario was employed (approximately 3.5°C warming above pre-industrial levels).

climate change, which amounts to about 10 percent for the future (2070–98) with respect to the JJA rainfall in the baseline period (1961–90), was accompanied by a 20-percent increase in the "flank periods" of May and October; this could indicate an increase in the length of the monsoon season. The relationship between monsoonal precipitation and ENSO appears to be unchanged for the time periods 2041–60 and 2070–98 with respect to the baseline. This is to some extent ambiguous, as the future expected warming could result in a more permanent El Niño-like state in the Pacific that could, in principle, lead to a decrease in monsoonal rainfall.

Although these results come with a considerable amount of uncertainty, K. K. Kumar et al. (2010) conclude that there are severe risks for critical socioeconomic sectors, including agriculture and health.

Regional Sea-level Rise

As explained in Chapter 2, current sea levels and projections of future sea-level rise are not uniform across the world. South Asian coastlines are situated between approximately 0° and 25° N. Being this close to the equator, projections of local sea-level rise show a stronger increase compared to higher latitudes (see Figure 2.10). For South Asian coastlines, sea-level rise is projected to be approximately 100–110 cm in a 4°C world and 60–80 cm in a 2°C world by the end of the 21st century (relative to 1986–2005). This is generally around 5–10 percent higher than the global mean. Figure 5.7 shows the regional sea-level rise for South Asian coastlines for 2081–2100 under the high emissions scenario RCP8.5 (a 4°C world). Note that these projections include only the effects of human-induced global climate change and not those of local land subsidence due to natural or human influences; these factors need to be accounted for in projecting the local and regional risks, impacts, and consequences of sea-level rise.

Figure 5.7: Regional sea-level rise for South Asia in 2081–2100 (relative to 1986–2005) under RCP 8.5

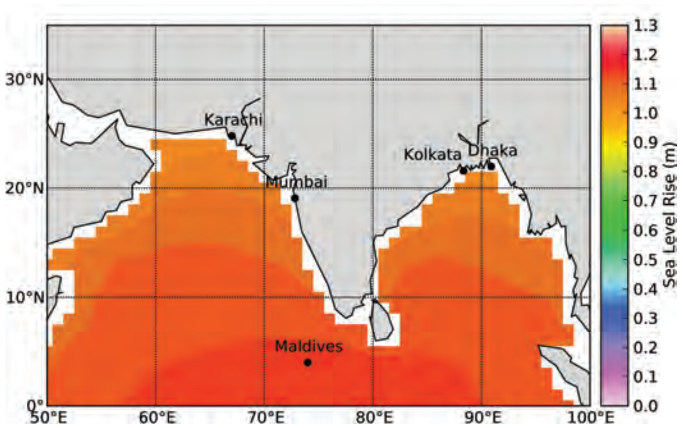
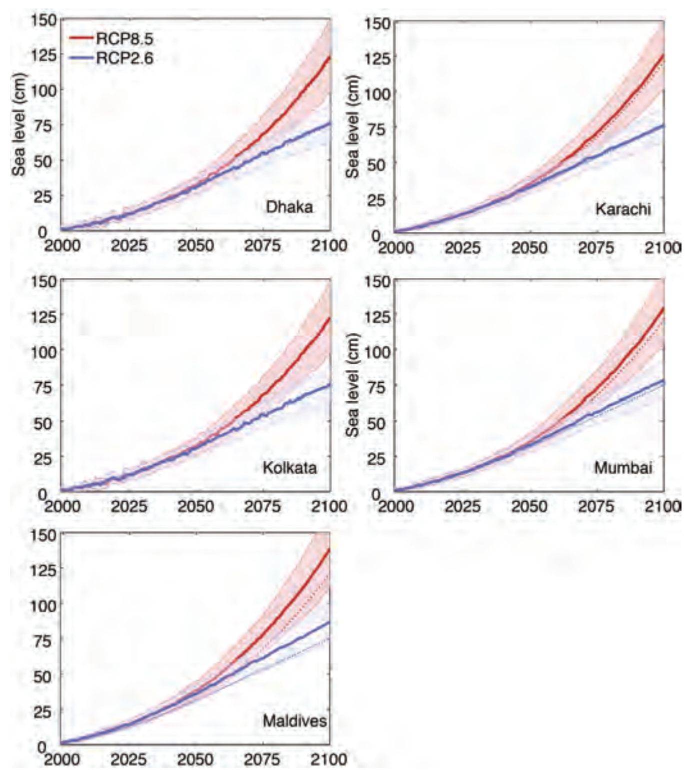


Figure 5.8 shows the time series of sea-level rise in a selection of locations in South Asia. These locations are projected to face a sea-level rise around 105 cm (66 percent uncertainty range of 85–125 cm) by 2080–2100. The rise near Kolkata and Dhaka is 5 cm lower, while projections for the Maldives are 10 cm higher. In a 2°C world, the rise is significantly lower for all locations, but still considerable at 70 (60–80) cm. According to the projection in this report, there is a greater than 66-percent chance that regional sea-level rise for these locations will exceed 50 cm above 1986–2005 levels by the 2060s in a 4°C world, and 100 cm by the 2090s; both of these dates are about 10 years before the global mean exceeds these levels. In a 2°C world, a rise of 0.5 meter is likely to be exceeded by about 2070, only 10 years after exceeding this level in a 4°C world. By that time, however, the high and low scenarios diverge rapidly, with one meter rise in a 2°C world not likely to be exceeded until well into the 22nd century.

Figure 5.8: Local sea-level rise above the 1986–2005 mean as a result of global climate change (excluding local changes due to land subsidence by nature or human causes)



Shaded areas indicate 66-percent uncertainty range and dashed lines indicate the global mean sea-level rise for comparison.

Water Resources

Apart from the monsoon, the dominant geographical feature of South Asia fundamentally influencing its water hydrography is the Hindu Kush and Himalayan mountain complex. These mountains block the northerly push of the monsoon, confining its precipitation effects to the South Asian subcontinent and providing, with their snow and glacial melt, the primary source of upstream freshwater for many of South Asia's river basins. Climate change impacts on the Himalayan and the Hindu Kush glaciers therefore directly affect the people and economies of the countries of Afghanistan, Bangladesh, Bhutan, India, Nepal, and Pakistan.

These "water towers of Asia" play a dominant role in feeding and regulating the flow of the major river systems of the region: the Indus, the Ganges, and the Brahmaputra. These rivers drain into the coast, with the Ganges and the Brahmaputra carrying huge sediment loads from the Himalayas, creating the densely populated mega-delta that encompasses West Bengal and Bangladesh (see Figures 5.10 and 5.11). Reductions in the glacial mass and snow cover of the Hindu Kush and the Himalayas can have a profound effect on the long-term water availability over much of the subcontinent. Changes in the characteristics of precipitation over the mountains, leading to increasingly intense rainfall, contribute along with other factors to much higher flood risks far downstream and interact adversely with rising sea levels on the coast.

The Indus, the Ganges, and the Brahmaputra basins provide water to approximately 750 million people (209 million, 478 million, and 62 million respectively in the year 2005; Immerzeel et al. 2010). The Ganges basin on the east of the subcontinent has the largest population size and density of the three basins. Both the Indus and the Ganges supply large areas with water for irrigation (144,900m² and 156,300m² respectively), while the 2,880-kilometer Indus River constitutes one of the longest irrigation systems in the world. All three rivers are fed by the Tibetan Plateau and adjacent mountain ranges (Immerzeel, Van Beek, and Bierkens 2010; Uprety and Salman 2011).

In fact, over 50 percent of the world's population lives downstream of the Greater Himalaya region, with snowmelt providing over 40 percent of pre- and early-monsoon discharge in the Greater Himalaya catchments, and more than 65 percent and 30 percent of annual discharge in the Indus and Tsangpo/Brahmaputra catchments, respectively. An increasing occurrence of extremely low snow years and a shift toward extremely high winter/spring runoff and extremely low summer runoff would therefore increase the flood risk during the winter/spring, and decrease the availability of freshwater during the summer (Giorgi et al. 2011).

The Indus and the Brahmaputra basins depend heavily on snow and glacial melt water, which make them extremely susceptible to climate-change-induced glacier melt and snowmelt (Immerzeel, Van Beek, and Bierkens 2010).[91] In fact, most of the Himalayan glaciers, where 80 percent of the moisture is supplied by the summer monsoon, have been retreating over the past century. Where the winter westerly winds are the major source of moisture, some of the glaciers in the northwestern Himalayas and in the Karakoram have remained stable or even advanced (Bolch et al. 2012; Immerzeel et al. 2010).

Projections for the future indicate an overall risk to the flow of these rivers. For the 2045–65 period (global mean warming of 2.3°C above pre-industrial levels), very substantial reductions in the flow of the Indus and Brahmaputra in late spring and summer are projected. These reductions would follow the spring period of increased flow due to melting glaciers and are not compensated by the projected increase in rainfall upstream. The Ganges, due to high annual downstream precipitation during the monsoon season, is less dependent on melt water (Immerzeel et al. 2010).[92]

Although snowfall in the mountainous areas in South Asia may increase (e.g., Immerzeel et al. 2010; Mukhopadhyay 2012), this may in the long run be offset by the decrease in glacial melt water as glaciers retreat due to warming (Immerzeel et al. 2010a). Furthermore, the distribution of the available river melt water runoff within the year may change due to accelerated snowmelt. This is caused by increased spring precipitation (Jeelani, Feddema, Van der Veen, and Stearns 2012), with less runoff available prior to the onset of the monsoon.

More recent research projects a rapid increase in the frequency of low snow years in the coming few decades, with a shift toward high winter and spring runoff and very low summer flows likely well before 2°C warming. These trends are projected to become quite extreme in a 4°C warming scenario (Diffenbaugh, Scherer, and Ashfaq 2012).

Combined with precipitation changes, loss of glacial ice and a changing snowmelt regime could lead to substantial changes in downstream flow. For example, the Brahmaputra River may experience extreme low flow conditions less frequently in the future (Gain,

91 Immerzeel et al. (2010) define a Normalized Melt Index (NMI) as a means to assess the relative importance of melt water, as opposed to downstream precipitation (less evaporation), in sustaining the flow of the three river basins. They define it as the volume of upstream melt water discharge divided by the downstream natural discharge, with the natural discharge calculated as the difference between the received precipitation and the natural evaporation in the basin. Changes in river basin runoff in both volume (volumetric discharge) and distribution throughout the year (seasonal distribution) are determined by changes in precipitation, the extent of the snow covered area, and evapotranspiration (Mukhopadhyay 2012).

92 To project the impacts of climate change on future runoff, Immerzeel et al. (2010) use a hydrological modeling approach and force the model through the output of 5 GCMs run under the A1B scenario for the time period of 2046–65 (global mean warming of 2.3°C above pre-industrial levels). They employ a best-guess glacial melt scenario for the future that assumes linear trends in degree-days and snowfall between the observational period and 2050, where degree-days (here expressed in mm/C) measure snow or ice melt expressed in depth of water for the difference between the base temperature (usually 0°C) and the mean air temperature per day (P. Singh, Kumar, and Arora 2000).

Immerzeel, Sperna Weiland, and Bierkens 2011). There could be a strong increase in peak flow, however, which is associated with flooding risks (Ghosh and Dutta 2012). Combined with projected sea-level rise, this could have serious implications for Bangladesh and other low-lying areas in the region (Gain et al. 2011).

Given the potential impacts across the Northern Hemisphere, this report highlights the likelihood of intensifying hydrologic stress in snow-dependent regions, beginning in the near-term decades when global warming is likely to remain within 2°C of the pre-industrial baseline.

Water Security

Water security is becoming an increasingly important development issue in South Asia due to population growth, urbanization, economic development, and high levels of water withdrawal. The assessment of water security threats is undertaken using differing metrics across the studies, which often makes a comprehensive assessment difficult. In India, for example, gross per capita water availability (including utilizable surface water and replenishable groundwater) is projected to decline from around 1,820m³ per year in 2001 to about 1,140m³ per year in 2050 due to population growth alone (Bates, Kundzewicz, Wu, and Palutikof 2008b; S. K. Gupta and Deshpande 2004). Although this estimate only includes blue water availability (water from rivers and aquifers), it has to be kept in mind that in South Asia, in contrast to Europe or Africa, the consumption of blue water in the agricultural sector exceeds that of green water (precipitation water infiltrating into the soil) (Rockström et al. 2009). Thus, climate change, by changing hydrological patterns and freshwater systems, poses an additional risk to water security (De Fraiture and Wichelns 2010; ESCAP 2011; Green et al. 2011), particularly for the agricultural sector (Sadoff and Muller 2009).

Water demand in agriculture and the competition for water resources are expected to further increase in the future as a side effect of population growth, increasing incomes, changing dietary preferences, and increasing water usage by industrial and urban users. Even without climate change, satisfying future water demand will be a major challenge. Observations and projections point to an increase in seasonality and variability of monsoon precipitation with climate change; this poses additional risks to human systems, including farming practices and irrigation infrastructure that have been highly adapted to the local climate. In fact, extreme departures from locally expected climates that delay the onset of monsoons and extend monsoon breaks may have a much more profound impact on agricultural productivity than changes in absolute water availability or demand (see Chapter 5 on "Agricultural Production").

Present Water Insecurity

Based on several different methods of measuring water security, the densely populated countries of South Asia are already exposed to a significant threat of water insecurity. Taking into account water quality and exposure to climate change and water-related disasters, ESCAP (2011) identifies India, Bangladesh, Pakistan, the Maldives, and Nepal as water hotspots in the Asia-Pacific region.

South Asia's average per capita water availability,[93] defined by the sum of internal renewable water sources and natural incoming flows divided by population size, is less than 2,500m³ annually (ESCAP 2011); this is compared to a worldwide average of almost 7,000m³ per capita per year (World Bank 2010c). In rural areas of India, Bangladesh, Pakistan, Nepal, and Sri Lanka,[94] 10 percent or more of the population still remain without access to an adequate amount of water, even if defined at the relatively low level of 20 liters per capita per day for drinking and other household purposes. Rates of access to sanitation are also low. In the year 2010 in India, only 34 percent of the population had access to sanitation; in Pakistan, that number is 48 percent and in Bangladesh it is 54 percent (2010 data based on World Bank 2013b).

Applying a multi-factorial water security index,[95] Vörösmarty et al. (2010) find that South Asia's present threat index varies regionally between 0.6 and 1, with a very high (0.8–1) threat over central India and Bangladesh on a threat scale of 0 (no apparent threat) to 1 (extremely threatened). Along the mountain ranges of the Western Ghats of South India, in Nepal, in Bhutan, in the northeastern states of India, and in the northeastern part of Afghanistan, the incident threat level is high to very high (0.6–0.8).[96] Another approach, in which a country is considered to be water stressed if less than 1,700m³ river basin runoff per capita is available, also found that South Asia is already a highly water-stressed region (Fung et al. 2011).

Projected Changes in Water Resources and Security

The prognosis for future water security with climate change depends on the complex relationship among population growth, increases in agricultural and economic activity, increases in total precipitation, and the ultimate loss of glacial fed water and snow cover, combined with regional variations and changes in seasonality across South Asia. Projections show that in most cases climate

93 Including Afghanistan, Iran and Turkey.

94 Bhutan and the Maldives have slightly higher levels of access to water.

95 Aggregating data on river flows, using cumulative weights based on expert judgment on 23 factors relating to catchment disturbance, pollution, water resource development, and biotic factors.

96 Insufficient river flow over parts of Pakistan, the southwestern parts of Afghanistan, and the northwestern arid desert regions of India, especially Rajasthan and the Punjab, precludes the investigation of ongoing changes in the water security index (Vörösmarty et al. 2010b). In these areas, water availability is predominantly influenced by snowmelt generated upstream in the Hindu Kush and Himalayas (Barnett and Webber 2010) and, as shown by Immerzeel et al. (2010), climate-change-induced glacier retreat can significantly influence water availability in river basins which heavily depend on snow and glacial melt water.

change aggravates the increasing pressure on water resources due to high rates of population growth and associated demand.

An example of this complexity can be seen in the work of Fung et al. (2011), who project the effects of global warming on river runoff in the Ganges basin.[97] A warming of about 2.7°C above pre-industrial levels is projected to lead to a 20-percent increase in runoff, and a 4.7°C warming to approximately a 50-percent increase. Without taking seasonality into account, the increase in mean annual runoff in a 4°C world is projected to offset increases in water demand due to population growth.[98] With 2°C warming, the total mean increase in annual runoff is not sufficiently large to mitigate the effects of expected population growth in these regions; water stress, therefore, would not be expected to decrease in South Asia.

While an increase in annual runoff sounds promising for a region in which many areas suffer from water scarcity (Bates et al. 2008; Döll 2009; ESCAP 2011), it has to be taken into account that the changes are unevenly distributed across wet and dry seasons. In projections by Fung et al. (2011), annual runoff increases in the wet season while further decreasing in the dry season—with the amplification increasing at higher levels of warming. This increase in seasonality implies severe flooding in high-flow seasons and aggravated water stress in dry months in the absence of large-scale infrastructure construction (Fung et al. 2011; World Bank 2012).

River runoff, however, is just one measure of available water; more complex indexes of water security and availability have also been applied. A recent example is that of Gerten et al. (2011c), who apply the concept of blue water and green water to evaluate the effects of climate change on available water supplies for agriculture and human consumption. They find that a country is water scarce if the availability of blue water used for irrigation and green water used for rainfed agricultural production does not exceed the required amount of water to produce a diet of 3,000 kilocalories per capita per day. For a diet based on 80 percent vegetal and 20 percent animal product-based calories, Gerten et al. (2011c) estimate this amount at 1,075m³ of water per capita per year.

For global warming of approximately 3°C above pre-industrial levels and the SRES A2 population scenario for 2080, Gerten et al. (2011) project that it is very likely (>90 percent confidence) that per capita water availability in South Asia[99] will decrease by more than 10 percent.[100] While the population level plays an important role in these estimates, there is a 10–30 percent likelihood that climate change alone is expected to decrease water availability by more than 10 percent in Pakistan and by 50–70 percent in Afghanistan. The likelihood of water scarcity driven by climate change alone is as high as >90 percent for Pakistan and Nepal and as high as 30–50 percent for India. The likelihood of a country becoming water scarce is shown in Figure 5.9.

Another study examining the effects of climate change on blue and green water availability and sufficiency for food production arrives at broadly similar conclusions. In a scenario of 2°C warming by 2050, Rockström et al. (2009) project food and water requirements in India to exceed green water availability by more than 150 percent, indicating that the country will be highly dependent on blue water (e.g., irrigation water) for agriculture production.[101] At the same time, blue water crowding, defined as persons per flow of blue water, is expected to increase due to population growth. As early as 2050, water availability in Pakistan and Nepal is projected to be too low for self-sufficiency in food production when taking into account a total availability of water below 1300m³ per capita per year as a benchmark for the amount of water required for a balanced diet (Rockström et al. 2009).

The projection of impacts needs to rely on accurate predictions of precipitation and temperature changes made by GCMs (see Chapter 5 on "Regional Patterns of Climate Change"). In addition, the estimation of impacts relies on (and depends on) hydrological models and their accurate representation of river runoff. Furthermore, as the above results demonstrate, water scarcity in the future is also highly dependent on population growth, which poses a large source of uncertainty. Finally, many studies use different metrics to estimate water resource availability and water scarcity, making direct intercomparison difficult. Irrespective of these multiple sources of uncertainty, with a growing population and strong indications of climate-related changes to the water cycle, clear and growing risks to stable and safe freshwater provisions to populations and sectors dependent on freshwater are projected to increase with higher levels of warming.

Projected Changes to River Flow

South Asia has very low levels of water storage capacity per capita, which increases vulnerability to fluctuations in water flows and changing monsoon patterns (Ministry of Environment and Forests 2012; Shah 2009). India, for example, stores less than 250m³ of water per capita (in contrast to countries such as Australia and the U.S., which have a water storage capacity of more than 5,000m³ per capita). There is a large potential in South Asian countries to both utilize existing natural water storage capacity and to construct additional capacity (Ministry of Environment and Forests, 2012). The potential for improvements in irrigation systems, water harvesting

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97 Estimates are based on an application of the climateprediction.net (CPDN). HADCM3 global climate model ensemble runs with the MacPDM global hydrological model and under the SRES A1B climate change scenario, together with the expected UN population division population growth scenario. Warming levels of 2°C and 4°C compared to the 1961–90 baseline were examined. The years by which the temperature increase is expected to occur varies as an ensemble of models was used.

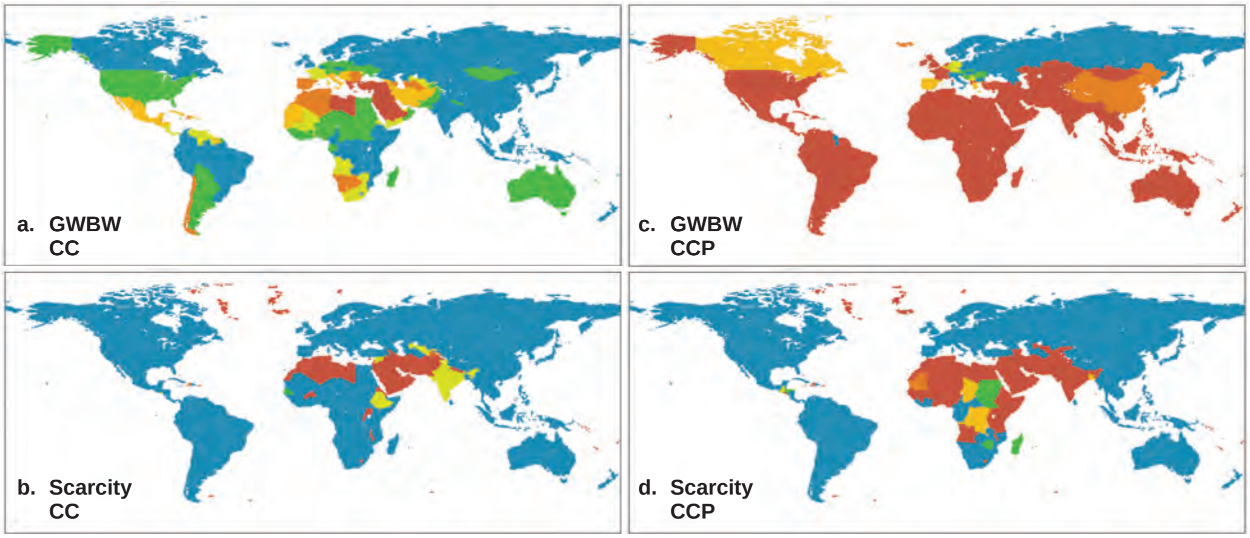
98 Population projections are based on UN population growth rate projections until 2050 and linear extrapolations for the 2060s.

99 Except for Sri Lanka; no estimates are reported for the Maldives.

100 Ensemble of 17 CMIP3 GCMs for SRES A2 and B1 climate and population change scenarios.

101 Using the LPJmL dynamic vegetation and a water balance model driven by climate output from $HadCM_2$ forced by A2 SRES emission scenario.

Figure 5.9: Likelihood (%) of (a),(c) a 10-percent reduction in green and blue water availability by the 2080s and (b),(d) water scarcity in the 2080s (left) under climate change only (CC; including CO_2 effects) and (right) under additional consideration of population change (CCP)



Note that the positive percentage scale indicates a 10% decrease in water availability. Results are presented for the A2 scenario. These likelihoods were derived from the spread of impacts under all climate models (e.g. 90 percent means that the given impact occurs in 9 out of 10 (~15 out of 17) climate change projections).

Source: Gerten et al. (2011).

techniques, and water productivity, and more-efficient agricultural water management in general, is also high; such improvements would serve to offset risks from climate variability.

A pronounced amplification of river flows, combined with large changes in the discharge cycle from glaciers and snowpack in the Himalayas, point to substantial risks, not least related to flooding, in the future. River flooding can have far-reaching consequences, directly affecting human lives and causing further cascading impacts on affected businesses, where small-scale enterprises are often the most vulnerable. Asgary, Imtiaz, and Azimi (2012) evaluated the impacts of the 2010 river floods on small and medium enterprises (SME) in Pakistan. The authors first found that 88 percent of the sample business owners had to evacuate their towns due to the flood, therefore causing a major disruption to business. They further found that 47 percent of the businesses had recovered within 1–3 months after the occurrence of the floods; 90 percent had recovered after six months. However, most of the businesses suffered losses and only a few of them were at the same level or wealthier afterwards than prior to the event. The authors further explain that small businesses have a higher probability of being located in hazard-prone areas, occupying unsafe business facilities and lacking the financial and human resources to cope with the consequences of disasters.

The climate model projections discussed in the previous section strongly indicate that there is likely to be a strong increase in seasonal flows due to global warming—on top of likely overall increases in precipitation. These patterns appear differently in different river basins. For example, recent work by Van Vliet et al. (2013) projects changes in low, mean, and high river flows globally and finds pronounced differences between the Indus and the Ganges-Brahmaputra basins.[102] For the Indus, the mean flow is projected to increase by the 2080s for warming levels of around 2–°C by around 65 percent, with low flow increasing by 30 percent and the high flow increasing by 78 percent. For the Ganges-Brahmaputra system, the mean flow increases by only 4 percent, whereas the low flow decreases by 13 percent and the high flow by 5 percent. The changes are amplified with higher levels of warming between the individual scenarios.

Given these large changes in seasonal amplification of river flows and rainfall amounts, it is clear that, even for 2°C warming, major investments in water storage capacity will be needed in order to utilize the potential benefits of increased seasonal runoff for improved water availability throughout the year. At the same time, infrastructure for flood protection has to be built. The required investment in water infrastructure is likely to be larger with a warming of above 4°C compared to a warming of above 2°C (Fung et al. 2011).

102 Three GCMs forced by the SRES A2 and B1 scenarios with hydrological changes calculated with the VIC (Variable Infiltration Capacity) model.

Cities and Regions at Risk of Flooding

Coastal and deltaic regions are particularly vulnerable to the risks of flooding. Cities in particular agglomerate high numbers of exposed people. A number of physical climatic changes indicate an increased risk of flooding, including more extreme precipitation events, higher peak river flows, accelerated glacial melt, increased intensity of the most extreme tropical cyclones, and sea-level rise. These changes are expected to further increase the number and severity of flood events in the future (Eriksson, Jianchu, and Shrestha 2009; Ministry of Environment and Forests 2012; Mirza 2010). A number of these projected changes are likely to interact, exacerbating damages and risk (e.g., higher peak river flows in low-lying coastal deltas potentially interacting with rising sea levels, extreme tropical cyclones, and associated storm surges). Such events could in turn pose additional threats to agricultural production and human health, as will be discussed in Chapter 5 under "Agricultural Production" and "Human Impacts."

A wide range of flooding events can be influenced or caused by climate change, including flash floods, inland river floods, extreme precipitation-causing landslides, and coastal river flooding, combined with the effects of sea-level rise and storm-surge-induced coastal flooding. In addition to floods and landslides, the Himalayan regions of Nepal, Bhutan, and Tibet are projected to be exposed to an increasing risk of glacial lake outbursts (Bates et al. 2008; Lal 2011; Mirza 2010).[103] The full scope of possible flooding events will not be explored; the focus of this section will instead be on low-lying river delta regions where there is a confluence of risk factors. This does not mean that other kinds of flooding events are not significant—merely that they fall outside the scope of this report.

Climate change is not the only driver of an increasing vulnerability to floods and sea-level rise. Human activities inland (such as upstream damming, irrigation barrages, and diversions) as well as activities on the delta (such as water withdrawal) can significantly affect the rate of aggradation and local subsidence in the delta, thereby influencing its vulnerability to sea-level rise and river floods. Subsurface mining is another driver (Syvitski et al. 2009). Subsidence, meanwhile, exacerbates the consequences of sea-level rise and increases susceptibility to river flooding.

The Current Situation in the Region

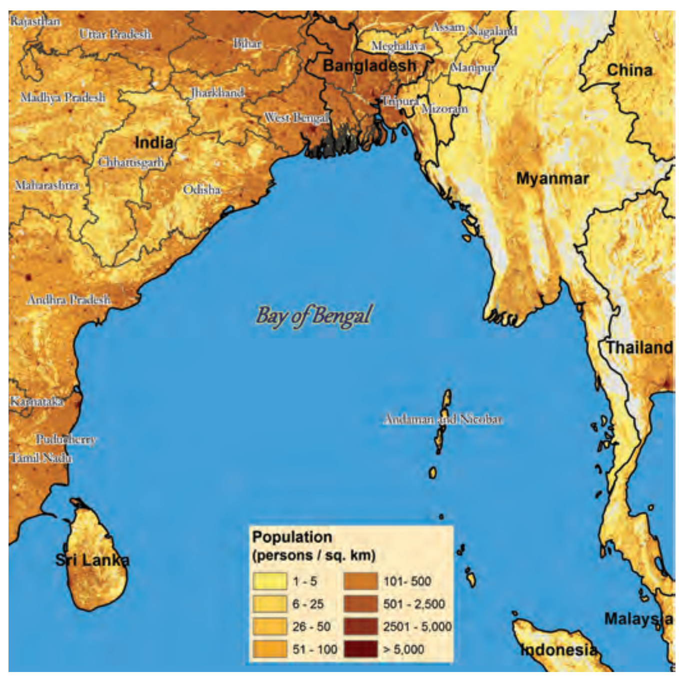
The frequency of extreme floods and the scope of flood-prone areas are increasing, particularly in India, Pakistan, and Bangladesh. Precipitation is the major cause of flooding (Mirza 2010). Since 1980, the risks from flooding have grown due mainly to population and economic growth in coastal regions and low-lying areas. In 2000, approximately 38 million people were exposed to floods in South Asia; almost 45 million were exposed in 2010, accounting for approximately 65 percent of the global population exposed to floods (UNISDR 2011). Figure 5.10 shows the population density in the Bay of Bengal region.

Deltaic regions in particular are vulnerable to more severe flooding, loss of wetlands, and a loss of infrastructure and livelihoods as a consequence of sea-level rise and climate-change-induced extreme events (Ian Douglas 2009; Syvitski et al. 2009; World Bank 2010d). It is important to recognize, however, that river deltas are very dynamic; where the rate of aggradation (inflow of sediment to the delta) exceeds the local rate of sea-level rise (taking into account subsidence caused by other factors), a delta may be stable in the face of rising sea levels. The vulnerability to climate-related impacts in the region is modulated by factors determining the level of sediment inflow. Reductions in sediment inflow have led to an increase in the relative sea-level rise in the deltas; where sediment inflow increases, relative sea-level rise may decrease.

The two major deltas in South Asia are those of the Ganges, Brahmaputra, and Meghna Rivers and of the Indus River:

- The Indus Delta in Pakistan has an area of 4,750 km² below 2 meters above sea level and a population of approximately

Figure 5.10: Population density in the Bay of Bengal region



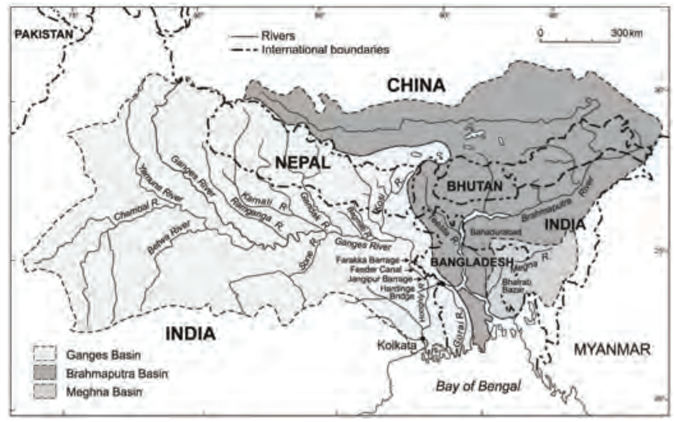
Source: Based on Landscan Population dataset, 2008, Oakridge National Laboratory (ORNL).

[103] The buildup of melt water behind glacial moraines as glaciers retreat forms lakes; eventually the moraine dams can burst, leading to catastrophic flooding downstream. An increase in the frequency of glacial lake outburst floods has already been observed (Bates et al. 2008).

350,000.[104] The storm-surge areas of the deltas are at present 3,390 km², and the recent area of river flooding is 680 km² (1,700 km² in situ flooding) (Syvitski et al. 2009). The Indus was recently ranked as a delta at greater risk, as the rate of degradation of the delta (including inflow of sediments) no longer exceeds the relative sea-level rise. In the Indus Delta, a sediment reduction of 80 percent has been observed and the observed relative sea-level rise is more than 1.1 mm per year (Syvitski et al. 2009), exacerbating the global sea-level rise of 3.2 mm/yr (Meyssignac and Cazenave 2012).

- The Ganges-Brahmaputra-Meghna Delta encompasses Bangladesh and West Bengal, including the city of Kolkata in India. Within Bangladesh's borders, the area of the delta lying below 2 meters is 6,170 km² and the population at present is more than 22 million. The storm-surge areas of the delta are at present 10.500km², and the recent area of river flooding in the Ganges-Brahmaputra-Meghna Delta is 52,800 km² (42,300 km² in situ flooding) (Syvitski et al. 2009). The Ganges-Brahmaputra Delta was recently ranked as a "delta in peril" due to reduced aggregation and accelerated compaction of the delta. This is expected to lead to a situation where sea-level rise rates are likely to overwhelm the delta. A sediment inflow reduction of 30 percent has been observed in this delta and aggradation no longer exceeds relative sea-level rise, which is particularly high in the Ganges Delta at 8–18 mm per year (Syvitski et al., 2009). Figure 5.11 shows the basins of the Ganges, Brahmaputra, and Meghna Rivers.

Figure 5.11: The Ganges, Brahmaputra, and Meghna basins



Source: Monirul Qader Mirza (2002).

Reprinted from Global Environmental Change, 12, Monirul Qader Mirza, Global warming and changes in the probability of occurrence of floods in Bangladesh and implications, 127-138, Copyright (2002), with permission from Elsevier. Further permission required for reuse.

Projections: Risks to Bangladesh

Bangladesh is one of the most densely populated countries in the world, with a large population living within a few meters of sea level (see Figure 5.10). Flooding of the Ganges-Brahmaputra-Meghna Delta occurs regularly and is part of the annual cycle of agriculture and life in the region.

Up to two-thirds of the land area of Bangladesh is flooded every three to five years, causing substantial damage to infrastructure, livelihoods, and agriculture—and especially to poor households (World Bank 2010d; Monirul Qader Mirza 2002).

Projections consistently show substantial and growing risks for the country, with more climate change and associated increases in river flooding and sea-level rise. According to Mirza (2010), changes in precipitation are projected to result in an increase in the peak discharges of the Ganges, the Brahmaputra, and the Meghna Rivers. Mirza (2010) estimates the flooded area could increase by as much as 29 percent for a 2.5°C increase in warming above pre-industrial levels, with the largest change in flood depth and magnitude expected to occur in up to 2.5°C of warming. At higher levels of warming, the rate of increase in the extent of mean-flooded-area per degree of warming is estimated to be lower (Mirza 2010).

Tropical cyclones also pose a major risk to populations in Bangladesh. For example, Cyclone Sidr exposed 3.45 million Bangladeshis to flooding (World Bank 2010d). In comparison to the no-climate-change baseline scenario, it is projected that an additional 7.8 million people would be affected by flooding higher than one meter in Bangladesh as a consequence of a potential 10-year return cyclone in 2050 (an increase of 107 percent). A total of 9.7 million people (versus the 3.5 million in the baseline scenario) are projected to be exposed to severe inundation of more than 3 meters under this scenario. Agriculture in the region would also be severely affected. In addition, rural communities representing large parts of the population are expected to remain dependent on agriculture despite structural economic changes in the future away from climate-sensitive sectors; this would leave them vulnerable to these climate change impacts. Furthermore, the highest risk of inundation is projected to occur in areas with the largest shares of poor people (World Bank 2010d).

Projections: Risks to Two Indian Cities

The following discussion of the climate-change-related risks to two Indian cities—Mumbai and Kolkata—is intended to be

[104] This estimate accounts for the population of the four Teluka (sub-districts of the Sind Province, based on the 1998 census) within the coastline. Mipur Sakro: 198,852; Keti Bunder: 25,700; Shah Buner: 100,575; Kharo Chann: 25,656. The data can be found at http://www.districtthatta.gos.pk/Taluka%20Administration.htm.

illustrative rather than to provide a comprehensive assessment of risks to urban areas in the region. The focus is on large cities as these represent high agglomerations of assets and people, which however does not imply a relatively higher human resilience in rural areas.

Mumbai

Mumbai, due to its geography, is particularly exposed to both flooding from heavy rainfall during the monsoon and sea-level rise inundation as large parts of the city are built on reclaimed land which lies lower than the high-tide level. Indeed, the city has the largest population exposed to coastal flooding in the world (IPCC 2012) (Box 5.3). The city's drainage system is already inadequate in the face of heavy rainfall, and rapid and unplanned urbanization is likely to further increase the flood risk in Mumbai (Ranger et al. 2011).

The projected increase in heavy precipitation events associated with climate change poses a serious risk to the city—and that does not even take into account the effects of sea-level rise. By the 2080s and with a warming of 3°C to 3.5°C above pre-industrial levels, climate projections indicate a doubling of the likelihood of an extreme event similar to the 2005 floods (and a return period reduced to around 1-in-90 years).[105] Direct economic damages (i.e., the costs of replacing and repairing damaged infrastructure and buildings) of a 1-in-100 year event are estimated to triple in the future compared to the present day and to increase to a total of up to $1.9 billion due to climate change only (without taking population and economic growth into account). Additional indirect economic costs, such as sectoral inflation, job losses, higher public deficit, and financial constraints slowing down the process of reconstruction, are estimated to increase the total economic costs of a 1-in-100 year event to $2.4 billion (Ranger et al. 2011). Without adaptation, population and economic growth would increase the exposure to and damage of flooding events in the future. In terms of adaptation, Ranger et al. (2011) estimate that improved building codes and improving the drainage system in Mumbai could reduce direct economic costs by up to 70 percent.

A limitation of Ranger et al. (2011) is that the study does not include the impacts of sea-level rise—even though it is very plausible that even low levels of sea-level rise would further reduce the effectiveness of drainage systems. This report projects the sea-level rise in Mumbai at around 35 cm by the 2050s under either of the emission pathways leading to the 2°C or 4°C worlds; for the 2° world, a rise of around 60 cm by the 2080s and, for the 4°C world, a rise of close to 80 cm (see Chapter 5 on "Regional Sea-level Rise").

Box 5.3: The 2005 Mumbai Flooding

Severe flooding in 2005 caused 500 deaths and an estimated $1.7 billion in economic damage in Mumbai, the commercial and financial hub of India and the city that generates about five percent of the nation's GDP (Ranger et al. 2011). The flood forced the National Stock Exchange to close, and automated teller machine banking systems throughout large parts of the country stopped working. This demonstrated how critical infrastructure can be affected by extreme events in mega-cities (Intergovernmental Panel on Climate Change 2012).

Kolkata

Kolkata is ranked among the top 10 cities in the world in terms of exposure to flooding under climate change projections (IPCC 2012; UN-HABITAT 2010b; World Bank 2011a). The elevation of Kolkata city and the metropolitan area surrounding the city ranges from 1.5–11 meters above sea level (World Bank 2011a). Kolkata is projected to be exposed to increasing precipitation, storm surges, and sea-level rise under climate change scenarios. Roughly a third of the total population of 15.5 million (2010 data; UN-HABITAT 2010) live in slums, which significantly increases the vulnerability of the population to these risk factors. Furthermore, 15 percent of the population live by the Hooghly River and are highly exposed to flooding. Another factor adding to the vulnerability of Kolkata is unplanned and unregulated urbanization; infrastructure development is insufficient and cannot keep pace with current urbanization rates (World Bank 2011a).

A recent study by the World Bank (2011a)[106] on urban flooding as a consequence of climate-change finds that a 100-year return period storm will result in doubling the area flooded by a depth of 0.5–0.75m (i.e. high threat level) under the A1F1 climate change scenario (this scenario considers a projected sea-level rise of 27 cm and a 16 percent increase in precipitation by 2050). This excludes Kolkata city, which is analyzed separately, as the city has sewerage networks in place; these sewerage networks are essentially absent in the peri-urban areas surrounding the city. According

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105 For these estimates, projections of precipitation are taken from the regional climate model PRECIS. They are driven by the A2 SRES scenario, which projects a 3.6°C mean temperature increase across India compared to the 1961–90 baseline period and a 6.5 percent increase in seasonal mean rainfall by 2080 representing an upper-end estimate of future climate risks (Ranger et al. 2011).

106 Projections are based on the A1F1 SRES emission scenario leading to a global-mean warming of 2.2°C above pre-industrial levels by 2050, 12 GCMs, and an estimated sea-level rise of 27 cm by 2050. Historical rainfall data for 1976–2001 represent the baseline (no climate change) scenario. Land subsidence was not accounted for in the study. Impacts were analyzed in terms of the projected extent, magnitude, and duration of flooding by deploying a hydrological model, a hydraulic model, and an urban storm drainage model. The population of Kolkata in 2050 was estimated by extrapolation based on the past decadal growth rates adjusted for likely future changes in population growth. A decadal population growth rate of 4 percent was applied. Past average per capita GDP growth rates were used to estimate property and income levels in 2050. The presented estimates are based on 2009 prices and thus do not consider inflation (World Bank 2011a).

to the projections presented in Chapter 5 on "Regional Sea-level Rise", the sea-level rise in Mumbai and Kolkata is expected to reach 25 cm by the 2030s–40s.

In Kolkata city, with a population of approximately five million and a population density almost three times higher than the metropolitan area (the city has a population density of 23,149 persons per km² while the metropolitan area has a population density of only 7,950 people per km²), a flood depth of more than 0.25 meters is expected to affect 41 percent of the city area and about 47 percent of the population in 2050 compared to 39 percent of the city area and 45 percent of the population under the baseline scenario (World Bank 2011a).

In terms of damages in Kolkata city only, which accounts for an area of around 185 km² (the metropolitan area surrounding the city is about 1,851 km²) the World Bank (2011a) study estimates the additional climate-change-related damages from a 100-year return-period flood to be $790 million in 2050 (including damages to residential buildings and other property, income losses, losses in the commercial, industrial, and health care sectors, and damages to roads and the transportation and electricity infrastructures). Due to data constraints, both total damages and the additional losses caused by increased flooding as a consequence of climate change should be viewed as lower-bound estimates (World Bank 2011a).

Given that sea-level rise is projected to increase beyond 25 cm to 50 cm by 2075 (and 75 cm by 2100) in the lower warming scenario of 2°C, these risks are likely to continue to grow with climate change.

Scale of Flooding Risks with Warming, and Sea-level Rise

With a few exceptions, most of the studies reviewed here do not examine how flooding risks change with different levels of climate change and/or sea-level rise. In specific locations, this very much depends on local topographies and geography; on a broader regional and global scale, however, the literature shows that river flooding risks are quite strongly related to the projected level of warming. Recent work by Arnell et al (2013) reinforces earlier work, showing that the proportion of the population prone to river flooding increases rapidly with higher levels of warming. Globally about twice as many people are predicted to be flood prone in 2100 in a 4°C world compared to a 2°C scenario. Arnell and Gosling (2013) find that increases in flooding risk are particularly large over South Asia by the 2050s, both in percentage and absolute terms. Reinforcing this are recent projections of the consequence of snow reductions in the Himalayan region: increasing frequency of extremely low snow years causes extremely high northern hemisphere winter/spring runoff increasing flood risks (Diffenbaugh et al 2012).

The response to coastal flooding caused by sea-level rise tends to be much less pronounced; this is principally because, by 2100, the differences between scenarios are not large when adaptation is assumed (i.e., rising wealth drives increasing levels of coastal protection) (Arnell et al 2013). The full difference in impacts would be felt in following centuries.

For the cases studied here, such as the Indus-Brahmaputra Delta, Bangladesh and the cities, it is plausible that higher rates of sea-level rise and climate change together will lead to greater levels of flooding risk. How these risks change, and likely increase, with high levels of warming and sea-level rise remains to be fully quantified.

Agricultural Production

Agriculture contributes approximately 18 percent to South Asia's GDP (2011 data based on World Bank 2013l); more than 50 percent of the population is employed in the sector (2010 data based on World Bank 2013m) and directly dependent on it. In Bangladesh, for example, rural communities, representing large parts of the population, are expected to remain dependent on agriculture despite structural changes in the economy away from climate-sensitive sectors in the future. As a result, much of the population will remain vulnerable to these climate change impacts (World Bank 2009). Productivity growth in agriculture is thus an important driver of poverty reduction, and it is highly dependent on the hydrological cycle and freshwater availability (Jacoby, Mariano, and Skoufias 2011).

The rice-wheat system in the Indo-Gangetic Plain, which meets the staple food needs of more than 400 million people, is a highly vulnerable regional system. The system, which covers an area of around 13.5 million hectares in Pakistan, India, Bangladesh, and Nepal, provides highly productive land and contributes substantially to the region's food production. Declining soil productivity, groundwater depletion, and declining water availability, as well as increased pest incidence and salinity, already threaten sustainability and food security in the region (Wassmann, Jagadish, Sumfleth, et al. 2009).

Climate change is projected to have a significant and often adverse impact on agricultural production in South Asia, the development of the sector, and the economic benefits derived from it (Nelson et al. 2009). There are a significant number of risks arising from climate-change-related phenomena that need to be considered in assessing the future impacts on the sector (Box 5.4). For example, the upper temperature sensitivity threshold for current cultivars for rice is 35–38°C and for wheat is 30–35°C (Wassmann, Jagadish, Sumfleth, et al. 2009). Future heat extremes may thus pose a significant risk to regional production of these crops. This section will provide a short overview of the major risks to crop and agricultural production in the region before turning to model-based projections of future agricultural output.

Box 5.4: Observed Rice Yield Declines

Observed Rice Yield Decline and Slowdown in Rice Harvest Growth

Using agro-meteorological crop modeling, Pathak et al. (2003) explain the observed rice yield decline in the IGP (1985–2000) as a result of the combined decrease in radiation and increase in minimum temperature.[a] Confirming this, Auffhammer, Ramanathan, and Vincent (2006) apply an agro-economic model over all of India and find that atmospheric aerosols and greenhouse gases, reducing radiation and increasing minimum temperatures, have contributed to the recent slowdown in rice harvest growth.

In more recent work, the effects of changes in monsoon, drought, and temperature have been disentangled. Auffhammer et al. (2011) find that rice yields in India would be 1.7 percent higher on average if the monsoon pattern had not changed since 1960, and an additional four percent higher if two further meteorological changes, warmer nights and less precipitation at the end of the growing season, had not occurred. The individual effect of increasing minimum temperatures is reported at 3.4 percent; this caused more than half of the total yield decline. Accordingly, the results indicate that average yield in India could have been almost six percent higher (75 million tons in absolute terms) without changing climatic conditions and confirm that increasing minimum temperatures have had a greater impact on yield than changing monsoon characteristics. The analysis does not account for adaptive responses by farmers. While controlling for increases of yield due to advances in agricultural technology, the authors assume that the simulated yield reduction is a lower bound estimate (Auffhammer et al. 2011). Auffhammer et al. (2011) further point out that, though their analysis is based only on observational data and not on climate models, the results are consistent with climate model projections—and yield reductions are likely to be larger in the future with projected increasing temperatures and, in some models, a continued weakening of the monsoon (Chapter 5 on "Precipitation Projections").

Wheat Yield Stagnation and High-Temperature Negative Effects

Recent work by Lin and Huybers (2012) shows that wheat crop yields peaked in India and Bangladesh around 2001 and have not increased despite increasing fertilizer applications. Using a crop growth model, Kalra et al. (2008) explain the wheat yield stagnation in most parts of northwest India through the interactions of radiation and temperature change.

Observations of crop responses to extremely high temperatures in northern India indicate a significant and substantial negative effect following exposure to temperatures above 34°C. The authors conclude that present crop models may underestimate by as much as 50 percent the yield loss from local warming of 2°C (David B. Lobell, Sibley, Ivan Ortiz-Monasterio, and Ortiz-Monasterio 2012).

[a] Rice harvests are positively correlated with solar radiation late in the season and negatively correlated with night-time temperature.

The effects of rainfall deficits, extreme rainfall events, and flooding are projected to be felt differently in different parts of South Asia. For examples, Asada and Matsumoto (2009) analyze the effects of variations in rainfall on rice production in the Ganges-Brahmaputra Basin in India and Bangladesh. This is one of the most important regions for rice production in South Asia and is responsible for about 28 percent of the world's total rice production. Their focus is on regional differences between the upper and the lower Ganges and the Brahmaputra Basin. Based on climate and rice production data from 1961–2000, Asada and Matsumoto (2009) apply statistical modeling and find that the effect of changes in rainfall differs among the regions analyzed. While rice production in the upper Ganges Basin is strongly affected by rainfall variation and is vulnerable to rainfall shortages, rice production in the lower Ganges Basin is more strongly affected by floods. In the Brahmaputra Basin, in contrast, the drought effect is stronger than the flood effect as a consequence of increasing rainfall variation, though crops are vulnerable to both droughts and floods. These findings are highly relevant in the context of climate change as they provide a better understanding of regional differences and vulnerabilities to provide a stronger basis for adaptation and other responses (Asada and Matsumoto 2009).

Climatic Risk Factors

Extreme Heat Effects

Heat stress, which can be particularly damaging during some development stages and may occur more frequently with climate change, is not yet widely included in crop models and projections. Lobell et al. (2012) use satellite data to investigate the extreme heat effects on wheat senescence; they find that crop models probably underestimate yield losses for +2°C by as much as 50 percent for some sowing dates. Earlier work by Lobell et al. (2011) shows the sensitivity of rice, and wheat in India to increases in maximum temperature in the growing season. Compared to calculations of potential yields without historic trends of temperature changes since the 1980s, rice and wheat yields have declined by approximately 8 percent for every 1°C increase in average growing-season temperatures (David B Lobell, Schlenker, and Costa-Roberts 2011).

If temperatures increase beyond the upper temperature for crop development (e.g., 25–31°C for rice and 20–25°C for wheat, depending on genotype), rapid decreases in the growth and productivity of crop yields could be expected, with greater temperature increases leading to greater production losses (Wassmann, Jagadish, Sumfleth, et al. 2009). By analyzing the heat stress in Asian rice production for the period 1950–2000, Wassmann et al. (2009) show that large areas in South Asia already exceed maximum average daytime temperatures of 33°C.

By introducing the response to heat stress within different crop models, A. Challinor, Wheeler, Garforth, Craufurd, and Kassam (2007) simulate significant yield decreases for rice (up to –21 percent under double CO_2) and groundnut (up to –50 percent). Under a doubling of atmospheric CO_2 from the 380 ppm baseline, they show that at low temperature increases (+1°C, +2°C), the CO_2 effect dominates and yields increase; at high temperature increases (+3°C, +4°C), yields decrease.

Areas, where temperature increases are expected to exceed upper limits for crop development in critical stages (i.e., the flowering and the maturity stage) are highly vulnerable to heat-induced yield losses. Aggravating heat stress due to climate change is expected to affect rice crops in Pakistan, dry season crops in Bangladesh, and crops in the Indian States of West Bengal, Bihar, Jharkhand, Orissa, Tamil Nadu, Kerala, and Karnataka. The situation may be aggravated by reduced water availability due to changes in precipitation levels and falling groundwater tables, as well as by droughts, floods, and other extreme events (Wassmann, Jagadish, Sumfleth, et al. 2009).

Water and Groundwater Constraints

Agriculture and the food demands of a growing population are expected to be the major drivers of water usage in the future (De Fraiture and Wichelns 2010; Ian Douglas 2009), demonstrating the direct linkage between water and food security. At present, agriculture accounts for more than 91 percent of the total freshwater withdrawal in South Asia (including Afghanistan); Nepal (98 percent), Pakistan (94 percent), Bhutan (94 percent) and India (90 percent) have particularly high levels of water withdrawal through the agricultural sector (2011 data by World Bank 2013d). Even with improvements in water management and usage, agriculture is expected to remain a major source of water usage (De Fraiture and Wichelns 2010).

Even without climate change, sustainable use and development of groundwater resources remain a major challenge (Green et al. 2011). In India, the "global champion in groundwater irrigation" (Shah 2009), resources are already at critical levels and about 15 percent of the country's groundwater tables are overexploited, meaning that more water is being extracted than the annual recharge capacity (Ministry of Environment and Forests 2012). The Indus Basin belongs to the areas where groundwater extraction exceeds annual replenishment. In addition, groundwater utilization in India is increasing at a rate of 2.5–4 percent (Ministry of Environment and Forests 2012). Year-round irrigation is especially needed for intensifying and diversifying small-scale farming. Without any measures to ensure a more sustainable use of groundwater resources, reductions in agricultural production and in the availability of drinking water are logical consequences—even without climate change (Rodell et al. 2009). Climate change is expected to further aggravate the situation (Döll 2009; Green et al. 2011).

Immerzeel, Van Beek, and Bierkens (2010) demonstrate how changes in water availability in the Indus, Ganges, and Brahmaputra rivers may impact food security. The authors estimate that, with a temperature increase of 2–2.5°C compared to pre-industrial levels, by the 2050s reduced water availability for agricultural production may result in more than 63 million people no longer being able to meet their caloric demand by production in the river basins.

Depending on rainfed agriculture for food production carries high risks, as longer dry spells may result in total crop failure (De Fraiture and Wichelns 2010). In India, for example, more than 60 percent of the crop area is rainfed (e.g., from green water), making it highly vulnerable to climate induced changes in precipitation patterns (Ministry of Environment and Forests 2012). The bulk of rice production in India, however, comes from irrigated agriculture in the Ganges Basin (Eriksson et al. 2009); changes in runoff patterns in the Ganges River system are projected to have adverse effects even on irrigated agriculture.

Based on projections for the 2020s and 2030s for the Ganges, Gornall et al. (2010) provide insight into these risks. Consistent with other studies, they project overall increased precipitation during the wet season for the 2050s compared to 2000,[107] with significantly higher flows in July, August, and September. From these global model simulations, an increase in overall mean annual soil moisture content is expected for 2050 (compared to 1970–2000); the soil is also expected to be subject to drought conditions for an increased length of time. Without adequate water storage facilities, however, the increase of peak monsoon river flow would not be usable for agricultural productivity; increased peak flow may also cause damage to farmland due to river flooding (Gornall et al. 2010).

Other river basins are also projected to suffer surface water shortages. Gupta, Panigrahy, and Paribar (2011) find that Eastern Indian agriculture may be affected due to the shortage of surface water availability in the 2080s as they project a significant reduction in the lower parts of the Ganga, Bahamani-Baitrani, and Subarnrekha rivers and the upper parts of the Mahanadi River.

In addition to the large river systems, groundwater serves as a major source of water, especially for irrigation in South Asia (here referring to India, Pakistan, lower Nepal, Bangladesh, and Sri Lanka) (Shah, 2009). In India, for example, 60 percent of irrigation for agriculture (Green et al. 2011) and 50–80 percent of domestic water use depend on groundwater, and yet 95 percent of total groundwater consumption is used for irrigation (Rodell, Velicogna, and Famiglietti 2009).

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[107] SRES A1F scenario leading to a temperature increase of approximately 2.3°C above pre-industrial levels by 2050.

With its impacts on surface water and precipitation levels, climate change would affect groundwater resources (Green et al. 2011). South Asia, and especially India and Pakistan, are highly sensitive to decreases in groundwater recharge as these countries are already suffering from water scarcity and largely depend on water supplied from groundwater (Döll 2009). Groundwater resources are particularly important to mitigate droughts and related impacts on agriculture and food security, and it is likely that groundwater resources will become even more important in the future at times of low surface water availability and dry spells (Döll 2009; Green et al. 2011). To date, climate-related changes in groundwater resources have been relatively small compared to non-climatic forces such as groundwater mining, contamination, and reductions in recharge.

Groundwater recharge is highly dependent on monsoon rainfall, and the changing variability of the monsoon season poses a severe risk to agriculture. Farming systems in South Asia are highly adapted to the local climate, particularly the monsoon. Approximately 80 percent of the rainfall over India alone occurs during the summer monsoon (June-September). This rainfall provides water for the rainfed and irrigated crops that depend largely on surface and groundwater reserves that are replenished by the monsoon rains. Observations indicate the agricultural sector´s vulnerability to changes in monsoon precipitation: with a 19-percent decline in summer monsoon rainfall in 2002, Indian food grain production was reduced by about 18 percent compared to the preceding year (and 10–15 percent compared to the previous decadal average) (Mall et al. 2006).

Observations of agricultural production during ENSO events confirm strong responses to variations in the monsoon regime. ENSO events play a key role in determining agricultural production (Iglesias, Erda, and Rosenzweig 1996). Several studies, using historical data on agricultural statistics and climate indices, have established significant correlations between summer monsoon rainfall anomalies, strongly driven by the ENSO events, and crop production anomalies (e.g., Webster et al. 1998).

Recent statistical analysis by Auffhammer, Ramanathan, and Vincent (2011) also confirm that changes in monsoon rainfall over India, with less frequent but more intense rainfall in the recent past (1966–2002) contributed to reduced rice yields. Droughts have also been found to have more severe impacts than extreme precipitation events (Auffhammer et al. 2011). This decrease in production is due to both direct drought impacts on yields and to the reduction of the planted areas for some water-demanding crops (e.g., rice) as farmers observe that the monsoon may arrive too late (Gadgil and Rupa Kumar 2006).

Salinization

Soil salinity has been hypothesized to be one possible reason for observed yield stagnations (or decreases) in the Indo-Gangetic Plain (Ladha et al. 2003). Climate change is expected to increase the risk of salinity through two mechanisms. First, deltaic regions and wetlands are exposed to the risks of sea-level rise and increased inundation causing salinity intrusion into irrigation systems and groundwater resources. Second, higher temperatures would lead to excessive deposits of salt on the surface, further increasing the percentage of brackish groundwater (Wassmann, Jagadish, Heuer, Ismail, Redonna, et al. 2009). However, similar to diminished groundwater availability, which is largely due to rates of extraction exceeding rates of recharge and is, in this sense, human induced (Bates 2008), groundwater and soil salinization are also caused by the excessive use of groundwater in irrigated agriculture. Salinity stress through brackish groundwater and salt-affected soils reduces crop yields; climate change is expected to aggravate the situation (Wassmann, Jagadish, Heuer, et al., 2009).

Drought

Droughts are an important factor in determining agricultural production and food security. They can also have severe implications for rural livelihoods, migration, and economic losses (Intergovernmental Panel on Climate Change 2012; UNISDR 2011). Evidence indicates that parts of South Asia have become drier since the 1970s (Intergovernmental Panel on Climate Change 2007) in terms of reduced precipitation and increased evaporation due to higher surface temperatures, although the attribution of these changes in dryness has not yet been resolved.

Bangladesh is regularly affected by severe droughts as a result of erratic rainfall and unstable monsoon precipitation. While country-wide droughts occur approximately every five years, local droughts in rainfed agricultural areas, such as the northwest of Bangladesh, occur more regularly and cause yield losses higher than those from flooding and submergence (Wassmann, Jagadish, Sumfleth, et al. 2009).

Droughts can be a result of an overall decline in rainfall in wet or dry season, a shift in the timing of the wet season, as well as a strong local warming that exhausts water bodies and soils by evaporation. Across models, total annual precipitation is projected on average to increase over southern India and decrease over northwestern India, Pakistan, and Afghanistan, while the difference between years might increase due to increased interannual variability of the monsoon (Chapter 5 on "Precipitation Projections"). Some models show a peak in precipitation increase over northern India and Pakistan rather than over southern India (e.g., Taylor et al. 2012). In the dry season, the models generally agree on a projected widespread reduction in precipitation across the region (Chapter 5 on "Precipitation Projections"), which increases the population's dependence on river flow, above ground water storage, and ground water for natural systems during the monsoon season. In a 4°C warming scenario globally, annual mean warming is projected to exceed 4°C in southern India and rise to more than 6°C in Afghanistan (Chapter 5 on "Projected Temperature Changes")—increasing both evaporation and water requirements of plants for evapotranspiration. Using such projections in precipitation and warming, (Dai 2012) estimates that, for a global mean warming of 3°C by the end of the 21st century, the drought risk expressed by the Palmer Drought Severity Index (PDSI) becomes higher across much of northwestern India, Pakistan, and Afghanistan but becomes lower across southern and eastern India.

It should be noted that such projections are uncertain, not only due to the spread in model projections but also to the choice of drought indicator (Taylor et al. 2012). For example, drought indicators like PDSI include a water balance calculation involving precipitation and evaporation and relate the results to present-day conditions, so that drought risk is presented relative to existing conditions. By contrast, Dai (2012) showed that projected changes in soil-moisture content indicate a drying in northwestern Pakistan, Afghanistan, and the Himalayas—but no significant drying or wetting over most of India.

Flooding and Sea-level Rise

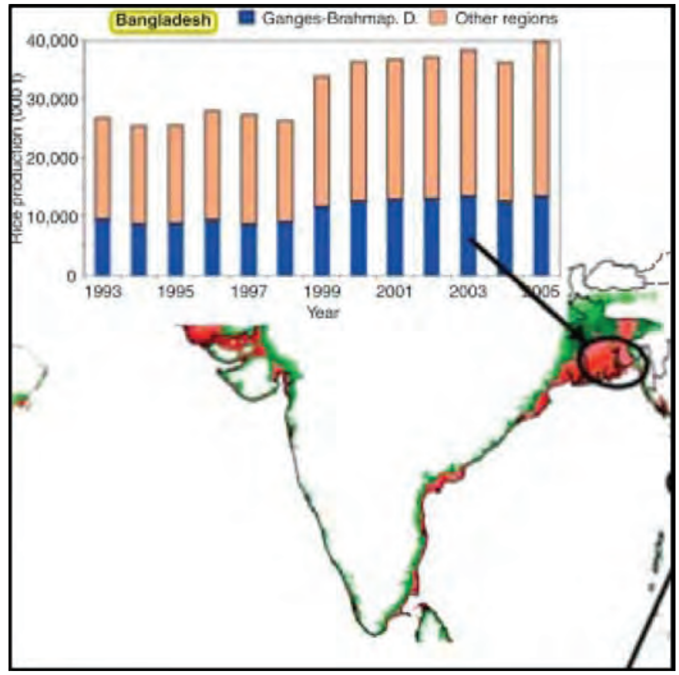
Flooding poses a particular risk to deltaic agricultural production. The rice production of the Ganges-Brahmaputra-Meghna Delta region of Bangladesh, for example, accounts for 34 percent of the national rice production and is used for domestic consumption only. Large parts of the area are less than five meters above sea level and therefore at high risk of sea-level rise (see Figure 5.12). Bangladesh is a rice importer; even today, food shortages are a persistent problem in the country, making it even more vulnerable to production shocks and rising food prices (Douglas 2009; Wassmann, Jagadish, Sumfleth, et al. 2009). Higher flood risk as a consequence of climate change poses a severe threat to the Aman rice crop in Bangladesh, which is one of the three rice crops in Bangladesh that grows in the monsoon season; it accounts for more than half of the national crop (Wassmann, Jagadish, Sumfleth, et al. 2009). Increased flood risk to the Aman and Aus (pre-monsoon) rice crops is likely to interact with other climate change impacts on the Boro (post-monsoon) rice crop production, leading to substantial economic damages (Yu et al. 2010). In this region, large amounts of productive land could be lost to sea-level rise, with 40-percent area losses projected in the southern region of Bangladesh for a 65 cm rise by the 2080s (Yu et al. 2010).

Tropical Cyclone Risks

Tropical cyclones already lead to substantial damage to agricultural production, particularly in the Bay of Bengal region, yet very few assessments of the effects of climate change on agriculture in the region include estimates of the likely effects of increased tropical cyclone intensity.

Tropical cyclones are expected to decrease in frequency and increase in intensity under future climate change (see Chapter 4 on "Tropical Cyclone Risks" for more discussion on tropical cyclones). More intense tropical cyclones, combined with sea-level rise, would increase the depth and risk of inundation from floods

Figure 5.12: Low elevation areas in the Ganges-Brahmaputra Delta



Source: Wassmann et al. (2009)

and storm surges and reduce the area of arable land (particularly in low-lying deltaic regions) (Box 5.5). In Bangladesh, for example, a projected 27 cm sea-level rise by 2050, combined with a storm surge induced by an average 10-year return-period cyclone such as Sidr, could inundate an area 88-percent larger than the area inundated by current cyclonic storm surges[108] (World Bank 2010d). Under this scenario, for the different crop seasons, the crop areas

Box 5.5: The Consequences of Cyclone Sidr

In 2007, category four cyclone Sidr (NASA, 2007) in Bangladesh caused a production loss of 800,000 tons of rice, or about 2 percent of total annual production in 2007 (FAO 2013). It also resulted in $1.7 billion in economic damages. The major damage occurred in the housing sector, followed by agriculture and infrastructure (Wassmann, Jagadish, Sumfleth, et al. 2009; World Bank 2010d).

[108] Based on the assumption that landfall occurs during high-tide and that wind speed increases by 10 percent compared to cyclone Sidr.

exposed to inundation are projected to increase by 19 percent for the Aman crop, by 18 percent for the Aus crop, and by 43 percent for the Boro crop. The projected regional sea-level rise by 2050 is estimated in Chapter 5 on "Regional Patterns of Climate Change" at around 30–35 cm under both the 2°C and 4°C scenarios, with sea levels rising to 80 cm by 2100 in the former scenario and to over a meter in the latter one.

Uncertain CO_2 Fertilization Effect

Despite the different representations of some specific biophysical processes, the simulations generally show that the positive fertilization effect of the increasing atmospheric CO_2 concentration may counteract the negative impacts of increased temperature (e.g., A. J. Challinor & Wheeler 2008). There are, however, regional differences: For the intensive agricultural areas of northwest India, enhanced wheat and rice yields might be expected under climate change, provided that current irrigation can be maintained. Enhanced yields could also be expected for rainfed rice in southwest India if the temperature increase remains limited, as water use efficiency is enhanced under elevated atmospheric CO_2 levels. Uncertainties associated with the representation or parameterization of the CO_2 fertilization effect, however, lead to a large range of results given by different crop models (see Chapter 3 on "Crops" for more discussion on the CO_2 fertilization effect). For example, large parts of South Asia are projected to experience significant declines in crop yield without CO_2 fertilization, while increases are projected when taking the potential CO_2 fertilization effect into account. However, controversy remains as to the strength of the effect, and there is considerable doubt that the full benefits can be obtained (Müller et al. 2010).

Projected Changes in Food Production

The impacts of climate change on crop production in South Asia could be severe. Projections are particularly negative when CO_2 fertilization, of which the actual benefits are still highly uncertain, is not accounted for. Low-cost adaptation measures may mitigate against yield declines up to 2.5°C warming if the CO_2 fertilization effect is taken into account; where the CO_2 fertilization effect is not accounted for, yields show a steady decline.

It is important to recognize that the assessments outlined below do not yet include the known effects of extreme high temperatures on crop production, the effects of extreme rainfall and increased seasonality of the monsoon, lack of needed irrigation water (many assessments assume irrigation will be available when needed), or the effects of sea-level rise and storm surges on loss of land and salinization of groundwater. The evidence from crop yields studies indicates that the CO_2 fertilization effect is likely to be outweighed by the negative effects of higher warming above 2.5°C.

The crop yield review here shows a significant risk, in the absence of a strong CO_2 fertilization effect, of a substantial, increasing negative pressure from present warming levels upward. The rapid increase in the area of South Asia expected to be affected by extreme monthly heat is 10 percent of total land area by 2020 and approximately 15 percent by 2030;[109] combined with evidence of a negative response to increases in maximum temperature in the growing season, this points to further risks to agricultural production in the region.

There are relatively few integrated projections to date of total crop production in South Asia. Most published studies focus on estimating changes in crop yield (that is, yield per unit area) for specific crops in specific regions, and examine the consequences of climate change and various adaptation measures on changes in yield. Although total crop production (for a given area over a given timeframe) is fundamentally influenced by crop yield, other factors (availability of water, soil salinization, land availability, and so forth) play an important role and need to be accounted for.

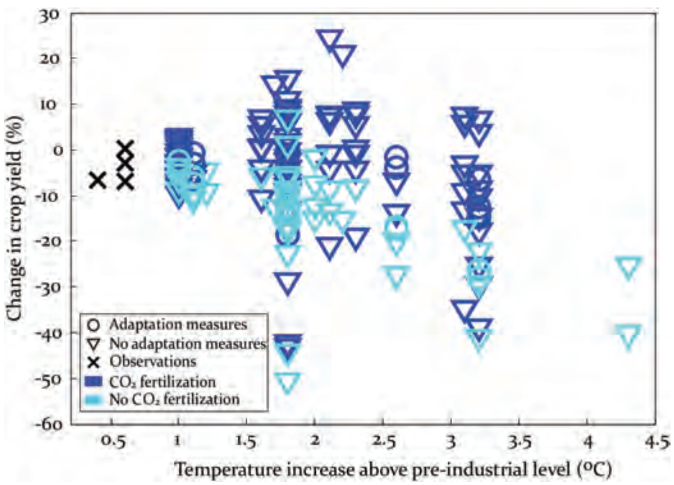
Crop yields in South Asia have improved over time, and it can be expected that future improvements may occur due to technological changes, cultivar breeding and optimization, production efficiencies, and improved farm management practices. A recent global assessment of crop yield trends, however, indicates grounds for concern in South Asia (Lobell, Schlenker, and Costa-Roberts 2011). In India, rice crop yields have been improving on about 63 percent of the cropped area—but not improving on the remainder. For wheat, crop yield is increasing on about 30 percent of the cropped area in India, but not on the rest. In Pakistan, wheat crop yields are improving on about 87 percent of the cropped area. For soybean crops in India, yield improvements are occurring on about half of the area. Maize, not yet a large crop in India, exhibits yields improving on over 60 percent of the cropped area.

Figure 5.13 shows the relationship between global mean temperature and yield changes for most of the crops grown in South Asia. Recent studies show results for different crops (maize, wheat, rice, groundnut, sorghum, and soybean), for different irrigation systems, and for different regions (see Appendix 4 for details). Often the results are presented as a range for different GCM models or for a region or sub-regions. In the following analysis, which is an attempt to identify a common pattern of the effects of CO_2 fertilization and adaptation measures on crop yield, all crops are gathered together without distinction among crop types, irrigation systems, or regions in Asia. In cases in which a study showed a range of GCM models for a specific crop, the average of the models was considered as representative of yield change.

Across the whole warming range considered, there exists a significant relationship between crop yield decrease and temperature increase ($F = 25.3$, $p < 0.001$) regardless of crop type or

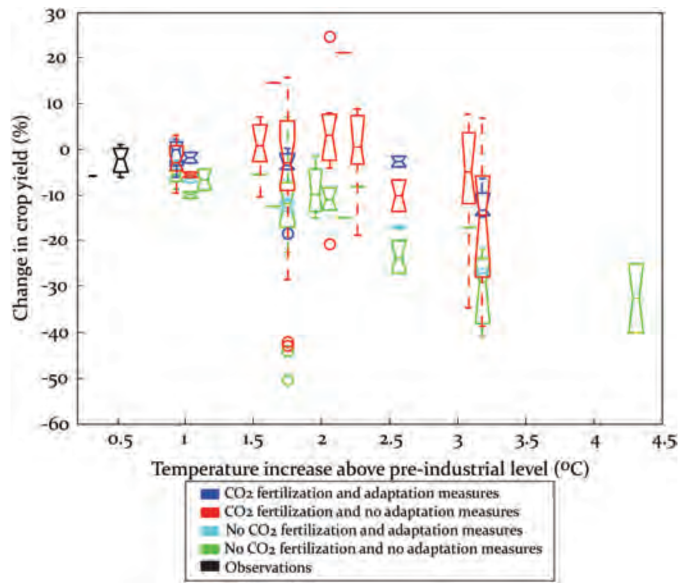
[109] Values for this timeframe are independent of the warming scenario that is projected for both a 2°C and a 4°C world.

Figure 5.13: Scatter plot illustrating the relationship between temperature increase above pre-industrial levels and changes in crop yield



Data points represent different types of crops, in different regions of Asia, considering different irrigation systems and the effects of CO_2 fertilization (dark blue) or not (light blue), and of adaptation measures (circles) or not (triangles).

Figure 5.14: Box plot illustrating the relationship between temperature increase above pre-industrial levels and changes in crop yield



The whiskers are lines extending from each end of the boxes to show the extent of the rest of the data. Outliers are data with values beyond the ends of the whiskers. Overlap of the narrowing around the median (notches) indicates that the difference between the medians is not significant to $p<0.05$.

whether the effects of CO_2 fertilization or adaptation measures are taken into account:

- For warming below about 2.1 degrees above pre-industrial levels, and with cases with and without CO_2 fertilization taken together, there is no longer a significant relationship between warming and yield loss. This suggests that the effects of adaptation measures and CO_2 fertilization are stronger and may compensate for the adverse effects of climate change under 2°C warming.
- If one excludes cases that include CO_2 fertilization, then significant yield losses may occur before 2°C warming.
- With increases in warming about 2°C above pre-industrial levels, crop yields decrease regardless of these potentially positive effects. While CO_2 fertilization partly compensates for the adverse effects of climate change, this compensation appears stronger under temperature increases below 2°C above pre-industrial levels.

The same data as above is shown in Figure 5.14 with statistical relationships. The median estimates of yields indicate that studies with CO_2 fertilization and adaptation measures (dark blue) and CO_2 fertilization without adaptation measures (red) show a fairly flat response to about 2°C warming—and then show a decreasing yield trend. Yields excluding these effects (green and light blue) show a decreasing yield trend with a temperature increase. There is no significant difference between red bars (adding only CO_2 fertilization effects) between 1.2–2.1°C temperature increase levels; this becomes significant at 2.5°C. If the effects of both CO_2 fertilization and adaptation measures are taken into account (dark blue bars), then the medians only differ significantly at the highest level of temperature increase. This suggests that a substantial, realized CO_2 fertilization effect and adaptation measures have positive effects at lower levels of temperature increases but that, at higher temperature increases, this effect is overshadowed by the stronger effects of greater climate change. If there is a strong CO_2 fertilization effect, the effects of warming might be compensated for by low-cost adaptation measures below about 2°C warming, whereas for warming greater than this yield levels are likely to decrease. With increases in warming above about 2°C above pre-industrial levels, crop yields appear likely to decrease regardless of these potentially positive effects.

This overall pattern of increasingly large and likely negative impacts on yields with rising temperatures would have a substantial effect on future crop production.

Lal (2011) estimates the overall consequences for crop production in South Asia. He finds that in the longer term CO_2 fertilization effects would not be able to offset the negative impacts of increases in temperatures beyond 2°C on rice and wheat yields in South Asia.

He estimates that cereal production would decline 4–10 percent under the most conservative climate change projections (a regional warming of 3°C) by the end of this century.

A recent assessment by Nelson et al. (2010) is a fully integrated attempt to estimate the global crop production consequences of climate change; this report draws substantially upon that work. The most important crops in South Asia are rice and wheat, accounting for about 50 percent and 40 percent of production, respectively. Nelson et al. (2009, 2010)[110] estimate the direct effects of climate change (changes in temperature and precipitation for rainfed crops and temperature increases for irrigated crops) on the production of different crops with and without the effect of CO_2 fertilization under a global mean warming of about 1.8°C above pre-industrial levels by 2050. They find that South Asia (including Afghanistan) is affected particularly hard by climate change—especially when the potential benefits of the CO_2 fertilization effect are not included (Nelson et al., 2009, 2010). The authors make the decision in conducting their analysis to show mainly results excluding the CO_2 fertilization effect as "this is the most likely outcome in farmers' fields."

Two climate model projections are applied for the South Asian region in 2050. One of the models (NCAR) projects a substantial (11 percent) increase in precipitation; the other (CSIRO) model projects about a 1.6 percent increase above 2000 levels. The CMIP5 projections reviewed above project about a 2.3 percent increase in precipitation per degree of global mean warming (1.3–3 percent range); hence, more recent projections than those deployed by Nelson et al. (2010) imply a likely total increase of about 4 percent in 2050. In analyzing the results of this work, this report averages the model results; in the case of South Asia there is little overall difference between the models.

Table 5.2 provides a summary of the assessment of the integrated effects of climate change on crop production in South Asia. Without climate change, overall crop production is projected to increase significantly (by about 60 percent) although, in per capita terms, crop production will likely not quite keep pace with projected

[110] The estimates are based on the global agriculture supply and demand model IMPACT 2009, which is linked to the biophysical crop model DSSAT. Climate change projections are based on the NCAR and the CSIRO models and the A2 SRES emissions scenario, leading to a global mean warming of about 2.0°C above pre-industrial levels by 2050 (Nelson et al. 2009, 2010). To capture the uncertainty in the CO_2 fertilization effect, simulations are conducted at two levels of atmospheric CO_2 in 2050: the year 2000 level of 369 ppm, called the no-CO_2fertilization scenario; and the projected level in 2050 for 532 ppm under the SRES A2 scenario, termed the with-CO_2 fertilization scenario.

Table 5.2: Major results from the Nelson et al. (2010) assessment of crop production changes to 2050 under climate change in South Asia

Crops	Crop Production (Year 2000)	Crop as Percentage of Total 2000	Projected Yield Improvements No Climate Change (% p.a.)	Crop Production 2050 No Climate Change	Crop Production 2050 with Climate Change and No CO_2 fertilization Effect	Average Annual Yield Change with Climate Change
Rice (mmt)	120	48%	0.9%	169	145	–0.2%
Wheat (mmt)	97	38%	1.6%	191	103	–1.3%
Maize (mmt)	16	6%	0.6%	19	16	0.1%
Millet (mmt)	11	4%	1.5%	12	11	0.0%
Sorghum (mmt)	8	3%	1.2%	10	8	1.4%
Total (mmt)	252			401	282	
Cereal Availability (kg/capita)	185			174	122	
Daily Per Capita Availability (kcal/capita/day)	2,424			2,660	2,241	
Total Population (million)	1,361			2,306	2,306	
Net Cereal Exports (mmt)	15			–20	–53	
Value of Net Cereal Trade (million $)	$2,589			-$2,238	-$14,827	
Number of Malnourished Children (million)	76			52	59	

Note that crop production in 2050 with climate change and no CO_2 fertilization effect is calculated as an average of the CSIRO and NCAR models used by Nelson et al. (2010) in the study. Projections start from climate conditions, including CO_2 concentration around year 2000. No explicit assumptions are made as to the effects of climate change to year 2000.

population growth. Under climate change, however, and assuming the CO_2 fertilization effect does not increase above present levels, a significant (about one-third) decline in per capita South Asian crop production is projected. With much larger yield reductions projected after 2050 than before (based on the above analysis), it could be expected that this food production deficit could grow further.

In South Asia, with the growth in overall crop production reduced from about 60 percent in the absence of climate change to a little over a 12 percent increase, and with population increasing about 70 percent over the same period, there would be a need for substantial crop imports. Nelson et al. (2010) estimate imports in 2050 to be equivalent to about 20 percent of production in the climate change scenario. Compared to the case without climate change, where about five percent of the assessed cereals would be imported in 2050 under the base scenario (costing over $2 billion per year), import costs would increase to around $15 billion per year.

In addition to the direct impacts of climate change on water and agricultural yield, there are also indirect impacts which have major implications for the food security of the region. These include food price fluctuations and trade and economic adjustments, which may either amplify or reduce the adverse effects of climate change.

Even without climate change, world food prices are expected to increase due to population and income growth as well as a growing demand for biofuels (Nelson et al. 2010). At the global level and with climate change, Nelson et al. (2010) estimate additional world food price increases to range from 32–37 percent for rice and from 94–111 percent for wheat by 2050 (compared to 2000). Adjusting for CO_2 fertilization as a result of climate change, price increases are projected to be 11–17 percent lower for rice, wheat, and maize, and about 60-percent lower for soybeans (Nelson et al. 2010).

While per capita calorie availability would be expected to increase by 9.7 percent in South Asia by 2050 without climate change, it is projected to decline by 7.6 percent below 2000 levels with climate change. Taking CO_2 fertilization into account, the decline would be 4.3 percent compared to calorie availability in 2000, which is still a significant change compared to the no-climate-change scenario. The proportion of malnourished children is expected to be substantially reduced by the 2050s without climate change. However, climate change is likely to partly offset this reduction, as the number of malnourished children is expected to increase by 7 million compared to the case without climate change (Nelson et al. 2010).[111]

Impacts in Bangladesh

While the risks for South Asia emerge as quite serious, the risks and impacts for Bangladesh are arguably amongst the highest in the region. Yu et al. (2010) conducted a comprehensive assessment of future crop performance and consequences of production losses for Bangladesh.

Yu et al. (2010) assess the impacts of climate change on four different crops under 2.1°C, 1.8°C, and 1.6°C temperature increases above pre-industrial levels in 2050.[112] They also take into account soil data, cultivar information, and agricultural management practices in the CERES (Crop Environment Resources Synthesis) model. The study accounts for temperature and precipitation changes, flood damage, and CO_2 fertilization for Aus (rice crop, planted in April), Aman (rice crop, planted in July), Boro (rice crop, planted in December), and wheat. Aman and Boro production areas represent 83 percent of the total cultivated area for these four crops, Aus production areas represent 11.1 percent, and wheat production areas represent 5.9 percent.

Yu et al. (2010) first estimate the impacts of climate change without taking into account the effects of flooding on production. They find that the Aus, Aman, and wheat yields are expected to increase whereas Boro production is expected to decrease as the Boro crop is more reactive to changes in temperature than changes in precipitation. When river and coastal flooding are taken into account, Aus and Aman crop production is expected to decrease. Note that Boro and wheat production are not expected to be affected by river or coastal flooding.

Yu et al. (2010) also evaluate the impact of coastal flooding on the production of rice and wheat in Bangladesh. The authors estimate the effects of floods on production using sea-level rise projections under the scenarios B1 and A2 only. Table 5.3 displays the sea-level rise values under the scenarios B1 and A2 used in this study. Taking into account the number of days of submergence, the relative plant height being submerged, and development stage of the plant (from 10 days after planting to maturity), the authors calculate the flood damage as a percentage of the yield reduction. Values for yield reduction vary from 0 percent when floods submerge the plants to 25–50 percent of the mature plant height for fewer than six days, to 100 percent when floods submerge more than 75 percent of plant height for more than 15 days at any stage of plant development.

Taking into account the impact of changes in temperature and precipitation, the benefits of CO_2 fertilization, mean changes in floods and inundation, and rising sea levels, the authors estimate that climate change will cause an approximately 80-million-ton reduction in rice production from 2005–50, or about 3.9 percent

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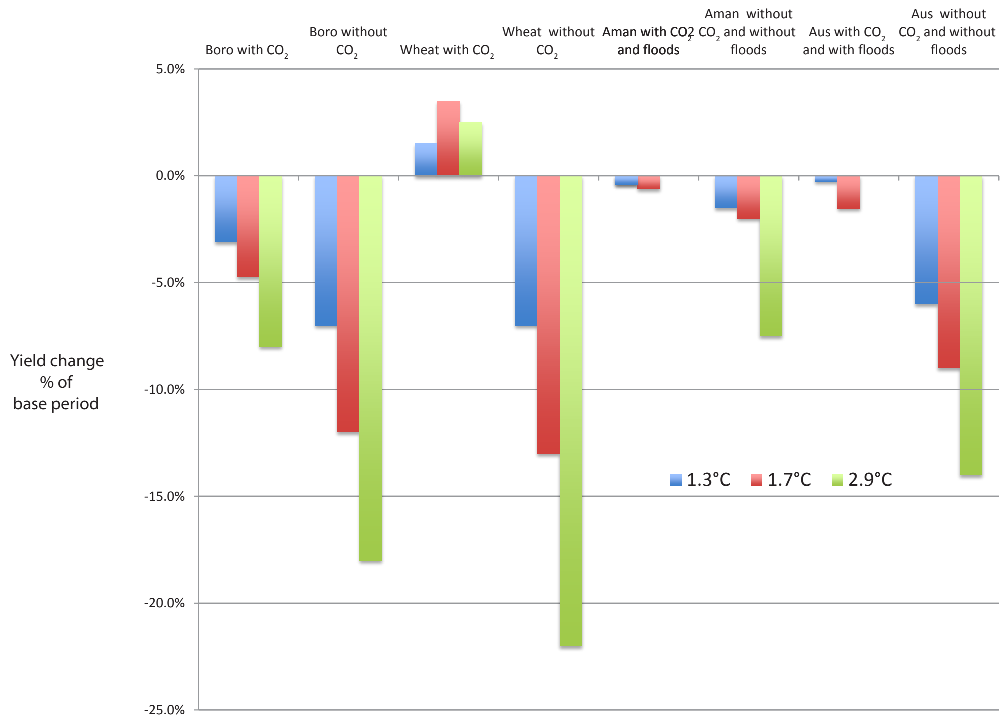
111 All estimates presented by Nelson et al. (2010) are based on the global agriculture supply and demand model IMPACT 2009, which is linked to the biophysical crop model DSSAT. Climate change projections are based on the NCAR and CSIRO models and the A2 SRES emissions scenario (global-mean warming of about 1.8°C above pre-industrial levels by 2050 globally). In this study, crop production growth is determined by crop and input prices, exogenous rates of productivity growth and area expansion, investments in irrigation, and water availability. Demand is a function of price, income, and population growth, and is composed of four categories of commodity demand: food, feed, biofuels, feedstock, and other uses.

112 These temperature increases are based on the IPCC SRES A1B, A2, and B1 scenarios, respectively.

Figure 5.15: Median production change averaged across the climate change scenarios (A1B, A2, and B1) with and without CO_2 fertilization



This figure compares the integrated effects of all factors (climate change, CO_2 fertilization, and planning) for each of the main crop types. Note that for Boro and wheat, flooding does not affect production. These are compared with the cases excluding CO_2 fertilization but including the effects of climate change.

Source: Data from Yu et al. (2010).

Table 5.3: Projected and estimated sea-level rise under B1 and A2 scenarios from Yu et al. (2010), compared to the 2°C and 4°C world projections in this report (see Chapter 5 on "Regional Patterns of Climate Change")

"Warming World"	Scenario/Decade	2030s	2050s	2080s
2°C World	IPCC SRES B1	5cm	8cm	15cm
	RCP2.6	20cm	35cm	55cm
4°C World	IPCC SRES A2	15cm	27cm	62cm
	RCP8.5	20cm	35cm	75cm

annually[113] (World Bank 2010a; Yu et al. 2010). With an annual rice production of 51 million tons (2011 data based on FAO 2013), this amount is almost equivalent to two years of current rice production in Bangladesh. The results should probably be seen as optimistic as the simulations include highly uncertain benefits from CO_2 fertilization (Yu et al. 2010).

Yu et al. (2010) estimate the discounted total economy-wide consequences of climate change at about $120 billion between 2005–50, or $2.68 billion per year. This represents a decline of 5.14 percent in the national GDP. In the scenario with the most severe climate change impacts, however, GDP is expected to decrease by about eight percent during the same period and up to 12.2 percent between 2040–50. They also find that the discounted total losses in agricultural GDP due to the combined impacts of climate change would be approximately $25.8 billion, or $0.57 billion per annum.

The Implications of Declining Food Production for Poverty

The impacts of climate change on food prices, agricultural yields, and production are expected to have direct implications for human well-being. In particular, per capita calorie availability and child

113 Projected annual reduction losses over the 45-year period range from 4.3 percent under the A2 scenarios to 3.6 percent under the B1 scenarios. GCM uncertainty further widens the range of projections from 2–6.5 percent. The 16 GCMs applied in this study for the two climate scenarios project a median warming of 1.6°C above 1970–99 temperatures (approximately 2°C above pre-industrial levels) and an increase of 4 percent in annual precipitation as well as greater seasonality in Bangladesh by 2050 (World Bank, 2010a).

malnutrition, affecting long-term growth and health, may be severely affected by climate change and its various effects on the agricultural sector (Nelson et al. 2010). Furthermore, uneven distribution of the impacts of climate change is expected to have adverse effects on poverty reduction.

Hertel et al. (2010) show that, by 2030, poverty implications due to rising food price in response to productivity shocks would have the strongest adverse effects on a selected number of social strata. In a low-productivity scenario, described as a world with rapid temperature increases and crops highly sensitive to warming, higher earnings result in declining poverty rates for self-employed agricultural households. This is due to price increases following production shocks. Non-agricultural urban households, in turn, are expected to suffer the most negative impacts of food price increases. As a result, the poverty rate of non-agricultural households in this scenario rises by up to a third in Bangladesh.[114]

Table 5.4: Electricity sources in South Asian countries

Country	Hydroelectricity (% of total)	Thermoelectricity (including coal, oil, natural gas and nuclear power) (% of total)
Bangladesh	3.9	96.0
Bhutan	n.a	n.a
India	11.9	85.5
Maldives	n.a	n.a
Nepal	99.9	0.1
Pakistan	33.7	66.3
Sri Lanka	52.3	47.5

Source: Adapted from" and then go one with World Bank (2013f); World Bank (2013f); World Bank (2013g); World Bank (2013h); World Bank (2013i); World Bank (2013j).

Human Impacts

Populations in the region are expected to experience further repercussions from the climatic risk factors outlined above. The human impacts of climate change will be determined by the socioeconomic context in which they occur. The following sections outline some of these expected implications, drawing attention to how particular groups in society, such as the poor, are the most vulnerable to the threats posed by climate change.

Risks to Energy Supply

Sufficient energy supply is a major precondition for development, and electricity shortages remain a major bottleneck for economic growth in South Asian countries (ADB 2012). A lack of energy, and poor infrastructure in general, deter private investment and limit economic growth (Naswa and Garg 2011). Only 62 percent of the South Asian population (including Afghanistan) has access to electricity, including 62 percent in Pakistan, 66 percent in India, 41 percent in Bangladesh, 43 percent in Nepal, and 77 percent in Sri Lanka; no data are available for Bhutan and the Maldives (2009 data; World Bank 2013e). This indicates that there is still a major gap in electricity supply to households—especially in rural areas.

As Table 5.4 shows, the two main sources of electricity in the region are hydroelectric and thermoelectric power plants. Both sources are expected to be affected by climate change.

The high proportion of electricity generation in South Asia that requires a water supply points to the potential vulnerability of the region's electricity sector to changes in river flow and in water temperature. Hydroelectricity is dependant only on river runoff (Ebinger and Vergara 2011). Thermoelectricity, on the other hand, is influenced by both river runoff and, more generally, the availability and temperature of water resources (Van Vliet et al. 2012).

Hydroelectricity

India is currently planning large investments in hydropower to close its energy gap and to provide the energy required for its targeted 8–9 percent economic growth rate (Planning Commission, 2012a). This is in spite of the potential negative impacts on local communities and river ecosystems (Sadoff and Muller 2009). The major as yet unexploited hydropower potential lies in the Northeast and Himalayan regions. As it is estimated that so far only 32 percent of India's hydropower potential, estimated at 149 GW, is being utilized, India is planning to harness the estimated additional capacity of 98,863 MW in the future (Planning Commission 2012a). Substantial undeveloped potential for hydropower also exists in other South Asian countries (Sadoff and Muller 2009). Nepal, for example, utilizes only approximately 0.75 percent of its estimated hydropower potential (Shrestha and Aryal 2010).

With the projected increasing variability of and long-term decreases in river flow associated with climate change, electricity generation via hydropower systems will become more difficult to forecast. This uncertainty poses a major challenge for the design and operation of hydropower plants. In Sri Lanka, for example, where a large share of the electricity is generated from hydropower, the multipurpose Mahaweli scheme supplies 29 percent of national power generation and 23 percent of irrigation water. A projected decrease in precipitation in the Central Highlands of Sri Lanka may cause competition for water across different sectors (Eriyagama, Smakhtin, Chandrapala, and Fernando 2010).

114 Hertel et al. (2010) assume an unchanged economy from 2001. Their low-productivity scenario is associated with a 32 percent food price increase.

Increasing siltation of river systems also poses a risk to hydropower. India, for example, has already recorded many cases of malfunctioning power turbines due to high levels of siltation (Naswa and Garg 2011; Planning Commission 2012b). Yet another climate-induced risk for hydropower systems is physical damage due to landslides, floods, flash floods, glacial lake outbursts, and other climate-related natural disasters (Eriksson et al. 2009; Naswa and Garg 2011; Shrestha and Aryal 2010). Nepal (with 2,323 glacial lakes) and Bhutan (with 3,252 glacial lakes) are particularly vulnerable to glacial lake outbursts. The glacial lake flood from the Dig Tsho in Nepal in 1985, for example, destroyed 14 bridges and caused approximately $1.5 million worth of damage to a small hydropower plant (Ebi, Woodruff, Hildebrand, and Corvalan 2007); it also affected a large area of cultivated land, houses, human inhabitants, and livestock (Shrestha and Aryal 2010).

As resources for rebuilding damaged infrastructure tend to be scarce and carry large opportunity costs, climate change may pose an additional risk and, indeed, a possible deterrent to infrastructure development in developing countries (Naswa and Garg 2011).

Thermal Power Generation

The primary source of vulnerability to a thermal power plant from climate change is potential impacts on its cooling system as the full efficiency of a plant depends on a constant supply of fresh water at low temperatures (I. Khan, Chowdhury, Alam, Alam, and Afrin 2012). Decreases in low flow and increases in temperature are the major risk factors to electricity generation (Mcdermott and Nilsen 2011). Heat waves and droughts may decrease the cooling capacity of power plants and reduce power generation (I. Khan et al. 2012).

Studies quantifying the impacts of climate change on thermal power generation in South Asia specifically are not available. However, a study by Van Vliet et al. (2012) evaluates these impacts in 2040 and 2080. They examine the effects of changes in river temperatures and in river flows, and find that the capacity of power plants could decrease 6.3–19 percent in Europe and 4.4–16 percent in the United States over the period 2031–60 for temperature ranges of 1.5–2.5°C. Other climate-related stressors may also affect electricity production in South Asia, including salinity intrusion due to sea-level rise, which can disturb the normal functioning of the cooling system; increasing intensity of tropical cyclones, which can disrupt or damage power plants within coastal areas; and river erosion, which can damage electricity generation infrastructures on the banks of rivers (I. Khan et al. 2012).

Health Risks and Mortality

Climate change is also expected to have major health impacts in South Asia, and it is the poor who are expected be affected most severely. The projected health impacts of climate change in South Asia include malnutrition and such related health disorders as child stunting, an increased prevalence of vector-borne and diarrheal diseases, and an increased number of deaths and injuries as a consequence of extreme weather events (Markandya and Chiabai 2009; Pandey 2010).

Childhood Stunting

Climate change is expected to negatively affect food production (see Chapter 5 on "Agricultural Production"), and may therefore have direct implications for malnutrition and undernutrition—increasing the risk of both poor health and rising death rates (Lloyd, Kovats, and Chalabi 2011). The potential impact of climate change on childhood stunting, an indicator measuring undernourishment, is estimated by Lloyd, Kovats, and Chalabi (2011). At present, more than 31 percent of children under the age of five in South Asia are underweight (2011 data based on World Bank 2013n).

Using estimates of changes in calorie availability attributable to climate change, and particularly to its impact on crop production, Lloyd et al. (2011) estimate that climate change may lead to a 62 percent increase in severe childhood stunting and a 29 percent increase in moderate stunting in South Asia by 2050 for a warming of approximately 2°C above pre-industrial levels.[115] As the model is based on the assumption that within-country food distribution remains at baseline levels, it would appear that better distribution could to some extent mitigate the projected increase in childhood stunting.

Diarrheal and Vector-Borne Diseases

Diarrhea is at present a major cause for child mortality in Asia and the Pacific, with 13.1 percent of all deaths under age five in the region caused by diarrhea (2008 data from ESCAP 2011). Pandey (2010) investigates the impact of climate change on the incidence of diarrheal disease in South Asia and finds a declining trend in the incidence of the disease but an increase of 6 percent by 2030 (and an increase of 1.4 percent by 2050) in the relative risk of disease from the baseline, compared to an average increase across the world of 3 percent in 2030 (and 2 percent in 2050) (Pandey 2010).[116] Noteworthy in this context is the finding by Pandey (2010) that, in the absence of climate change, cases of diarrheal disease in South Asia (including Afghanistan) would decrease earlier, as the expected increase in income would allow South Asian countries to invest in their health services.

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[115] The estimates are based on the climate models NCAR and CSIRO, which were forced by the A2 SRES emissions scenario (ca. 1.8°C above pre-industrial by 2050 globally). By 2050, the average increases in maximum temperature over land are projected as 1.9°C with the NCAR and 1.2°C with the CSIRO model, compared to a 1950–2000 reference scenario (Lloyd et al. 2011).

[116] This study is based on two GCMs, NCAR, the colder and drier CSIRO model, and the A2 scenarios (global-mean warming about 1.2°C by 2030 and 1.8°C by 2050 above pre-industrial levels). For establishing the baseline incidence of these diseases (for 2010, 2030, and 2050), the author uses WHO projections. Population estimates are based on UN projections, and GDP estimates are based on an average of integrated models.

Climate change is expected to affect the distribution of malaria in the region, causing it to spread into areas at the margins of the current distribution where colder climates had previously limited transmission of the vector-borne disease (Ebi et al. 2007). Pandey (2010) finds that the relative risk of malaria in South Asia is projected to increase by 5 percent in 2030 (174,000 additional incidents) and 4.3 percent in 2050 (116,000 additional incidents) in the wetter scenario (NCAR). The drier scenario (CSIRO) does not project an increase in risk; this may be because calculations of the relative risk of malaria consider the geographical distribution and not the extended duration of the malarial transmission season (Pandey 2010). As in the case of diarrheal disease, malaria cases are projected to significantly decrease in the absence of climate change (from 4 million cases in 2030 to 3 million cases in 2050).

Salinity intrusion into freshwater resources adds another health risk. About 20 million people in the coastal areas of Bangladesh are already affected by salinity in their drinking water. With rising sea levels and more intense cyclones and storm surges, the contamination of groundwater and surface water is expected to intensify. Contamination of drinking water by saltwater intrusion may cause an increasing number of cases of diarrhea. Cholera outbreaks may also become more frequent as the bacterium that causes cholera, *vibrio cholerae*, survives longer in saline water (A. E. Khan, Xun, Ahsan, and Vineis 2011; A. E. Khan, Ireson, et al. 2011). Salinity is particularly problematic in the dry season, when salinity in rivers and groundwater is significantly higher due to less rain and higher upstream freshwater withdrawal. It is expected to be further aggravated by climate-change-induced sea-level rise, reduced river flow, and decreased dry season rainfall.

A study conducted in the Dacope sub-district in Bangladesh found that the population in the area consumed 5–16g of sodium per day from drinking water alone in the dry season, which is significantly higher than the 2g of dietary sodium intake per day recommended by WHO and FAO. There is strong evidence that higher salt intake causes high blood pressure. Hypertension in pregnancy, which is found to be 12 percent higher in the dry season compared to the wet season in Dacope, also has adverse effects on maternal and fetal health, including impaired liver function, intrauterine growth retardation, and preterm birth (A. E. Khan, Ireson, et al. 2011).

The Effects of Extreme Weather Events

In South Asia, unusually high temperatures pose health threats associated with high mortality. This is particularly so for rural populations, the elderly, and outdoor workers. The most common responses to high average temperatures and consecutive hot days are thirst, dizziness, fatigue, fainting, nausea, vomiting and headaches. If symptoms are unrecognized and untreated, heat exhaustion can cause heatstroke and, in severe cases, death. In Andhra Pradesh, India, for example, heat waves caused 3,000 deaths in 2003 (Ministry of Environment and Forests 2012). In May 2002, temperatures increased to almost 51°C in Andhra Pradesh, leading to more than 1,000 deaths in a single week. This was the highest one-week death toll due to extreme heat in Indian history. In recent years, the death toll as a consequence of heat waves has also increased continuously in the Indian states of Rajasthan, Gujarat, Bihar, and Punjab (Lal 2011).

In their global review, Hajat and Kosatky (2010) find that increasing population density, lower city gross domestic product, and an increasing proportion of people aged 65 or older were all independently linked to increased rates of heat-related mortality. It is also clear that air pollution, which is a considerable problem in South Asia, interacts with high temperatures and heat waves to increase fatalities.

Most studies of heat-related mortality to date have been conducted for cities in developed countries, with relatively few published on developing country cities and regions (Hajat and Kosatky 2010). Cities such as New Delhi, however, exhibit a significant response to warming above identified heat thresholds. One recent review found a 4-percent increase in heat-related mortality per 1°C above the local heat threshold of 20°C (range of 2.8–5.1 °C) (McMichael et al. 2008).

A study by Takahashi, Honda, and Emori (2007) further found that most South Asian countries are likely to experience a very substantial increase in excess mortality due to heat stress by the 2090s, based on a global mean warming for the 2090s of about 3.3°C above pre-industrial levels under the SRES A1B scenario and an estimated increase in the daily maximum temperature change over South Asia in the range of 2–3°C. A more recent assessment, by Sillmann and Kharin (2012), based on the CMIP5 models, projects an annual average maximum daily temperature increase in the summer months of approximately 4–6°C by 2100 for the RCP 8.5 scenario. The implication may be that the level of increased mortality reported by Takahashi et al. (2007) could occur substantially earlier and at a lower level of global mean warming (i.e., closer to 2°C) than estimated. Takahashi et al. (2007) assume constant population densities. A further risk factor for heat mortality is increasing urban population density.

While methodologies for predicting excess heat mortality are still in their infancy, it is clear that even at present population densities large rates of increase can be expected in India and other parts of South Asia. The projections used in this report indicate a substantial increase in the area of South Asia exposed to extreme heat by as early as the 2020s and 2030s (1.5°C warming above pre-industrial levels), which points to a significantly higher risk of heat-related mortality than in the recent past.

The Effects of Tropical Cyclones

Although only 15 percent of all tropical cyclones affect South Asia, India and Bangladesh alone account for 86 percent of global deaths from cyclones. The high mortality risk is mainly due to high population density in the region (Intergovernmental Panel on Climate Change 2012). Projected casualties for a 10-year return cyclone in 2050 in Bangladesh are estimated to increase to 4,600 casualties (for comparison, Cyclone Sidr caused 3,406 deaths), with as many as 75,000 people projected to be injured (compared to 55,282 as a result of Cyclone Sidr)(World Bank 2010d).[117]

Besides deaths and injuries, the main health effects of floods and cyclones are expected to result from indirect consequences, including disruptions to both the food supply and to access to safe drinking water. An increased intensity of tropical cyclones could therefore pose major stresses on emergency relief and food aid in affected areas.

Population Movement

Migration, often undertaken as short-term labor migration, is a common coping strategy for people living in disaster-affected or degraded areas (World Bank 2010f). (See Chapter 3 on "Population Movement" for more discussion on the mechanisms driving migration.) There is no consensus estimate of future migration patterns resulting from climate-change-related risks, such as extreme weather events and sea-level rise, and most estimates are highly speculative (Gemenne 2011; World Bank 2010g). Nevertheless, the potential for migration, including permanent relocation, is expected to be heightened by climate change, and particularly by sea-level rise and erosion. Inland migration of households and economic activity has already been observed in Bangladesh, where exposed coastal areas are characterized by lower population growth rates than the rest of the country (World Bank 2010d). A sea-level rise of one meter is expected to affect 13 million people in Bangladesh (World Bank 2010d),[118] although this would not necessarily imply that all people affected would be permanently displaced (Gemenne 2011).

Hugo (2011) points out that migration occurs primarily within national borders and that the main driver of migration is demographic change; environmental changes and other economic and social factors often act as contributing causes. In the specific case of flooding, however, environmental change is the predominant cause of migration. Hugo (2011) identifies South Asia as a hotspot for both population growth and future international migration as a consequence of demographic changes, poverty, and the impacts of climate change.

Conflict

Although there is a lack of research on climate change and conflicts, there is some evidence that climate change and related impacts (e.g., water scarcity and food shortages) may increase the likelihood of conflicts (De Stefano et al. 2012; P. K. Gautam 2012).

A reduction in water availability from rivers, for example, could cause resource-related conflicts and thereby further threaten the water security of South Asia (P. K. Gautam 2012). The Indus and the Ganges-Brahmaputra-Meghna Basins are South Asia's major transboundary river basins, and tensions among the riparian countries over water use do occur.

In the context of declining quality and quantity of water supplies in these countries, increasing demand for water is already causing tensions over water sharing (De Stefano et al. 2012; Uprety and Salman 2011). Water management treaties are considered to be potentially helpful in minimizing the risk of the eruption of such conflicts (Bates et al. 2008; ESCAP 2011). There are bilateral water treaties established for the Indus Basin (although Afghanistan, to which 6 percent of the basin belongs, and China, to which 7 percent of the basin belongs, are not signatories), between India and Bangladesh for the Ganges, and between India and Nepal for the most important tributaries of the Ganges; there are, however, no water treaties for the Brahmaputra (Uprety and Salman 2011).

It has been noted that China is absent as a party to the above-mentioned treaties, though it is an important actor in the management of the basins (De Stefano et al. 2012). Although water-sharing treaties may not avert dissension, they often help to solve disagreements in negotiation processes and to stabilize relations (De Stefano et al. 2012).

Uprety and Salman (2011) indicate that sharing and managing water resources in South Asia have become more complex due to the high vulnerability of the region to climate change. Based on the projections for water and food security presented above, it is likely that the risk of conflicts over water resources may increase with the severity of the impacts.

Conclusion

The key impacts that are expected to affect South Asia are summarized in Table 5.5, which shows how the nature and magnitude of impacts vary across different levels of warming.

Many of the climatic risk factors that pose potential threats to the population of the South Asian region are ultimately related to changes in the hydrological regime; these would affect populations via changes to precipitation patterns and river flow. One of the most immediate areas of impact resulting from changes in the

117 These projections assume no changes in casualty and injury rates compared to Cyclone Sidr.

118 The World Bank (2010a) estimation of the number of people affected by a one meter sea-level rise in Bangladesh refers to Huq, Ali, and Rahman (1995), an article published in 1995. More recent projections estimate that between 1.5 million people (Dasgupta, Laplante, Meisner, Wheeler, and Yan 2008), and up to 1.540 million people by 2070 could be affected by a one meter sea-level rise and increased storminess in the coastal cities of Dhaka, Chittagong, and Khulna (Brecht, Dasgupta, Laplante, Murray, and Wheeler 2012). With a different methodology, Hanson et al. (2011) find that approximately 17 million people could be exposed to 0.5 meter sea-level rise. More details on the methodologies can be found in Chapter 4 on "Risks to Coastal Cities."

hydrological regime is agriculture, which is highly dependent on the regularity of monsoonal rainfall. Negative effects on crop yields have already been observed in South Asia in recent decades. Should this trend persist, substantial yield reductions can be expected in the near and midterm.

The region's already large population of poor people is particularly vulnerable to disruptions to agriculture, which could undermine livelihoods dependent on the sector and cause food price shocks. These same populations are likely to be faced with challenges on a number of other fronts, including limited access to safe drinking water and to electricity. The proportion of the population with access to electricity is already limited in the region. Efforts to expand power generation capacity could be affected by climate change via changes in water availability, which would affect both hydropower and thermoelectricity, and temperature patterns, which could put pressure on the cooling systems of thermoelectric power plants.

The risks to health associated with inadequate nutrition or unsafe drinking water are significant: childhood stunting, transmission of water-borne diseases, and hypertension and other disorders associated with excess salinity. Inundation of low-lying coastal areas due to sea-level rise may also affect health via saltwater intrusion. Other health threats are also associated with flooding, heat waves, tropical cyclones, and other extreme events. Population displacement, which already periodically occurs in flood-prone areas, is likely to continue to result from severe flooding and other extreme events.

Bangladesh is potentially a hotspot of impacts as it is projected to be confronted by a combination of increasing challenges from extreme river floods, more intense tropical cyclones, rising sea levels, and extraordinary temperatures.

The cumulative threat posed by the risks associated with climate change, often taking the form of excesses or scarcities of water, would substantially weaken the resilience of poor populations in the region. While the vulnerability of South Asia's large and poor populations can be expected to be reduced in the future by economic development and growth, projections indicate that high levels of vulnerability are likely to persist. Many of the climate change impacts in the region, which appear quite severe with relatively modest warming of 1.5–2°C, pose a significant challenge to development. Major investments in infrastructure, flood defense, and the development of high temperature and drought resistant crop cultivars, and major improvements in sustainability practices (e.g., in relation to groundwater extraction), would be needed to cope with the projected impacts under this level of warming.

Table 5.5: Impacts in South Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Regional Warming		2011 annual mean temperature for India was ninth warmest on record (0.4°C above 1961–90 average). 2009 was the warmest since 1901 at 0.9°C above 1961–90 average[2]		Summer warming peaking at about 1.5°C above the 1951–1980 baseline by 2050.[3] Warm spells[4] lengthen to 20–45 days. Warm nights occur at a 40 percent frequency[5]		Summer temperatures reach about 5°C above the 1951–1980 baseline by 2100.[6] Warm spells lengthen to 150–200 days. Warm nights occur at frequency of 85 percent[7]
Heat Extremes	**Unusual Heat Extremes**	Virtually absent	About 15 percent of land boreal summer months (June, July, August) (JJA)	About 20 percent of land boreal summer months (JJA)	>50 percent of land boreal summer months (JJA)	>70 percent of land boreal summer months (JJA); in the south, almost all (>90 percent) summer months are projected to be unusually hot
	Unprecedented Heat Extremes	Absent	Virtually absent	<5 percent of land boreal summer months (JJA), except for the southernmost tip of India and Sri Lanka with 20–30 percent of summer months experiencing unprecedented heat	About 20 percent of land boreal summer months (JJA)	>40 percent of land boreal summer months (JJA)
Precipitation	**Rainfall**	Decline in South Asian monsoon rainfall since the 1950s but increases in frequency of most extreme precipitation events	Change in rainfall uncertain	Change in rainfall highly uncertain	About 5 percent increase in summer (wet season) rainfall[8]	About 10 percent increase in summer (wet season) rainfall.[9] The region stretching from the northwest coast to the southeast coast of peninsular India is projected to experience the highest percentage (~30 percent) increase in annual mean rainfall. Winter (DJF) precipitation shows a relative decrease in the central India and north India regions
	Variability					Intra-seasonal variability of monsoon rainfall increases by a mean of about 10 percent across a set of 10 CMIP5 models.[10]
	Extremes			Median 20 percent increase of extreme wet day precipitation share of the total annual precipitation[11]		Median 75 percent increase of extreme wet day precipitation share of the total annual precipitation
Drought		Increased frequency short droughts			Increased drought over northwestern India, Pakistan, and Afghanistan[12]	Increased length of dry spells measured by consecutive dry days in eastern India and Bangladesh[13]

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Table 5.5: Impacts in South Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Sea-level Rise (above present)		About 21 cm to 2009[14]	30cm–2040s, 50cm–2070 70cm (60–80) cm by 2080–2100[15]	30cm–2040s, 50cm–2070 70cm (60–80) cm by 2080–2100	30cm–2040s, 50cm–2060 85cm (70–100) cm by 2080–2100	30cm–2040s, 50cm–2060 105 cm (66 percent uncertainty range 85–125 cm) by 2080–2100, higher by 5–10 cm around Maldives, Kolkata, and Dhaka (5 cm lower)
Tropical Cyclone Impacts		Category Four Cyclone Sidr in 2004 exposed 3.45 million Bangladeshis to flooding,[16], causing crop losses equal to about 2 percent of the total annual production[17] and economic damages and total losses of $1.7 billion (2.6 percent of GDP)[18]		An additional[19] 7.8 million people would be affected by flooding higher than 100 cm in Bangladesh as a consequence of a 10-year return cyclone in 2050; 9.7 million people (3.5 million people in the baseline scenario) are projected to be exposed to severe inundation of more than 3m under this scenario. More intense tropical cyclones, combined with sea-level rise, would increase the depth and risk of inundation from floods and storm surges. In Bangladesh, a projected 27cm sea-level rise by 2050, combined with a storm surge induced by an average 10-year return-period cyclone such as Sidr, could inundate an area 88 percent larger than the area inundated by current cyclonic storm surges[20]		
Flooding (combined effects of river flooding, sea-level rise and storm surges)	**Bangladesh**			Mirza (2010) estimates the flooded area could increase by as much as 29 percent for a 2.5°C increase in warming above pre-industrial levels, with the largest change in flood depth and magnitude expected to occur up to 2.5°C of warming.[21] Hanson et al (2011) project that 17 million people might be exposed to 0.5m sea-level rise	At higher levels of warming the rate of increase in the extent of mean flooded area per degree of warming is estimated to be lower[22]	A 100cm sea-level rise is expected to affect 1.5–17 million people,13 million in Bangladesh alone[23] Brecht et al. (2012) estimate that by 2070, approximately 1.5 million people in coastal cities would be affected by coastal floods. Dasgupta et al. (2008) also project 1.5 million people affected by floods

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Table 5.5: Impacts in South Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
	Kolkata	Kolkata is ranked among the top ten cities in the world in terms of exposure to flooding.[24]	33 percent of the Kolkata metropolitan area is projected to be exposed to an inundation of more than 0.25m in the event of 100-year return-period rainfall patterns by 2050.[25] In Kolkata City, with its much higher population density, the same scenario is projected to affect 41 percent of the area and 47.4 percent of the population in 2050 (compared to 38.5 percent and 44.9 percent under the baseline scenario)			
	Mumbai	Severe flooding in 2005 caused 500 fatalities and an estimated $1.7 billion in economic damage. Mumbai is the commercial and financial hub of India and generates about 5 percent of India's GDP[26]			By the 2080s, the likelihood of a 2005-like extreme event could more than double, and the return period could be reduced to around 1-in–90 years.[27] Direct economic damages, are estimated to triple compared to the present and increase to up to $1,890 million due to climate change only—without taking population and economic growth into account	

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Table 5.5: Impacts in South Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
River Runoff	**Indus**			Mean flow increase of about 65 percent by the 2080s, with low flow increasing by 30 percent and the high flow increasing by 78 percent.[28] When reductions in glacial melt are accounted for, very substantial reductions in late spring and summer flow[29] could be likely	Mean flow increase of about 65 percent by the 2080s, with low flow increasing by 30 percent and the high flow increasing by 78 percent.[30] When reductions in glacial melt are accounted for, very substantial reductions in late spring and summer flow[31] could be likely	
	Ganges			20 percent increase in runoff.[32] Mean flow of the Ganges-Brahmaputra increases by only 4 percent, whereas low flow decreases by 13 percent and high flow by 5 percent[33]	20 percent increase in runoff [32]	50 percent increase in runoff[34]
	Brahmaputra			Very substantial reductions in late spring and summer flow.[29] Mean flow of the Ganges-Brahmaputra increases by only 4 percent, whereas the low flow decreases by 13 percent and high flow by 5 percent[35]		May experience extreme low flow conditions less frequently in the future. Significant increase in peak flow is projected[36]
Water Availability	**Overall**	In India, gross per capita water availability (including utilizable surface water and replenishable groundwater) is projected to decline from around 1,820m³ per year in 2001 to about 1,140m³ per year in 2050 due to population growth alone[37]		Food water requirements in India are projected to exceed green water availability by more than 150 percent, indicating the country would be highly dependent on blue water (irrigation water) agriculture production. By 2050, water availability in Pakistan and Nepal is projected to be too low for self-sufficiency in food production.[38] Without adequate water storage facilities, the increase of peak monsoon river flow would not be usable for agricultural productivity; increased peak flow may also cause damage to farmland due to river flooding[39]	It is very likely that per capita water availability in South Asia will decrease by more than 10 percent[40]	

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Table 5.5: Impacts in South Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
	Groundwater Recharge	Groundwater resources already under stress[41]	Climate change is projected to further aggravate groundwater stress[42]	Climate change is projected to further aggravate groundwater stress[43]	Climate change is projected to further aggravate groundwater stress[44]	Climate change is projected to further aggravate groundwater stress[45]
Crop Production				Without climate change, overall crop production is projected to increase by about 60 percent. In per capita terms, however, crop production may not quite keep pace with projected population increase. Under climate change, and assuming the CO_2 fertilization effect does not increase above present levels, overall crop production is projected to increase by about 12 percent above 2000 levels, leading to a significant projected decline by about one third in per capita crop production.[46] Reductions in water availability in the Indus, the Ganges, and the Brahmaputra due in part to loss of glacial melt water from the Himalayas, may impact food security. Using a scaling approach, it has been estimated that more than 63 million fewer people can be fed by the river basins due to reduced water availability[47]		

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Table 5.5: Impacts in South Asia

Risk/Impact		Observed Vulnerability or Change	Around 1.5°C (2030s[1])	Around 2°C (2040s)	Around 3°C (2060s)	Around 4°C and Above (2080s)
Yields	**All crops**	Changes in monsoon rainfall over India with less frequent but more intense rainfall in the recent past (1966–2002) have contributed to reduced rice yields,[48] especially in rain-fed areas. Droughts were found to have more severe impacts than extreme precipitation events[49]	Review shows that when cases that include CO_2 fertilization are excluded significant yield losses may occur before 2°C warming; if CO_2 fertilization is effective with some adaptation measures, yields remain approximately flat. Data suggests that the effects of adaptation measures and CO_2 fertilization are stronger and may compensate for the adverse effects of climate change under 2°C warming	With increases in warming above about 2°C above pre-industrial levels, crop yields decrease regardless of potentially positive effects. CO_2 fertilization partly compensates for the adverse effects of climate change	With increases in warming above about 2°C above pre-industrial levels, crop yields decrease regardless of potentially positive effects. CO_2 fertilization partly compensates for the adverse effects of climate change	With increases in warming above about 2°C above pre-industrial levels, crop yields decrease regardless of potentially positive effects. CO_2 fertilization partly compensates for the adverse effects of climate change
Health- and Poverty-related Issues	**Malnutrition and Childhood Stunting**	Present baseline is 23 percent of children under 5 moderately stunted, and 19 percent severely stunted[48]		Without climate change, reductions in the percentage of moderately stunted children is projected to reduce to 11 percent, of severely stunted to 3 percent, by 2050. With climate change, these percentages increase to 14.6 percent and about 5 percent respectively[50]		
	Malaria		Relative risk of malaria projected to increase by 5 percent in 2030[51]	Relative risk of malaria projected to increase by 5 percent in 2050[52]		
	Diarrheal Disease		Relative risk of diarrheal disease increases by 6 percent by 2030 compared to the 2010 baseline[53]	Relative risk of diarrheal disease increases by 1.4 percent by 2050 compared to the 2010 baseline[54]		
	Heat Waves Vulnerability	New Delhi exhibits a 4 percent increase in heat-related mortality per 1°C above the local heat threshold of 20°C (range of 2.8–5.1 percent/C[55])			Most South Asian countries are likely to experience a very substantial increase in excess mortality due to heat stress by the 2090s[56]	

Notes to Table 5.5

[1] Years indicate the decade during which warming levels are exceeded in a business-as-usual scenario, not in mitigation scenarios limiting warming to these levels, or below, since in that case the year of exceeding would always be 2100, or not at all.
[2] Blunden, J. and D. S. Arndt (2012).
[3] Under RCP2.6. Regional warming is somewhat less strong than that averaged over the total global land area.
[4] Consecutive days beyond the 90th percentile.
[5] Sillmann and Kharin (2013).
[6] Under RCP8.5. This is consistent with the CMIP3 projections (K. K. Kumar et al. 2010) under the SRES-A2 scenario (leading to 4.1°C above pre-industrial levels), with local temperature increases exceeding 4°C for Northern India.
[7] Sillmann and Kharin (2013).
[8] The latest generation of models (CMIP5) projects an overall increase of approximately 2.3 percent per degree warming for summer monsoon rainfall (Menon et al., 2013)
[9] Menon et al. (2013); Jourdain, Gupta, Taschetto, et al., (2013).
[10] Mean for RCP 8.5 of 10 models that best simulate the monsoon system (Menon et al. 2013).
[11] Sillmann and Kharin (2013).
[12] Dai (2012).
[13] Sillmann and Kharin (2013).
[14] Above 1880 estimated global mean sea level.
[15] For a scenario in which warming peaks above 1.5°C around the 2050s and drops below 1.5°C by 2100. Due to the slow response of oceans and ice sheets, the sea-level response is similar to a 2°C scenario during the 21st century; it deviates from it after 2100.
[16] World Bank (2010a).
[17] FAO (2013).
[18] Wassmann et al. (2009); World Bank (2010a).
[19] In comparison to the no-climate change baseline scenario.
[20] World Bank (2010a). Based on the assumption that landfall occurs during high tide and that wind speed increases by 10 percent compared to Cyclone Sidr.
[21] Mirza (2010).
[22] Mirza (2010).
[23] World Bank (2010b) estimation of 13 million people in Bangladesh affected by 100cm SLR in Bangladesh refers to Huq, Ali, and Rahman (1995), an article published in 1995.
[24] Intergovernmental Panel on Climate Change (2012); UN-HABITAT (2010); World Bank (2011b). Roughly a third of the total population of the metropolitan area of 15.5 million (2010 data; UN-HABITAT 2010) live in slums, which significantly increases the vulnerability of the population to these risk factors.
[25] World Bank (2011b) uses A1F1 scenario for this study, corresponding to a 2.2°C warming by 2050 and 27cm SLR by 2050. Urban flooding as a consequence of climate-change-induced increases in extreme precipitation, sea-level rise, and storm surges. Total losses in 2050 are estimated at $6.8 billion, with residential property and other buildings and the health care sector accounting for the largest damages. Due to data constraints, both total damages and the additional losses due to increased flooding as a consequence of climate change should be viewed as lower-bound estimates (World Bank 2011).
[26] Ranger et al. (2011). The flood forced the National Stock Exchange to close, and automated teller machine banking systems throughout large parts of the whole country stopped working; this demonstrated how critical infrastructure can be affected by extreme events in mega-cities (Intergovernmental Panel on Climate Change 2012).
[27] Ranger et al. (2011). Warming of 3°C to 3.5°C above pre-industrial levels. Additional indirect economic costs, such as sectoral inflation, job losses, higher public deficits, and financial constraints slowing down the process of reconstruction, are estimated to increase the total economic costs of a 1-in-100-year event to $2,435 million.
[28] Van Vliet et al. (2013) for warming of 2.3°C and of 3.2°C.
[29] For the 2045–65 period (global mean warming of 2.3°C above pre-industrial levels). Immerzeel, Van Beek, and Bierkens (2010).
[30] Van Vliet et al. (2013) for warming of 2.3°C and of 3.2°C.
[31] For the 2045–65 period (global mean warming of 2.3°C above pre-industrial levels). Immerzeel et al. (2010).
[32] Fung, Lopez, and New (2011). SRES A1B warming of about 2.7°C above pre-industrial levels.
[33] Van Vliet et al. (2013) for warming of 2.3°C and of 3.2°C.
[34] Fung, Lopez, and New (2011). SRES A1B warming of about 4.7°C above pre-industrial levels.
[35] Van Vliet et al. (2013) for warming of 2.3°C and 3.2°C.
[36] Gain, Immerzeel, Sperna Weiland, and Bierkens (2011). SRES A1B and B2.
[37] Bates, Kundzewicz, Wu, and Palutikof (2008); Gupta and Deshpande (2004).
[38] When taking a total availability of water below 1300m^3 per capita per year as a benchmark for water amount required for a balanced diet.
[39] Gornall et al. (2010). Consistent with others projecting overall increased precipitation during the wet season for the 2050s, with significantly higher flows in July, August, and September than in 2000. An increase in overall mean annual soil moisture content is expected for 2050 (compared to 1970–2000), although the soil is also expected to be subject to drought conditions for an increased length of time.
[40] Gerten et al., (2011). For a global warming of approximately 3°C above pre-industrial and the SRES A2 population scenario for 2080
[41] Rodell, Velicogna, and Famiglietti (2009); Döll (2009); Green et al. (2011).
[42] Döll (2009); Green et al. (2011).
[43] Döll (2009); Green et al. (2011).
[44] Döll (2009); Green et al. (2011).
[45] Döll (2009); Green et al. (2011).
[46] Nelson et al. (2010).
[47] Immerzeel, Van Beek, and Bierkens (2010). Scenario with increase of 2–2.5°C compared to pre-industrial levels by the 2050s.
[48] Auffhammer, Ramanathan, and Vincent (2011).
[49] Auffhammer, Ramanathan, and Vincent (2011).
[50] Lloyd et al. (2011). South Asia by 2050 for a warming of approximately 2°C above pre-industrial levels (SRES A2).
[51] Pandey (2010). 174,000 additional incidents, SRES A2 for 1.2°C warming.
[52] Pandey (2010). 116,000 additional incidents, 1.8°C increase in SRES A2 scenario.
[53] Pandey (2010). 1.2°C increase in the A2 scenario.
[54] Pandey (2010). 1.8°C increase in the A2 scenario.
[55] McMichael et al. (2008).
[56] Takahashi, Honda, and Emori (2007) find this result for global mean warming in the 2090s of about 3.3°C above pre-industrial levels under the SRES A1B scenario, with an estimated increase in the daily maximum temperature change over South Asia in the range of 2 to 3°C.

Chapter 6

Global Projections of Sectoral and Inter-sectoral Impacts and Risks

Climate change may strongly alter the conditions for human and biological systems over the coming decades, as described by the IPCC (2007). Climate effects can amplify each other, greatly increasing exposure and limiting options to respond, making the consistent assessment of parallel multisector impacts particularly important beyond detailed sectoral analyses and sectoral interactions. In recent years the scientific community has made efforts to identify regions, sectors, and systems that may be particularly at risk or exposed to particularly large or prominent climate changes. Often these have been termed "hotspots", although there is no common definition.

This chapter identifies hotspots of coinciding pressures from the agriculture, water, ecosystems, and health (malaria) sectors at different levels of global warming. It does so by synthesizing the findings presented in Piontek et al. (accepted) obtained as part of the ISI-MIP[119] project; that made an initial attempt at defining multisector hotspots or society-relevant sectors simultaneously exposed to risks. It introduces a number of recent attempts to identify different kinds of hotspots to help put the ISI-MIP results into a broader context. These are further complemented by a review of observed vulnerability hotspots to drought and tropical cyclone mortality risk. This review helps gain an appreciation of factors of vulnerability that are not included within the ISI-MIP framework but that are known to pose severe risks in the future under climate change. It also allows the systematic comparison of impacts within a number of sectors for different levels of global warming.

The methodology for multisectoral exposure hotspots for climate projections from ISI-MIP models is first introduced (Chapter 6 on "Multisectoral Exposure Hotspots for Climate Projections from ISI-MIP Models"). Results are then presented for changes to water availability (Chapter 6 on "Water Availability"; based on Schewe, Heinke, Gerten, Haddeland et al.) and biome shifts (Chapter 6 on "Risk of Terrestrial Ecosystem Shifts"; based on Warszawski, Friend, Ostberg, and Frieler n.d.). Furthermore, the ISI-MIP framework allows for a first estimate of cascading interactions between impacts, presented in Chapter 6 on "Crop Production and Sector Interactions" (based on Frieler, Müller, Elliott, Heinke et al. in review). Overlaying impacts across four sectors (agriculture-crop productivity, water resources, ecosystems, and health-malaria) allows for identification of multisectoral hotspots (Chapter 6 on "Regions Vulnerable to Multisector Pressures" based on Piontek et al.), denoting vulnerability to impacts within these sectors. In order to capture vulnerability to further impacts, hotspots of observed tropical cyclone mortality complement the sectoral assessment. Finally, non-linear and cascading impacts are discussed (Chapter 6 on "Non-linear and Cascading Impacts").

Multisectoral Exposure Hotspots for Climate Projections from ISI-MIP Models

The following analysis relies on biophysical climate change impacts and examines the uncertainty across different climate and impact models. It complements previous studies on hotspots based on pure climate indicators, such as temperature and precipitation and their variability, or with single models. The impacts in the

[119] Note that the studies referenced—Warszawski et al., Frieler et al. Schewe et al., —are in review and results may be subject to change.

four sectors taken into account here represent important risk multipliers for human development (UNDP 2007). It is likely that overlapping effects increase risk as well as the challenge presented for adaptation, especially in regions with low adaptive capacity. Furthermore, impact interactions may amplify each impact (see Chapter 6 on "Crop Production and Sector Interactions"), which is not captured in the following analysis.

Hotspots are understood to be areas in which impacts in multiple sectors fall outside their respective historical range—resulting in significant multisectoral pressure at the regional level. Significant pressure in this context means conditions being altered so much that today's extremes become the norm. Figure 6.1 shows the steps for identifying multisectoral hotspots.[120]

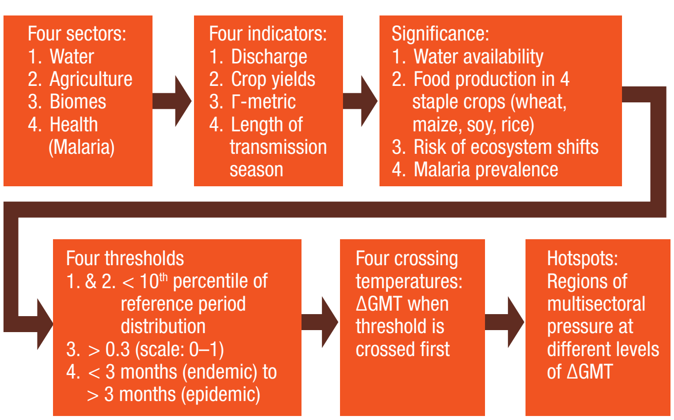
For each sector, a representative indicator with societal relevance is selected, together with a corresponding threshold for significant change, owing to the structural differences between the sectors. The focus is on changes resulting in additional stress for human and biological systems as the basis for analyses of vulnerability, leaving aside any positive effects climate change may have.

Emerging Hotspots in a 4°C World

The overall image that emerges from the hotspots assessments is a world in which no region would be immune to climate impacts in a 4°C world but some regions and people would be affected in a disproportionately greater manner.

While the depicted pattern of vulnerability hotspots often depends on the metric chosen to measure the impact exposure, it is important to remember that the impacts are not projected to increase in isolation from one another. As a result, maps of exposure and vulnerability hotspots (e.g., Figure 6.8) should be understood as complementary to each other—and certainly not exhaustive.

Figure 6.1: The method to derive multisectoral impact hotspots. ΔGMT refers to change in global mean temperature and G refers to the gamma-metric as described in Appendix 3



It is important to note that hotspot mapping based on projections inherit the uncertainty from the climate or impact modeling exercise and are subject to the same limitations as the projections themselves. Thus, in the agricultural sector, sensitivity thresholds of crops are mostly not included, leading to a potentially overly optimistic result. The uncertainty of the CO_2 fertilization effect further obscures any clarity in the global image.

Further research is therefore needed to better understand the consequences of overlapping sectoral and other impacts. Particular attention will need to be drawn to potential interactions between impacts, as well as on including more relevant sectors and tying analyses in with comprehensive vulnerability analyses. While further research can reduce uncertainty, it should be clear that uncertainty will never be eradicated.

Water Availability

Freshwater resources are of critical importance for human livelihoods. For the three regions analyzed in this report, large quantities—between 85–95 percent of the total freshwater withdrawal (World Bank, 2013a)—are required for agriculture, while a lesser share (1–4 percent) is currently required for industrial purposes such as generating hydropower and cooling thermoelectric power plants (Kummu, Ward, De Moel, and Varis, 2010; Wallace 2000). Freshwater availability is a major limiting factor to food production and economic prosperity in many regions of the world (OKI et al. 2001; Rijsberman 2006).

In the framework of ISI-MIP, a set of 11 global hydrological models (GHMs), forced by five global climate models (General Circulation Models [GCMs]), was used to simulate changes in freshwater resources under climate change and population change scenarios. This allows for an estimate of the effects of climate change on water scarcity at a global scale and enables the assessment of the degree of confidence in these estimates based on the spread in results across both hydrological models and climate models.

Whether water is considered to be scarce in a given region is determined by the amount of available water resources and by the population's demand for water. Water demand depends on many factors that may differ from region to region, such as economic structure and land-use patterns, available technology and infrastructure, and lifestyles (Rijsberman 2006). Most importantly, it depends directly on the size of the regional population—more people need more water. Given the current rates of population growth around the world, and the fact that this growth is projected to continue for the better part of the 21st century, water scarcity will increase almost inevitably simply because of population changes (Alcamo, Flörke, and Märker 2007; N. W. Arnell 2004; C.

120 See Appendix 3 for further information on methodology.

J. Vorosmarty 2000). Thus, when assessing the effect of climate change on water scarcity, one has to realize that climate change does not act on a stationary problem but on a trajectory of rapidly changing boundary conditions.

Water Availability in Food Producing Units

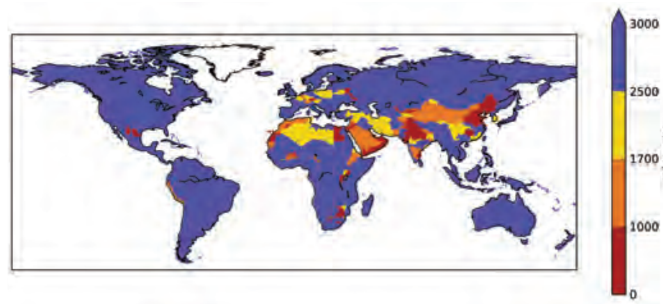
The relative changes in water availability reflect adaptation challenges that may arise in the affected regions. Such challenges will be harder to tackle if a region is affected by water shortages in an absolute sense. A widely used, simplified indicator of water scarcity is the amount of available water resources divided by the population in a given country (or region)—the so-called "water crowding index" (M. Falkenmark et al. 2007; Malin Falkenmark, Lundqvist, and Widstrand 1989). To estimate water resources per country, simply summing up discharge would lead to individual water units being counted multiple times. Using runoff, on the other hand, would not account for flows of water between countries within a river basin. Here, runoff in each basin is redistributed according to the pattern of discharge in the basin (Gerten et al. 2011). The resulting "blue water" resource can then be aggregated over a country or region.

To capture the baseline for future changes, the multi-model median of present-day availability of blue-water resources is shown in Figure 6.2, aggregated at the scale of food-producing units (FPU; intersection of major river basins and geopolitical units). Results given in this section are based on Schewe et al., in review. Importantly, the scale of aggregation influences the resulting water scarcity estimate considerably. For example, if water resources are aggregated at the scale of food productivity units, one FPU within a larger country may fall below a given water scarcity threshold, while another does not. The same country as a whole, on the other hand, may not appear water scarce if a lack of water resources in one part of the country is balanced by abundant resources in another. Thus, global estimates of present-day water scarcity are usually higher when resources are aggregated on smaller scales (for example, FPUs) rather than on a country-wide scale.

It is difficult to determine which scale is more appropriate to assess actual water stress. While FPUs give a more detailed picture and can highlight important differences within larger countries, the country scale takes into account the transport of food (and thus "virtual water") from agricultural areas to population centers within a country, and may be deemed more realistic in many cases. Nonetheless, assessments of water availability should be viewed as approximations.

Results show that corresponding to the regional distribution of changes in water discharge, climate change is projected to diminish per-capita water availability in large parts of North, South, and Central America as well as in the Mediterranean, Middle East, western and southern Africa, and Australia (Figure 6.3, left panel). In a 4°C world, the decreases exceed 50 percent in many FPUs by

Figure 6.2: Multi-model median of present-day (1980–2010) availability of blue-water resources per capita in food producing units (FPU)



The color scale corresponds to the FAO categories of water scarcity (below 1,000 m³/capita, red), water stress (orange), and water resources vulnerability (yellow).

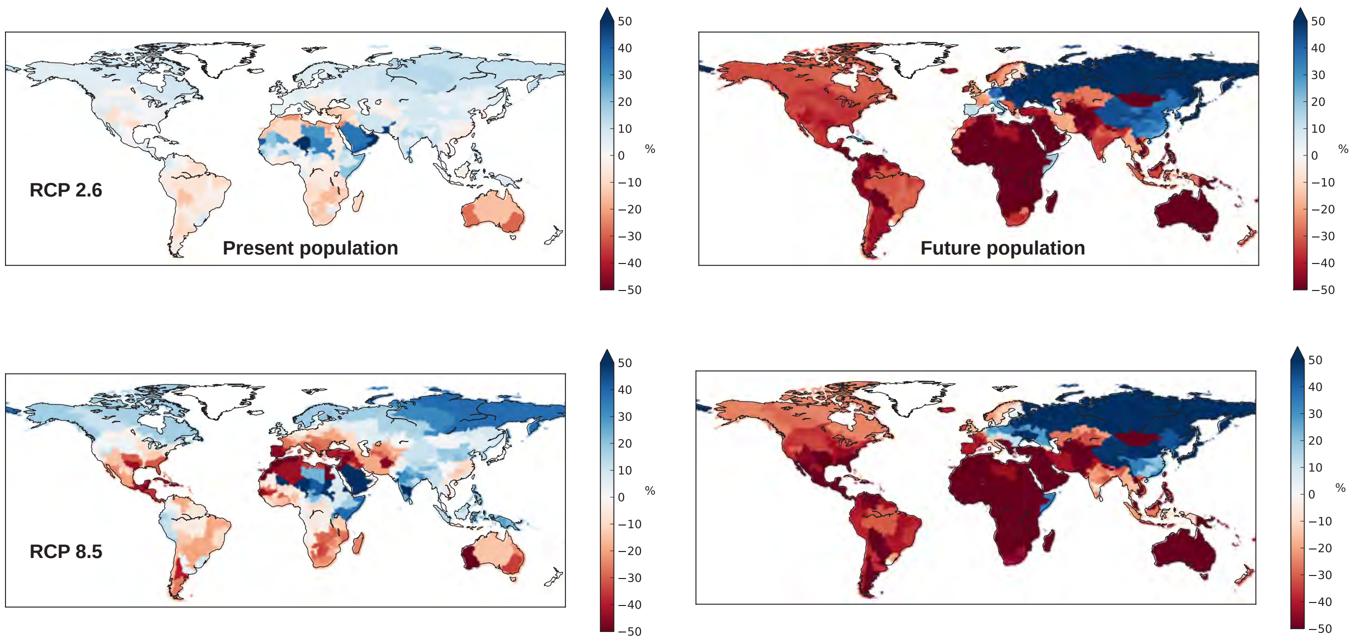
the end of the century, compared to decreases of 10–20 percent under 2°C warming. The effects of projected population changes are even larger than those of climate change, and the combination of both leaves much of the world threatened by a severe reduction in water availability (Figure 6.3, right panel). Moreover, the spread across the multi-model ensemble is large; thus, more negative outcomes than reflected in the multi-model mean cannot be excluded.

These results illustrate that the effect of climate change on water resources are regionally heterogeneous. Some countries are expected to benefit from more abundant resources even after other countries have become water-scarce because of shrinking resources.

In terms of the regions reviewed in this report, these results broadly show:

- **Sub-Saharan Africa:** In the absence of population increase, increased projected rainfall in East Africa would increase the level of water availability, whereas in much of southern Africa water availability per capita would decrease, with the patterns increasing in strength with high levels of warming. With high levels of warming, West Africa would also show a decrease in water availability per capita. With projected population increase, climate change reduces water resources per capita (compared to the recent 20-year period) over most of Africa in the order of 40–50 percent under both a 1.8°C and a 3.8°C warming scenario by 2069–99.
- **South Asia:** Consistent with the expected increase in precipitation with warming and assuming a constant population, the level of water availability per capita would increase in South Asia. With the projected population increase factored in, however, a large decrease in water availability per capita in the order of 20–30 percent is estimated under a 1.8°C warming by 2069–99. A higher level of warming is projected to further

Figure 6.3: Multi-model median of the relative change in blue-water resources per capita, in 2069–99 relative to 1980–2010, for RCP2.6 (top) and RCP8.5 (bottom)



In the left-hand side panels, population is assumed to remain constant at present-day (year 2000) levels, while in the right-hand side panels it is assumed to change according to the SSP2 population scenario, which projects global population to peak near 10 billion just before the end of the century and includes changes in the regional distribution of population.

increase average precipitation, and the decrease in water availability per capita would be reduced to 10 to 20 percent over much of South Asia.

- **South East Asia:** A very similar broad pattern to that described in South Asia is exhibited in the results shown here. Under a constant population, climate change is expected to increase the average annual water availability per capita. Population growth, however, puts water resources under pressure, decreasing water availability per capita by up to 50 percent by the end of the century.

Review of Climate Model Projections for Water Availability

The ISI-MIP results shown above apply a range of CMIP5 GCMs and a set of hydrology models to produce the model intercomparison and median results (Schewe et al. in review.). Recent work based on the earlier generation of climate models (CMIP3) and one hydrology model[121] shows similar overall results for the three regions (Arnell 2013).

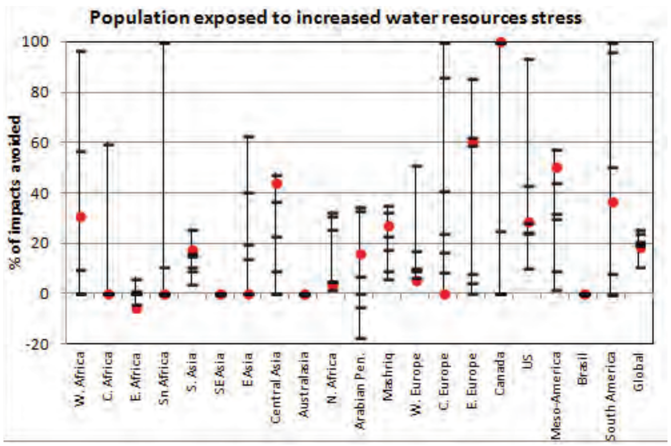
Of interest here are the levels of impacts and different levels of warming. This work examines the change in population exposed to increased water resources stress (using 1,000 m³ of water per capita threshold) between a warming of just above 2°C and scenarios reaching between 4°C and 5.6°C by 2100. In this work, the SRES A1B population scenario was assumed, which has quite different and lower regional population numbers compared to the SSP2 population scenario used in the ISI-MIP analysis.[122]

Figure 6.4 shows the level of impact avoided due to limiting warming to under 2°C compared to a warming of 4–5.6°C by 2100 by indicating the percentage of the population that would be spared the exposure to increased stress on water resources. Compared to many other regions, the level of avoided impact in South Asia is relatively low (in the order of 15–20 percent). South East Asia shows very little, if any, avoided impacts against this metric. Similarly, for East Africa, where increased rainfall is projected, there are very few, if any, avoided impacts. For West Africa, where models diverge substantially, the median of avoided impacts is in the order of 50 percent, with a very wide range. In Southern Africa, where the CMIP5 models seem to agree on a reduction in rainfall, the CMIP3 models show a range from 0–100 percent

121 HADCM3, HadGEM1, ECHAM5, IPSL_CM4, CCSM3.1 (T47), CGCM3.1 (T63), and CSIRO_MK3.0, and MacPDM hydrology model. Precipitation for the different scenarios was pattern scaled.

122 In the SRES A1B population scenario, global population peaks at 8.7 billion in 2050 and then decreases to about 7 billion in 2100 (equal to 2010 global population).

Figure 6.4: The percentage of impacts under a 4 to 5.6°C warming avoided by limiting warming to just over 2°C by 2100 for population exposed to increased water stress (water availability below 1000 m^3 per capita)



Red dots show impacts avoided under HADCM3 GCM, the range from all seven GCMs shown by seven of the vertical black lines and the horizontal black tick marks indicate the other six models.

Source: N. W. Arnell et al. (2013).

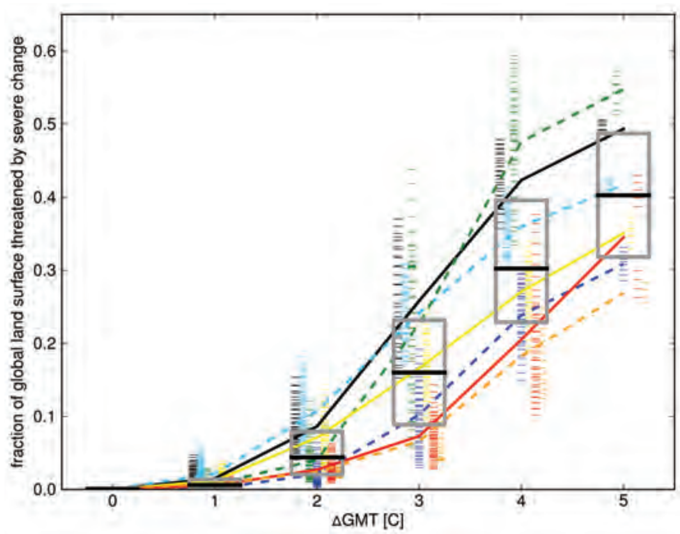
in avoided impacts. At the global level, limiting warming to 2°C reduces the global population exposed to 20 percent.

Risk of Terrestrial Ecosystem Shifts

Climate change in the 21st century poses a large risk of change to the Earth's ecosystems: Shifting climatic boundaries trigger changes to the biogeochemical functions and structures of ecosystems. Such changing conditions would render it difficult for local plant and animal species to survive in their current habitat.

The extent to which ecosystems will be affected by future climate change depends on relative and absolute changes in the local carbon and water cycles, which partly control the composition of vegetation. Such shifts are likely to imply far-reaching transformations in the underlying system characteristics, such as species composition (Heyder, Schaphoff, Gerten, and Lucht 2011) and relationships among plants, herbivores, and pollinators (Mooney et al. 2009); they are thus essential to understanding what constitutes "dangerous levels of global warming" with respect to ecosystems. Feedback effects can further amplify these changes, both by contributing directly to greenhouse gas emissions (Finzi et al. 2011) and through accelerated shifts in productivity and decomposition resulting from species loss (Hooper et al. 2012).

Figure 6.5: Fraction of land surface at risk of severe ecosystem change as a function of global mean temperature change for all ecosystems models, global climate models, and emissions scenarios



The colors represent the different ecosystems models, which are also horizontally separated for clarity. Results are collated in unit-degree bins, where the temperature for a given year is the average over a 30-year window centered on that year. A black horizontal line denotes the median in each bin. The grey boxes span the 25th and 75th percentiles across the entire ensemble. The short, horizontal stripes represent individual (annual) data points; the curves connect the mean value per ecosystem model in each bin. The solid (dashed) curves are for models with (without) dynamic vegetation composition changes. It is important to note that changes are compared to the present baseline.

A unified metric—which aggregates information about changes to the carbon stocks and fluxes, and to the water cycle and vegetation composition across the global land surface—is used to quantify the magnitude and uncertainty in the risk of these ecosystem changes (with respect to 1980–2010 conditions) occurring at different levels of global warming since pre-industrial times. The metric uses changes in vegetation composition as an indicator of risk to underlying plant and consumer communities. Both local (relative) and global (absolute) changes in biogeochemical fluxes and stocks contribute to the metric, as well as changes in the variability of carbon and water fluxes and stocks as an indicator of ecosystem vulnerability. The metric projects a risk of severe change for terrestrial ecosystems when very severe change is experienced in at least one of the metric components, or moderate to severe change in all of them. Marine ecosystems, which are not taken into account here, are further outlined in Chapter 4 on "Coastal and Marine Ecosystems."

[123] Three of the seven models consider dynamic changes to vegetation composition, and all models only consider natural vegetation, ignoring human-induced land-use and land-cover changes. The response of models in terms of the unified metric is shown to be reasonably predicted by changes in global mean temperatures. Note that the ecosystems changes are with respect to 1980–2010 conditions.

The fraction of the global land surface at risk of severe ecosystem change is shown in Figure 6.5 for all seven models as a function of global mean temperature change above pre-industrial levels.[123] Under 2°C warming, 3–7 percent of the Earth's land surface is projected to be at risk of severe ecosystem change, although there is limited agreement among the models on which geographical regions face the highest risk of change. The extent of regions at risk of severe ecosystem change is projected to rise with changes in temperature, reaching a median value of 30 percent of the land surface under 4°C warming and increasing approximately four-fold between 2°C and 3°C. The regions projected to face the highest risk of severe ecosystem changes by 4°C include the tundra and shrub lands of the Tibetan Plateau, the grasslands of eastern India, the boreal forests of northern Canada and Russia, the savannah region in the Horn of Africa, and the Amazon rainforest.

In some regions, projections of ecosystem changes vary greatly across models, with the uncertainty arising mostly from the ecosystem models themselves rather than from differences in the projections of the future climate. Global aggregations, such as reported here, should be treated cautiously, as they can obscure the fact that these arise from significantly different spatial distributions of change. Nonetheless, clear risks of biome shifts emerge when looking at the global picture, which can serve as a backdrop for more detailed assessments.

Review of Climate Model Projections for Terrestrial Ecosystem Shifts

Projections of risk of biome changes in the Amazon by a majority of the ecosystem models in the ISI-MIP study (Warszawski et al. n.d.) arise in most cases because of increases in biomass over this region. This is in agreement with studies considering 22 GCMs from the CMIP3 database with a single ecosystem model (not used in ISI-MIP), which projected biomass increases by 2100 between 14–35 percent over 1980 levels (Huntingford et al. 2013). When considering only projections in the reduction in areal extent of the climatological niche for humid tropical forests, up to 75 percent (climate model mean is 10 percent) of the Amazon is at risk (Zelazowski, Malhi, Huntingford, Sitch, and Fisher 2011). Such discrepancies between ecosystem models and climatological projections are already present in the historical data, in particular with respect to the mechanisms governing tree mortality resulting from drought and extreme heat. For example, observations in the Amazon forest link severe drought to extensive increases in tree mortality and subsequent biomass loss (C. D. Allen et al. 2010). Even in regions not normally considered to be water limited, observed increases in tree mortality suggest a link to global temperature rises because of climate change (Allen et al. 2010; Van Mantgem et al. 2009).

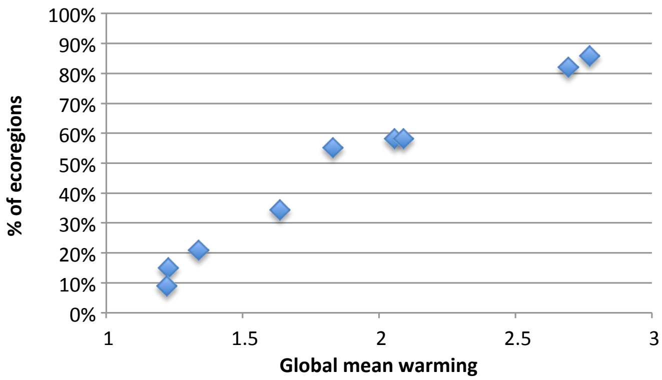
More generally, the recent emergence of a pattern of drought and heat-induced tree mortality, together with high fire occurrence and reduced resistance to pests globally points to a risk that is not presently included in ecosystem models. These observations point to potential for more rapid ecosystem changes than presently projected in many regions (C. D. Allen et al. 2010). The loss and or transformation of ecosystems would affect the services that they provide to society, including provisioning (food and timber) and such support services as soil and nutrient cycling, regulation of water and atmospheric properties, and cultural values (Anderegg, Kane, and Anderegg 2012).

The projected rate of ecosystem change is large in many cases compared to the ability of species and systems to migrate (Loarie et al. 2009). One measure of this, which has been termed the "velocity of climate change," represents the local horizontal velocity of an ecosystem across the Earth´s surface needed to maintain constant conditions suitable for that ecosystem. For the tropical and subtropical grasslands, savannahs, and shrub lands which are characteristic of much of Sub-Saharan Africa (see also Chapter 3 on "Projected Ecosystem Changes"), an average velocity of 0.7 km per year is projected under approximately 3.6°C warming by 2100. For the tropical and subtropical broadleaved forest ecosystems characteristic of much of South and South East Asia, the average velocity is about 0.3 km per year, but with a wide range (Loarie et al. 2009). Under this level of warming, the global mean velocity of all ecosystems is about 0.4 km per year; whereas for a lower level of warming of approximately 2.6°C by 2100, this rate of change is reduced to about 0.3 km per year. As horizontal changes are measured, relatively slow velocity is measured in mountainous regions in contrast to flatter areas. For some species, however, such shifts may not be possible, putting them at risk of extinction (La Sorte and Jetz 2010).

Under future warming, regions are expected to be subject to extreme or unprecedented heat extremes (see also Chapter 2 on "Projected Changes in Heat Extremes"). (Beaumont et al. (2011) measure the extent to which eco-regions, which have been classified as exceptional in terms of biodiversity, are expected to be exposed to extreme temperatures. They find that, by 2100, 86 percent of terrestrial and 83 percent of freshwater eco-regions are projected to experience extreme temperatures on a regular basis, to which they are not adapted (see Figure 6.6).

In conclusion, the state-of-the-art models of global ecosystems project an increasing risk of severe terrestrial ecosystem change with increasing global mean temperature. The area affected increases rapidly with warming. The affected surface increases almost four-fold between warming levels of 2°C and 3°C. The most extensively affected regions lie in the northern latitudes, where current climate conditions would find no analogue in a warmer world. These changes, resulting in shifts in the variability and mean values of carbon and water stock and fluxes and, in some cases, vegetation composition, would pose a major challenge to the survival of plant and animal species in their current habitat.

Figure 6.6: The proportion of eco-regions projected to regularly experience monthly climatic conditions that were considered extreme in the period 1961–90



Source: based on (Beaumont et al. 2011)

Crop Production and Sector Interactions

Population increases and diet changes because of economic development are expected to impose large pressures on the world's food production system. Meeting future demand for food requires substantially improving yields globally as well as coping with pressures from climate change, including changes in water availability.

There are many uncertainties in projecting both future crop yields and total production. One of the important unresolved issues is the CO_2 fertilization effect on crops. As atmospheric CO_2 concentrations rise, the CO_2 fertilization effect may increase the rate of photosynthesis and water use efficiency of plants, thereby producing increases in grain mass and number; this may offset to some extent the negative impacts of climate change (see Laux et al. 2010 and Liu et al. 2008). Projections of crop yield and total crop production vary quite significantly depending on whether the potential CO_2 fertilization effect is accounted for. As is shown in the work of Müller, Bondeau, Popp, and Waha (2010), the sign of crop yield changes (that is, whether they are positive or negative) with climate change may be determined by the presence or absence of the CO_2 fertilization effect. Their work estimates the effects of climate change with and without CO_2 fertilization on major crops (wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed) in different regions.[124]

Uncertainty surrounding the CO_2 fertilization effect remains, however, meaning that the extent to which the CO_2 fertilization effect could counteract potential crop yield reductions associated with climatic impacts is uncertain. This is problematic for risk assessments in the agricultural sector. When compared with the results from the free-air CO_2 enrichment (FACE) experiments, the fertilization effects used in various models appear to be overestimated (e.g., P. Krishnan, Swain, Chandra Bhaskar, Nayak, and Dash 2007; Long et al. 2005). Further, the C4 crops, including maize, sorghum, and pearl millet—among the dominant crops in Africa—are not as sensitive to elevated carbon dioxide as the C3 crops.[125] Consequently, the benefits for many of the staple crops of Sub-Saharan Africa are not expected to be as positive (Roudier et al. 2011). A recent review of the experimental evidence for CO_2 fertilization indicates that there may be a tendency in crop models to overestimate the benefits for C4 crops, which appear more likely to benefit in times of drought (Leakey 2009).

Although, in CO_2 fertilization experiments, the grain mass, or grain number of C3 crops generally increases, the protein concentration of grains decreases, particularly in wheat, barley, rice, and potatoes (e.g., Taub, Miller, & Allen, 2008). In other words, under sustained CO_2 fertilization the nutritional value of grain per unit of mass decreases. A recent statistical meta-analysis (Pleijel and Uddling 2012) of 57 CO_2 fertilization experiments on wheat shows that if other limiting factors prevent CO_2 fertilization from enhancing grain mass, or number, the diluting effect of enhanced CO_2 on protein content still operates, hence effectively decreasing the total nutritional value of wheat harvests.

The IPCC AR4 found that in the tropical regions a warming of 1–2°C locally could have significant negative yield impacts on major cereal crops, whereas in the higher latitudes in temperate regions there could be small positive benefits on rainfed crop yields for a 1–3°C local warming. Research published since has tended to confirm the picture of a significant negative yield potential in the tropical regions, with observed negative effects of climate change on crops in South Asia (David B. Lobell, Sibley, and Ivan Ortiz-Monasterio 2012), Africa (David B Lobell, Bänziger, Magorokosho, and Vivek 2011; Schlenker and Lobell 2010) and the United States (Schlenker and Roberts 2009) and concerns that yield benefits may not materialize in temperate regions (Asseng, Foster, and Turner 2011). In particular, the effects of high temperature on crop yields have become more evident, as has the understanding that the projected global warming over the 21st century is likely to lead to growing seasonal temperatures exceeding the hottest presently on record. Battisti and Naylor (2009) argue that these factors indicate a significant risk that stress on crops and livestock

124 For their projections, the authors apply three SRES scenarios (A1B, A2, and B1 leading to a global-mean warming of 2.1°C, 1.8°C, and 1.6°C above pre-industrial levels by 2050) and five GCMs, and compare the period 1996–2005 to 2046–55.

125 C3 plants include more than 85 percent 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 out perform 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.

production will become global in character, making it extremely challenging to balance growing food demand.

The scope of the potential risk can be seen in the results of a recent projection of global average crop yields for maize, soya bean, and wheat by 2050 (Deryng, Sacks, Barford, and Ramankutty 2011). Including adaptation measures, the range of reductions for maize is –6 to –18 percent, for soya bean is –12 to –26 percent, and for spring wheat is –4 to –10 percent, excluding the CO_2 fertilization effect. Losses are larger when adaptation options are not included.

A recent review of the literature by J. Knox, Hess, Daccache, and Wheeler (2012) indicates significant risks of yield reductions in Africa, with the mean changes being –17 percent for wheat, –5 percent for maize, –15 percent for sorghum, and –10 percent for millet. For South Asia, mean production is –16 percent for maize and –11 percent for sorghum. Knox et al. (2012) find no mean change in the literature for rice. However, analysis by Masutomi, Takahashi, Harasawa, and Matsuoka (2009) points to mean changes in Asia for rice yields of between –5 and –9 percent in the 2050s without CO_2 fertilization and between +0.5 and –1.5 percent with CO_2 fertilization.

To cope with the scale of these challenges (even if they are significantly less than shown here) would require substantial increases in crop productivity and yield potential. The recent trend for crop yields, however, shows a worrying pattern where substantial areas of crop-growing regions exhibit either no improvement, stagnation, or collapses in yield. Ray, Ramankutty, Mueller, West, and Foley (2012) show that 24–39 percent of maize, rice, wheat, and soya growing areas exhibited these problems. The top three global rice producers—China, India, and Indonesia—have substantial areas of cropland that are not exhibiting yield gains. The same applies to wheat in China, India, and the United States. Ray et al. (2012) argue that China and India are now "hotspots of yield stagnation," with more than a third of their major crop-producing regions not experiencing yield improvements.

Within ISI-MIP, climate-change-induced pressure on global wheat, maize, rice, and soy production was analyzed on the basis of simulations by seven global crop models assuming fixed present day irrigation and land-use patterns (Portmann, Siebert, & Döll, 2010). In a first step, runoff projections of 11 hydrological models were integrated to estimate the limits of production increases allowing for extra irrigation but accounting for limited availability of renewable irrigation water. In a second step, illustrative future land-use patterns, provided by the agro-economic land-use model MAgPIE (Lotze-Campen et al., 2008; Schmitz et al., 2012), were used to illustrate the negative side effects of the increase in crop production on natural vegetation and carbon sinks due to land use changes. To this end, simulations by seven global biogeochemical models were integrated. Given this context, the urgency of a multi-model assessment with regard to projections of global crop production is evident and has been addressed by the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al. 2013), with results that will be forthcoming. Similarly, cross-sectoral assessments are needed, as potential sectoral interactions can be expected.

Potential impact cascades are found that underline the critical importance of cross-sectoral linkages when evaluating climate change impacts and possible adaptation options. The combination of yield projections and biogeochemical and hydrological simulations driven by the same climate projections provides a first understanding of such interactions that need to be taken into account in a comprehensive assessment of impacts at different levels of warming. The impacts, which would not occur in isolation, are likely to amplify one another.

Regions Vulnerable to Multisector Pressures

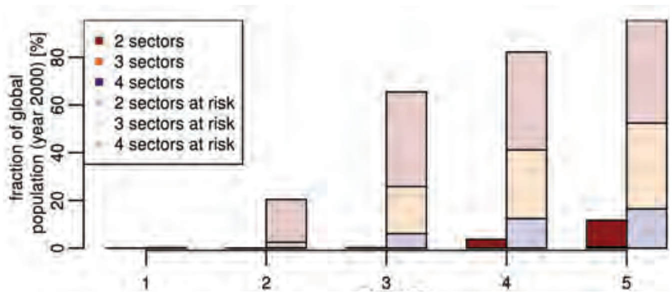
At 4°C above pre-industrial levels, the exposure to multisectoral climate change impacts starts to emerge under the robustness criteria. This means that the sectoral thresholds for severe changes have been crossed at lower levels of global mean temperature. At 5°C above pre-industrial levels, approximately 11 percent of the global population (based on the 2000 population distribution[126]) is projected to be exposed to severe changes in conditions resulting from climate change in at least two sectors (Figure 6.7, bright colored bars).

At the global mean temperature levels in this study, no robust overlap of the four sectors is seen. The fraction of the population affected in the risk analysis is much higher, going up to 80 percent at 4°C above pre-industrial levels, with the effects starting at 2°C (Figure 6.7, light colored bars). There is a clear risk of an overlap of all four sectors.

Multisectoral pressure hotspots are mapped based on pure climate exposure (Figure 6.8, left panel) as well as on a simple measure for vulnerability based on the number of sectors affected and the degree of human development (Figure 6.8, right panel). The grey-colored areas in the left panel are areas at risk. The southern Amazon Basin, southern Europe, eastern Africa, and the north of South Asia are high-exposure hotspots. The Amazon and the East African highlands are particularly notable because of their exposure to three overlapping sectors. Small regions in Central America and western Africa are also affected. The area at risk covers most of the inhabited area, highlighting how common overlapping impacts could be and, therefore, their importance for possible adaptation strategies.

[126] The gridded population distribution for 2000 is based on UNPWWW data (UNDESA 2010), scaled up to match the country totals of the Socio-Economic Pathways database (http://secure.iiasa.ac.at/web-apps/ene/SspDb) using the NASA GPWv3 2010 gridded dataset (http://sedac.ciesin.columbia.edu/data/collection/gpw-v3).

Figure 6.7: Fraction of global population (based on year 2000 population distribution), which is affected by multiple pressures at a given level of GMT change above pre-industrial levels



The bright-colored bars are based on the conservative robust estimates, the light-colored bars on the risk analysis with low likelihood.

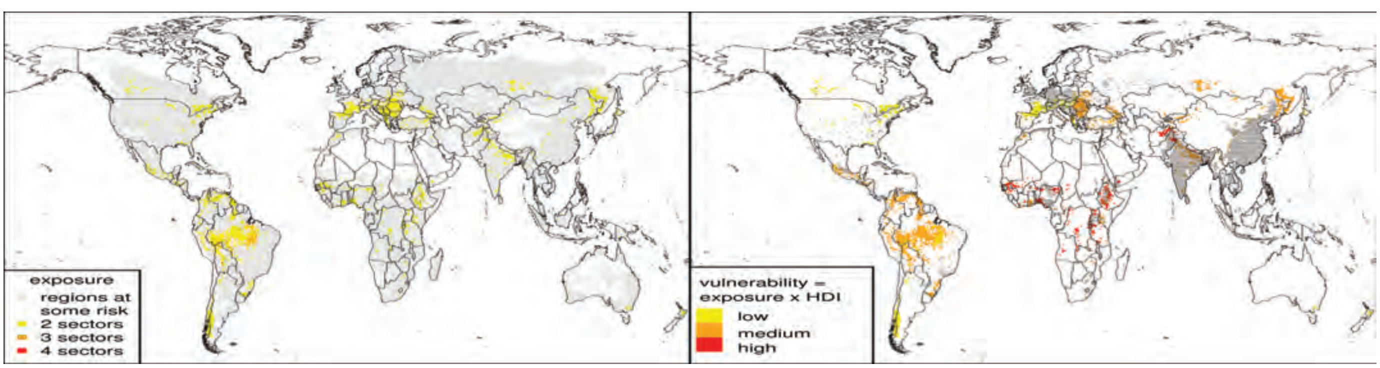
To get a simplified measure for vulnerability, the number of overlapping exposed sectors is combined with the level of human development as provided by the Human Development Index (UNDP 2002), which is a simple proxy for adaptive capacity (Figure 6.8). Based on that vulnerability measure, all regions in Sub-Saharan Africa affected by multisectoral pressures clearly stand out as the most vulnerable areas (Figure 6.8, right panel). Latin America, South Asia, and Eastern Europe are also vulnerable. Weighing it with population density would paint a slightly different picture (hatched regions in the lower panels of Figure 6.8, based on year 2000 population), with large numbers of people potentially affected by multiple pressures in Europe and India. Of note, the vulnerable regions extend over developing, emerging, and developed economic areas.

These results are very conservative. While the thresholds are defined based on historical observations within each sector, the interactions between impacts in each sector are not taken into account. Furthermore, the probability of overlap between the sectors is restricted by the choice of sectors. Agricultural impacts are only taken into account in currently harvested areas and malaria impacts are very limited spatially. Taking into account extreme events would possibly lead to the emergence of a very different hotspot picture. Therefore, what follows is a discussion on the state of knowledge on vulnerability to a subset of extreme events.

Regions with Greater Levels of Aggregate Climate Change

Climate change occurs in many different ways. Increases in mean temperature or changes in annual precipitation as well as seasonal changes, changes in variability, and changes in the frequency of

Figure 6.8: Maps of exposure (left panel) and vulnerability (right panel, defined as the overlap of exposure and human development level as shown in the table) to parallel multisectoral pressures in 2100



Vulnerability = exposure x human development level		Level of human development		
		Low	Medium	High
# of overlapping sectors	2	Medium	Low	Low
	3	High	Medium	Low
	4	High	High	Medium

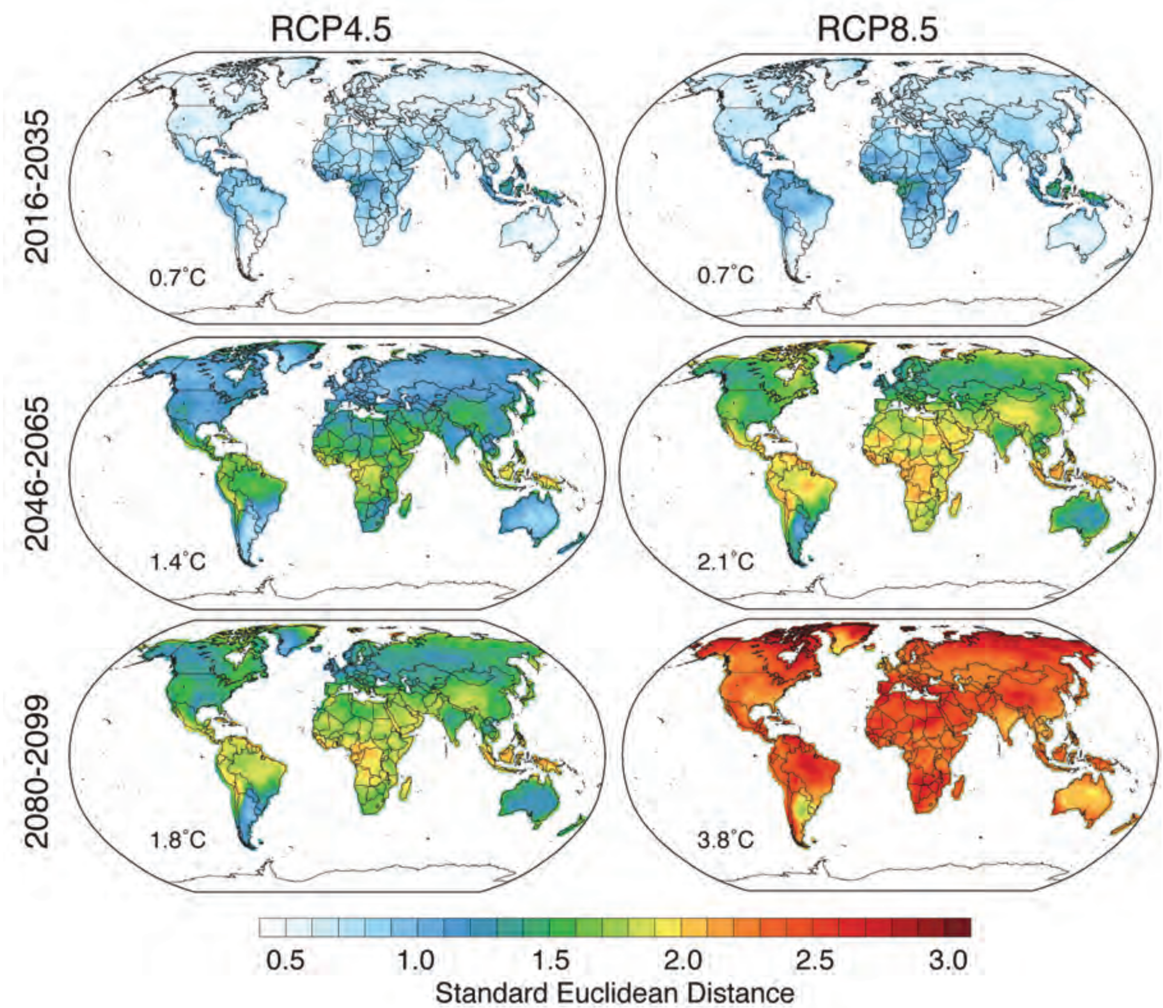
Grey regions in the left panel show areas at risk of multisectoral pressure, if conservative assumptions are relaxed (see Appendix 3 for Method). Vulnerability (right) is a combination of number of sectors affected and level of human development as measured by the year 2000 Human Development Index (UNDP 2002). Hatched regions are regions with very high population density (year 2000), which is expected to act as an additional pressure.

certain kinds of extremes all affect the way in which impacts are expected to unfold and be felt. A region with the largest change in average annual temperature may not be the one with the most overall impact, or the annual average temperature change may not be as significant as other effects, such as seasonal changes. To capture this complexity, Diffenbaugh and Giorgi (2012) used the new CMIP5 global climate models, applying seven climate indicators from each of the four seasons to generate a 28-dimensional measure of climate change.[127]

The picture that emerges is of an increasingly strong change of climatic variables with greater levels of global mean warming. The greater global warming is, the larger the difference between the present climate and the aggregated climate change metric—in other words, the larger the overall effects of climate change (Figure 6.9). This analysis indicates a strong intensification of climate change at levels of warming above 2°C above pre-industrial

[127] Diffenbaugh and Giorgi (2012) considered land grid points north of 60° southern latitude. To calculate the change in each climate indicator, each one is first normalized to the maximum global absolute value in the 2080–99 period for the highest scenario (RCP 8.5), and then the standard Euclidean distance between each of the 28 dimensions and the base period is calculated.

Figure 6.9: Relative level of aggregate climate change between the 1986–2005 base period and three different 20 year periods in the 21st-century



The three different 20 year periods in the 21st-century are the 2020s (1.5°C above pre-industrial levels), 2050s (2.2–2.9°C above pre-industrial levels), and 2090s (2.6–4.6°C above pre-industrial levels) under two different RCP scenarios. To convert the temperatures given in the maps to global mean warming above pre-industrial levels, add 0.8°C.

Source: Diffenbaugh and Giorgi (2012).

levels. It is also clear that some regions begin to show strong signs of overall change at lower levels of global mean warming than others. In terms of the regions studied in this report, much of Africa stands out: West Africa, the Sahel, and Southern Africa emerge consistently with relatively high levels of aggregate climate change. South Asia and South East Asia show moderate to high levels of climate change above 1.5°C compared to more northerly and southerly regions.

Vulnerability Hotspots for Wheat and Maize

Fraser et al. (2012) identify hotspots for wheat and maize based on a comparison of regions subject to increasing exposure to yield decreases that are predicted to experience declining adaptive capacity. Where these regions overlap, a hotspot is identified for the time period studied: the 2050s and 2080s. They identify five wheat hotspots (southeastern United States, southeastern South America, northeast Mediterranean region, and parts of central Asia). For maize, three hotspots are found: southeastern South America, parts of southern Africa, and the northeastern Mediterranean. This study uses only one climate model and one hydrology model, limiting the ability to understand the uncertainty of climate model and hydrology model projections in identifying regions at risk. It should be noted that maize is particularly important in Southern Africa.

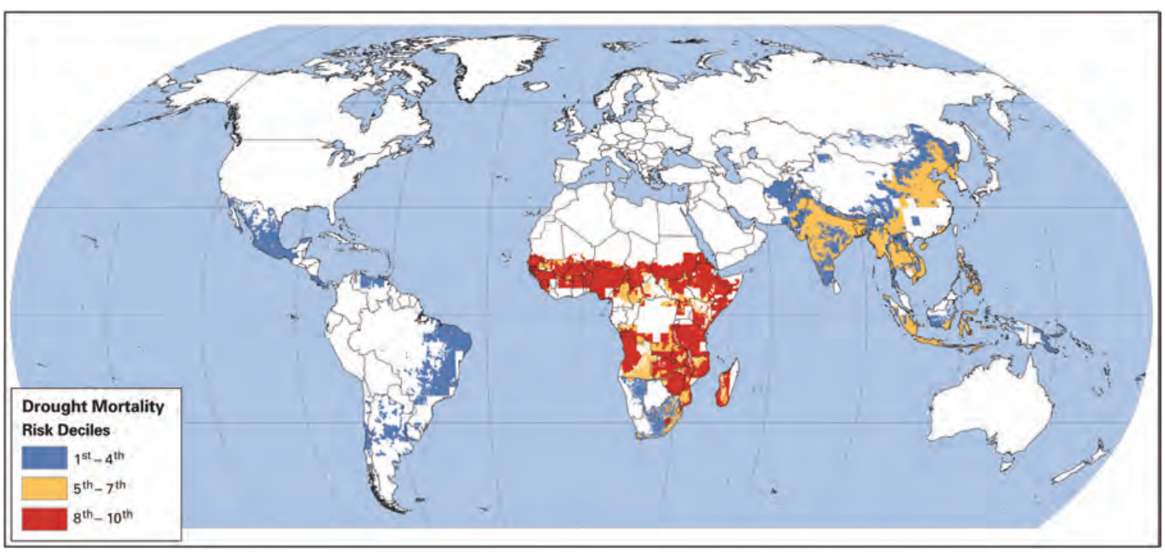
Vulnerability Hotspots for Drought and Tropical Cyclones

Droughts and tropical cyclones have been among the most severe physical risk factors that are projected to increase with climate change, and the severity and distribution of these impacts may change in the future. Looking at impacts from past occurrences illustrates regional vulnerabilities that could be amplified with increasing exposure in the future.

Vulnerability hotspots related to droughts have in the past been highest in Sub-Saharan Africa, with exceptions in southern Africa (Figure 6.10). Much of South Asia and South East Asia also show high levels of vulnerability. It should be noted that the analysis is based only on drought-related mortality. Impacts on agricultural productivity (as have been observed during the Russian drought in 2010 and the American (U.S.) drought in 2012) are not included here.

Taking into account observed vulnerability to tropical cyclones, the East and South East Asian coasts, as well as the eastern North American and Central American coasts, emerge as vulnerability hotspots (Figure 6.11). Madagascar and the densely populated deltaic regions of India and Bangladesh, as well as parts of the Pakistan coast, mark areas of extreme vulnerability. As noted before, the hotspots are based on observed events.

Figure 6.10: Hotspots of drought mortality risk, based on past observations. Regions marked in red (8^{th}–10^{th} deciles) mark the 30 percent of land area that is most severely impacted



Risks are shown for year 2000 population levels (with exposure probabilities average over 1981–2000.) White areas are masked due to low population density or no significant impact observed.

Source: Dilley et al. (2005).

Figure 6.11: Hotspots of cyclone mortality risk, based on past observations. Regions marked in red (8th–10th deciles) mark the 30 percent of land area that is most severely impacted

Risks are shown for year 2000 population levels (with exposure probabilities average over 1981–2000.) White areas are masked due to low population density or no significant impact observed.

Source: Dilley et al. (2005).

Implications for Poverty

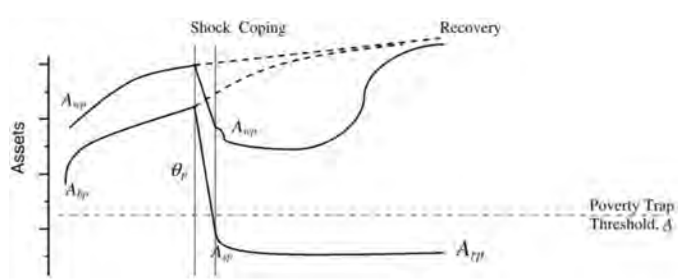
Climate impacts can have negative effects on poverty reduction. While the population´s vulnerability is determined by socioeconomic factors, increased exposure to climate impacts can have adverse consequences for these very factors. It has been observed that natural disasters, such as droughts, floods, or cyclones, have direct and indirect impacts on household poverty—and in some cases could even lead households into poverty traps.

A study assessing the impacts of a three-year long drought in Ethiopia (1998–2000) and category 5 Hurricane Mitch in Honduras found that these shocks have enduring effects on poor households' assets and recovery (Carter, Little, Mogues, and Negatu 2007). The authors observed a critical differential impact of cyclones on poorer households (representing a quartile of the population). Before the occurrence of the disasters, it was assessed that these poor households accumulated assets faster than rich households. As a consequence, this faster accumulation led to a convergent growth path between poorer and richer households. The authors found, however, that both slow and sudden onset disasters slowed down poor households' capacity to accumulate assets.

Figure 6.12 illustrates the impacts of such shocks as cyclones and droughts on the assets of two categories of households (rich and poor). This simplified model only illustrates how climate-induced shocks could drive households into poverty traps.

Because of the consequences of the shocks, assets at the household level significantly decrease; they later increase during the recovery period. For the poorer households, the decrease in assets has the potential to lead them below the poverty trap threshold, preventing households from recovering from the disaster. This figure only gives a schematic representation, however, of the potential impacts of natural disasters on rich and poor households.

Figure 6.12: Asset shocks and poverty traps



Awp represents the assets owned by the rich household; Abp, Asp, and Arp represent the assets owned by the poor households, before the shock (Abp), after the shock (Asp), and after the recovery period (Arp).

Source: Carter et al. (2007).

Hallegatte and Przyluski (2010) find that these poverty traps at the household level induced by natural disasters could lead to poverty traps at the macroeconomic level. Poor countries' limited capacity to rebuild after disasters, long reconstruction periods, the relatively large economic costs of natural disasters, reduced accumulation of capital and infrastructure, and reduced economic development contribute to amplifying the consequences of these natural disasters. From a long-term perspective, this loop reduces the capacity of a country to cope with the consequences of a disaster. Furthermore, this feedback loop reduces the capacity of developing countries to benefit from natural disasters through the accelerated replacement of capital (Hallegatte and Dumas 2009) after the occurrence of disaster as the damages from the disaster exceed their capacity for reconstruction.

Non-linear and Cascading Impacts

In this report the risks of climate change for a number of major sectors were examined within three regions at different levels of global mean warming. While the attempt was made to draw connections between sectors, the literature does not yet permit a comprehensive assessment of the quantitative magnitude of these risks to elucidate risks of multiple and/or cascading impacts which occur on a similar timescale in the same geographical locations. Nevertheless, one of the first studies of these risks indicates that the proportion of the global population at risk from simultaneous, multiple sectoral impacts increases rapidly with warming. By the time warming reaches 4°C, more than 80 percent of the global population is projected to be exposed to these kinds of risks (see Chapter 6 on "Regions Vulnerable to Multisector Pressures"). While adaptation measures may reduce some of these risks and/or impacts, it is also clear that adaptation measures required would need to be substantial, aggressive and beyond the scale of anything presently contemplated, and occur simultaneously across multiple sectors to significantly limit these damages.

There is also limited literature on non-linear effects and risks. Potential tipping points and non-linearities due to the interactions of impacts are mostly not yet included in available literature. The tentative assessment presented here indicates the risk of such interactions playing out in the focus regions of this report and suggests a need for further research in this field.

In some cases of non-linear behavior observed in certain sectors, such as high-temperature thresholds for crop production, response options are not readily available. For example crop cultivars do not presently exist for the high temperatures projected at this level of warming in current crop growing regions in the tropics and mid-latitudes.

To point the way to future work assessing the full range of risks, it is useful to conclude this report with a brief set of examples that illustrate the risk of non-linear and cascading impacts occurring around the world. The physical mechanisms and thresholds associated with these risks are uncertain, but have been clearly identified in the scientific literature.

Non-Linear Responses of the Earth System

- **Sea-level rise.** In this report the focus has been on sea-level rise of up to a meter in the 21st-century. This excluded an assessment of faster rates, and of longer term, multi-meter sea-level rise increases and what this might mean for the regions studied. Disintegration of the West Antarctic ice sheet could raise sea levels by 4–5 m over a number of centuries, and there is already evidence that the ice sheet is responding rapidly to a warming ocean and climate. Complete loss of the Greenland ice sheet over many centuries to millennia would raise sea levels by 6–7 m. A recent analysis estimates the warming threshold for the Greenland Ice Sheet to irreversibly lose mass at 1.6°C global-mean temperature increase above pre-industrial levels (range of 0.8°C – 3.2°C). Already the damages projected for a 0.5 metre and 1 metre sea level rise in the three regions are very substantial and very few studies have examined the consequences of two, three or 5 m sea-level rise over several centuries. Those that are based on such assessments, however, show dramatic problems. In this report Bangladesh was identified as a region facing multiple simultaneous impacts for large vulnerable populations, due to the combined effects of river floods, storm surges, extreme heat and sea-level rises of up to a meter. Multi-meter sea level rise would compound these risks and could pose an existential risk to the country in coming centuries.
- **Coral reefs.** Recent studies suggest that with CO_2 concentrations corresponding to 2°C warming, the conditions that allow coral reefs to flourish will cease to exist. This indicates a risk of an abrupt transition, within a few decades, from rich coral reef ecosystems to much simpler, less productive and less diverse systems. These changes would lead to major threats to human livelihoods and economic activities dependent upon these rich marine ecosystems, in turn leading to the feedbacks in social systems exacerbating risks and pressures in urban areas.
- **Ecosystems in Sub-Saharan Africa.** The complex interplay of plant species in the African savannas and their different sensitivities to fire regimes and changes in atmospheric CO_2 concentrations implies a potential tipping point from a C4 (grass) to a C3 (woody plants) dominated state at the local scale. Such a transition to a much less productive state, exacerbated by already substantial pressures on natural systems in Africa, would place enormous, negative pressure on many species and threaten human livelihoods in the region.
- **The Indian monsoon.** Physically plausible mechanisms have been proposed for a switch in the Indian monsoon, and changes

in the tropical atmosphere that could precipitate a transition of the monsoon to a drier state are projected in the present generation of climate models. An abrupt change in the monsoon, towards a drier, lower rainfall state, could precipitate a major crisis in South Asia, as evidenced by the anomalous monsoon of 2002, which caused the most serious drought in recent times, with rainfall about 19 percent below the long term normal, and food grain production reductions of about 10–15 percent compared to the average of the preceding decade.

Non-linearity due to Threshold Behavior and Interactions

- **Crop yields.** Non-linear reductions in crop yields have been observed once high temperature thresholds are crossed for many major crops including rice, wheat and maize in many regions. Within the three regions studied temperatures already approach upper limits in important food growing regions. Present crop models have not yet fully integrated the consequences of these responses into projections, nor are high-temperature, drought resistant crop cultivars available at present. When these regional risks are put into the context of probable global crop production risks due to high temperatures and drought, it is clear that qualitatively new risks to regional and global food security may be faced in the future that are little understood, or quantified.
- **Aquaculture in South East Asia.** Temperature tolerance thresholds have been identified for important aquaculture species farmed in South East Asia. More frequent temperatures above the tolerance range would create non-optimum culture conditions for these species and are expected to decrease aquaculture yields. Such damages are expected to be contemporaneous in time with saltwater intrusion losses and inundation of important rice growing regions in, for example Vietnam, as well as loss of marine natural resources (Coral reefs and pelagic fisheries) upon which people depend for food, livelihoods and tourism income.
- **Livestock production in Sub-Saharan Africa,** particularly in the case of small-scale livestock keeping in dryland areas, is under pressure from multiple stressors. Heat and water stress, reduced quantity and quality of forage and increasing prevalence of diseases have direct impacts on livestock. Changes in the natural environment due to processes of desertification and woody plant encroachment may further limit the carrying capacity of the land. Traditional responses are narrowed where diversification to crop farming may no longer be viable and mobility to seek out water and forage is restricted by institutional factors. These stress factors compound one another, placing a significantly greater pressure on affected farmers than if impacts were felt in isolation.

Cascading Impacts

A framing question for this report was the consequence for development of climate change. What emerges from the analyses conducted here and the reviewed literature is a wide range of

Box 6.1: Emerging Vulnerability Clusters: the Urban Poor

The picture that emerges from the three regional analyses is of new clusters of vulnerability appearing in urban areas as urbanization rates increase. Although the urbanization trend is driven by a host of factors, climate change is becoming an increasingly significant driver as it places livelihoods in rural areas under mounting pressure.

However, there are risks associated with the observed and projected urbanization trends. The location of many cities in coastal areas further means that a large and growing number of people are exposed to the impacts of sea-level rise. Similarly, health impacts of heat waves are reportedly high in cities, where the built environment amplifies the warming effect.

Many impacts are expected to disproportionately affect the urban poor. The concentration of large populations in informal settlements, where basic services and infrastructure tend to be lacking, is a considerable source of vulnerability. In such areas, people are highly exposed to extreme weather events, such as storms and flooding. Furthermore, informal settlements often provide conditions particularly conducive to the transmission of the vector and water borne diseases that are projected to become more prevalent with climate change. The urban poor, as net buyers of food, have also been identified as the group most vulnerable to increases of food prices following production shocks and declines.

There are multiple co-benefits to be gained from urban planning which takes into account the risks projected to accompany climate change. Urban areas account for the largest proportions of global greenhouse gas emissions (UN Habitat, 2011) and hence a great potential exists in these areas for mitigation of climate change. Similarly, careful urban planning can strongly increase human resilience to the impacts of climate change. Efficient provision of basic services, which is central to meeting human development needs in urban areas, will assist large communities to cope with the adverse effects associated with rising atmospheric CO_2 concentrations.

Thus, while cities currently often concentrate vulnerability, future patterns of urbanization provide the opportunity to significantly increase the resilience of urban populations.

risks. One cluster of impacts that needs to be highlighted is the risk of negative feedbacks on poverty from climate shocks on poor countries, leading to the potential for climate driven poverty traps migration (see Box 6.1). Recent observational evidence indicates that the poor countries that are most vulnerable to increases in temperature show the least resilience to shocks of extremes. The impacts of a three year long drought in Ethiopia (1998 2000), for example or the Category Five Hurricane Mitch in Honduras have been observed to have long-lasting effects on poverty. These climate-related extreme events and natural disasters can overwhelm a poor country's ability to recover economically, reducing the accumulation of capital and infrastructure, leading to a negative economic feedback. This would reduce the capacity of developing countries to economically benefit from natural disasters through more rapid replacement of capital as the reconstruction capacity is exceeded by the disaster damages.

Increases in climatic extremes of all kinds are projected for the three regions studied: increased tropical cyclone intensity in South East Asia, extreme heat waves and heat intensity in all regions, increased drought in many regions, an increased risk of flooding and consequent damages on agriculture and infrastructure in many regions. Few studies have really integrated these risks into projections of future economic growth and development for these regions.

The analyses presented in this report show that there are substantial risks to human development in the three regions assessed and a consideration of the risks of non-linearity and cascading impacts tends to amplify this picture. Impacts have already begun to occur and in many cases are projected to be severe under 1.5–2°C warming, depending upon the sector and the region. As warming approaches 4°C, very severe impacts are projected, affecting ever larger shares of the global population. Critically the risk of transgressing thresholds and tipping points within sectors and on vital human support systems increases rapidly with higher levels of warming. While limiting warming to 1.5 to 2°C does not eliminate risk and damage to many sectors and regions, it does create breathing space for adaptation measures to limit damage and for populations to learn to cope with the significant, inevitable damage that would occur even at this level of change.

Appendixes

Appendix 1

Background Material on the Likelihood of a 4°C and a 2°C World

4°C - Business-As-Usual Emission Estimates

Recent independent estimates by an international consortium of eight Integrated Assessment Modeling (IAM) research groups investigated how the world can be expected to evolve under a wide variety of climate policies (Kriegler et al. 2013; Riahi et al. 2013; Schaeffer et al. 2013). One of the scenarios investigated is known as the "business-as-usual" (BAU) pathway. In this scenario, which is characterized by a lack of strong climate policies throughout the 21^{st} century, GDP (Kriegler et al. 2013) and population projections (UN 2010) continue to drive energy demand. Global energy intensity roughly follows historical rates of improvements because of the lack of targeted policies. Accordingly, greenhouse gas emissions continue to rise in the estimates of each respective research group and follow an intermediate-to-high BAU path compared to the earlier literature (Nakicenovic and Swart 2000; IPCC 2007a; Rogelj et al. 2011; Riahi et al. 2012).

Recently, questions have been raised in the scientific literature about the validity of the high fossil fuel production outlooks required for such high-emissions BAU scenarios (e.g., Höök et al. 2010). While these critiques, which infer a possible global peak in fossil fuel availability, are not irrelevant, they mainly result from a different interpretation of the availability of fossil fuels from "reserves," "estimated ultimately recoverable resources," and additional "unconventional" resources. The recent Global Energy Assessment (Rogner et al. 2012) provides a discussion of this issue and a detailed assessment of fossil fuel resources. It concludes that enough fossil fuels will be available to satisfy future demand and to continue on a very high emissions pathway (see the GEA-Supply baseline in Riahi et al. 2012). This is in line with the RCP8.5 scenario used in this report (see Box I below), which forms a basis for some of the impacts studies in the rest of this report.

Temperature Changes Implied by Business-As-Usual Emissions Estimates

To compute the global mean temperature increase implied by the business-as-usual scenarios discussed above and in Box A1.1, the authors run a reduced-complexity carbon cycle and climate model in a probabilistic setup, which closely represents the uncertainty assessments of the earth system's response to increasing emissions.

Figure A1.1 below shows global mean temperature projections above pre-industrial levels. In the left panel, the "best-estimate"[128] projections (lines) are put in the context of carbon-cycle and climate-system uncertainties (shaded areas). According to the RCP8.5 scenario, the best-estimate warming is approximately 5.2°C by 2100. There is a 66 percent likelihood[129] that emissions consistent with RCP8.5 lead to a warming of 4.2–6.5°C, and a remaining 33 percent chance that warming would be either lower than 4.2°C or higher than 6.5°C by 2100.

The eight BAU scenarios generated by the international IAM research groups included here are on average slightly lower than RCP8.5, with some scenarios above it. On average,

128 In this report, the authors speak of "best-estimate" to indicate the median estimate, or projection, within an uncertainty distribution, that is, there is a 50-percent probability that values lie below and an equal 50-percent probability that values lie above the "best-estimate."

129 A probability of greater than 66 percent is labeled "likely" in IPCC's uncertainty guidelines (Mastrandrea et al. 2010) adopted here.

these scenarios lead to warming projections close to those of RCP8.5 and a medium chance that end-of-century temperature rise exceeds 4°C (see Figure A1.1, right-hand panel). Across all these scenarios, the median projections reach a warming of 4.7°C above pre-industrial levels by 2100.[130] This level is achieved 10 years earlier in RCP8.5.

By contrast, the *CAT reference scenario* (see Box A1.1), used in this report to derive the *CAT Current Pledges* scenario (Climate Analytics et al. 2011), results in warming below the BAU median across the IAM models, with only about 15 percent of climate projections using the IAM results lying below the *CAT Reference BAU*[131] (see Figure A.1, right-hand panel).

Thus, the most recent generation of energy-economic models estimate emissions in the absence of further substantial policy

[130] Note the uncertainty ranges in Figure 2.4: among the various other BAU scenarios, about 30 percent reach a warming higher than RCP8.5 by 2100 (compare light-red shaded with black line).

[131] The lower emissions in the CAT Reference BAU scenario compared to the recent BAU literature scenarios is explained by the fact that the CAT Reference BAU includes more of the effects of currently implemented energy policies than the BAU scenarios from the literature. This also explains why the reduction in future warming is stronger between the multi-model Reference and Current Pledge scenarios than in the CAT cases, since some policies required to achieve current pledges are already included in the CAT Reference BAU (Figure 2.4).

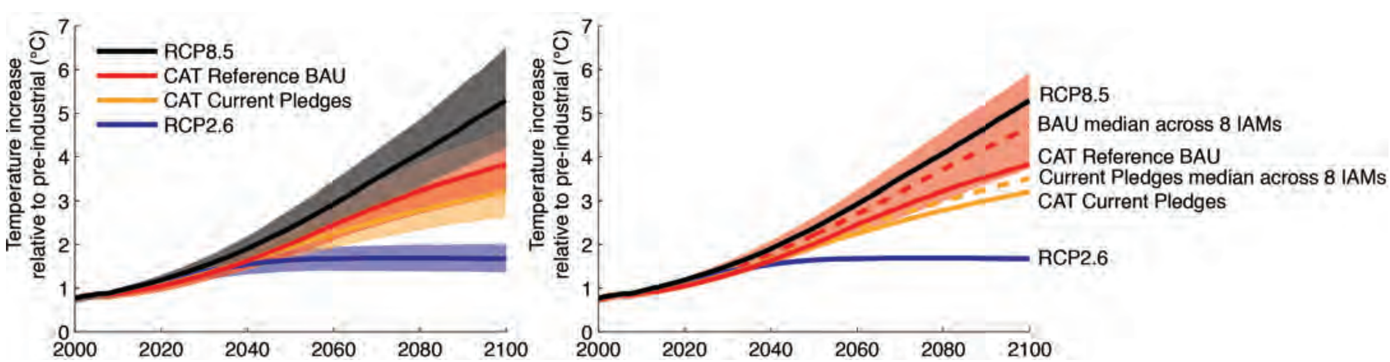
Box A1.1 Emission Scenarios in this Report

To frame its assessment, this report uses four main scenarios that span the range between a lausible high emissions future—leading to end-of-century warming exceeding 4°C with a high robability (ca. 85 percent)—and a feasible low emissions path, likely keeping temperature rise to below 2°C (ca. 85 percent probability).

a. *RCP8.5*: A no-climate-policy baseline with comparatively high greenhouse gas emissions (Riahi et al. 2011), which is used by many studies that are being assessed for the upcoming IPCC Fifth Assessment Report (AR5). This scenario is also the underlying high emissions scenario for impacts assessed in other parts of this report. In this report, the authors refer to the RCP8.5 as a 4°C world.
b. CAT Reference BAU: A lower reference BAU scenario that includes existing climate olicies, but not pledged emission reductions, as estimated by Climate Action Tracker (Climate Analytics et al. 2011).
c. CAT Current Pledges: A scenario also incorporating reductions currently pledged internationally by countries, as assessed by the Climate Action Tracker (Climate Analytics et al. 2011).
d. RCP2.6: A scenario that is representative of the literature on mitigation scenarios aiming to limit the increase of global mean temperature to 2°C (Van Vuuren et al. 2011). Similar to RCP8.5, this emissions path is used by many studies that are being assessed for AR5 and is the underlying low emissions scenario for impacts assessed in other parts of this report. In this report, the authors refer to the RCP2.6 as a 2°C world.

Without predicting what the future will bring, these scenarios are representations of distinct groups of plausible and possible futures that society can decide to work toward. As such,

Figure A1.1 Projections for surface-air temperature increase. The left-hand panel shows probabilistic projections by the SCM (see Box A.1.2)



Lines show "best-estimate" (median) projections for each emission scenario, while shaded areas indicate the 66 percent uncertainty range. The shaded ranges represent the uncertainties in how emissions are translated into atmospheric concentrations (carbon cycle uncertainty) and how the climate system responds to these increased concentrations (climate system uncertainty). The right-hand panel shows projections of temperature increase for the scenarios assessed in this report in the context of BAU projections from the recent Integrated Assessment Model (IAM) literature discussed in the text. The light-red shaded area indicates the 66 percent uncertainty range around the median (red dashed line) of BAU projections from 10 IAMs.

action (business as usual), with the median projections reaching a warming of 4.7°C above pre-industrial levels by 2100—with a 40-percent chance of exceeding 5°C.

Probabilities

From a risk assessment point of view, the probability that specific levels of warming are exceeded in the course of the 21st century is of particular interest. The probabilistic uncertainty ranges of the Simple Climate Model (SCM; see Box A 1.2) projections in this report, as well as the spread in results of complex Atmosphere Ocean General Circulation Models (AOGCMs), provide valuable information for this. For the four emission scenarios, Figure A1.2 shows the gradually increasing probability of exceeding warming levels of 3°C and 4°C. 4°C is "likely" (with a greater than 66-percent chance) exceeded around 2080 for *RCP8.5*. Consistent with the SCM, 80 percent of the AOGCMs project warming higher than 4°C by the 2080–2100 period. For other scenarios, lower probabilities of exceeding 4°C are found.

Figure A1.2 also shows that the *CAT Reference BAU* results in a 40-percent probability of exceeding 4°C by the end of the century, and still increasing thereafter. Recalling that the *CAT Reference BAU* is situated at the low end of most recent reference BAU estimates from the literature and that real-world global CO_2 emissions continue to track along a high emission pathway (Peters et al. 2013), the authors conclude that in the absence of greenhouse gas mitigation efforts during the century, the likelihood is considerable that the world will be 4°C warmer by the end of the century.

The results presented above are consistent with recently published literature. Newly published assessments of the recent trends in the world's energy system by the International Energy Agency in its World Energy Outlook 2012 indicate global mean warming above pre-industrial levels would approach 3.8°C by 2100. In this assessment, there is a 40-percent chance of warming exceeding 4°C by 2100 and a 10-percent chance of warming exceeding 5°C. The updated UNEP Emissions Gap Assessment, released at the Climate Convention Conference in Doha in December 2013, found that present emission trends and pledges[132] are consistent with emission pathways that reach warming in the range of 3–5°C by 2100, with global emissions estimated for 2020 closest to levels consistent with a 3.5–4°C pathway.

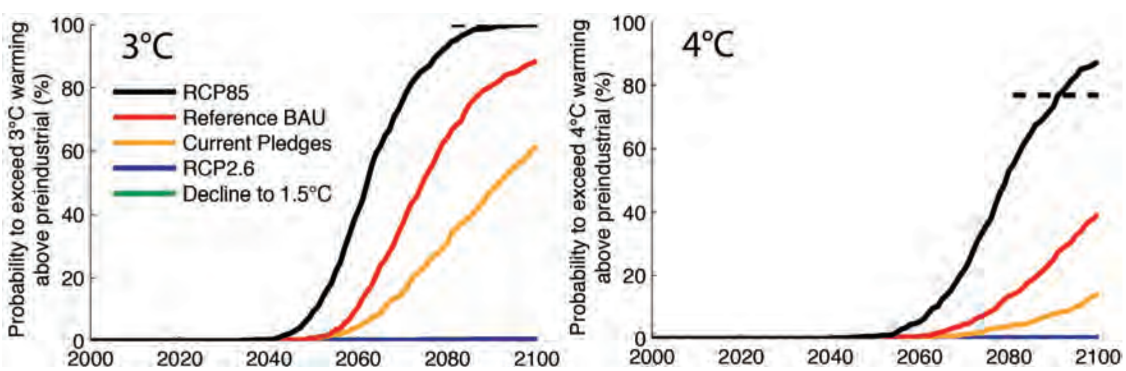
Can Warming Be Held Below 2°C?

The previous section explained why it is still plausible that a high-carbon emissions future could lead to a considerable probability that warming exceeds 4°C by the end of the century. The question that now arises is whether the significant reduction in greenhouse gas emissions required to hold the global temperature increase to below 2°C is feasible. This section discusses some of the latest scientific insights related to keeping warming to low levels.

First of all, most recent results with state-of-the-art AOGCMs and SCMs show that under reference emissions temperatures can exceed 2°C as early as the 2040s, but can also be held to below 2°C relative to pre-industrial levels with a high probability if emissions are reduced significantly (see Box A1.2, Figures A1.1, A1.2, and A1.3). This shows that, from a geophysical point of view, limiting temperature increase to below 2°C is still possible. Other assessments that take into account a large set of scenarios from the literature come to the same conclusion with

132 "Unconditional pledges, strict rules" case.

Figure A1.2 The probability that temperature increase exceeds 3°C or 4°C above pre-industrial levels projected by a simple coupled carbon cycle/climate model (SCM, see Box III)



The dashed line indicates the percentage of complex Atmosphere Ocean General Circulation Models (AOGCMs) and Earth-System Models (ESMs) as reported by the CMIP5 program that exceeds these temperature thresholds around the year 2090 for the RCP8.5 scenario (zero for RCP2.6).

Box A1.2 Climate Projections and the Simple Climate Model (SCM)

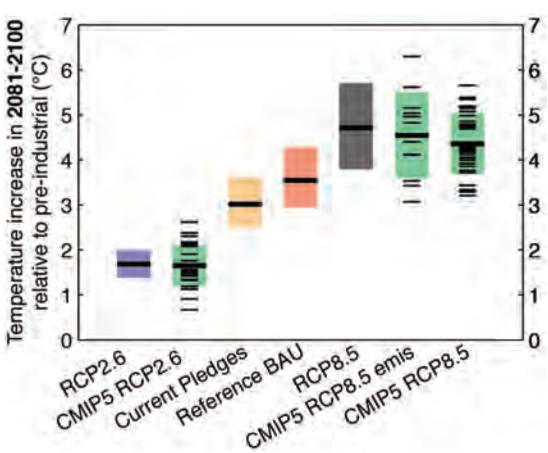
This report uses the reduced-complexity carbon cycle and climate model MAGICC (Meinshausen et al. 2011a, 2011b) to compute estimates of atmospheric greenhouse gas concentrations and their climatic outcomes. MAGICC is the primary simple climate model that has been used in past IPCC Assessment Reports and has been applied, further developed, and scientifically scrutinized for over two decades (Wigley and Raper 1987, 1992, 2001, 2005). MAGICC is a simple climate model (SCM) that can closely emulate the large-scale behavior of much more complex state-of-the-art Atmosphere Ocean General Circulation Models (AOGCMs) for a large range of scenarios.

AOGCMs and Earth-System Models (ESMs, AOGCMs with a coupled carbon cycle), are used to compute geographically explicit projections of a wide range of climate variables, such as temperature near the surface as well as higher up in the atmosphere or down in the ocean, precipitation, winds, ocean currents, and so on. Because these models are very complex and operate on high spatial resolution and small time steps, only a handful of emission scenarios can be run. For the IPCC's upcoming Fifth Assessment Report (AR5), the Coupled Model Intercomparison Project-Phase 5 (CMIP5 Taylor et al. 2012) has collected AOGCM and ESM output for the four new IPCC scenarios (RCPs—Vuuren et al. 2011). These results form an important basis for the climate impact projections presented in much of this report. A subset of five models from the CMIP5 project underlies the temperature and precipitation projections in the report.

The SCM MAGICC is used, however, to compute the global mean response of the carbon cycle and climate system for other scenarios in this report. It is no substitute for AOGCMs, but provides a tool to make synthesized knowledge obtained with AOGCMs available for large scenario numbers and at low computational cost.

Because of uncertainties in the carbon cycle and climate response of the earth system to increasing greenhouse gases, there is a range in the expected temperature outcome (see Figure SPM.5 in IPCC 2007). To sample this uncertainty, the SCM MAGICC has here been used in a probabilistic setup that, by running 600 simulations per scenarios, can closely match the assessment of carbon cycle and climate uncertainties in the IPCC AR4 (Meinshausen et al. 2009). Furthermore, the temperature simulations are also constrained by observations of hemispherical temperatures and heat uptake. Detailed background to the model structure is provided by Meinshausen and Raper et al. (2011a). Figure A1.3 shows the consistency of the global mean temperature response of the SCM with the state-of-the-art AOGCMs of the Coupled Model Intercomparison Project-Phase 5 (CMIP5 Taylor et al. 2012) for both the lowest (RCP2.6) and the highest (RCP8.5) scenario (see also Box A1.1).

Figure A1.3 Projected global-mean temperature increase relative to pre-industrial levels in 2081–2100 for the main scenarios used in this report (see Box A1.1)



The SCM projections (blue, orange, red, and grey ranges) are compared to simulations by complex AOGCMs and Earth-System Models (ESMs) as reported by the CMIP5 project. Only for the RCP2.6 and RCP8.5 scenarios, comparison data are available from CMIP5. For GCMs and ESMs, the black line indicates the mean across all models that ran a particular scenario, thin black lines individual model results, and the green shaded area a standard deviation above and below the mean. The complex models were driven by prescribed greenhouse gas concentrations, except for the"RCP8.5 emis" scenario, for which models were driven by emissions. This scenario leads to somewhat higher warming because of feedbacks in the carbon cycle, which is also the case for all of the SCM scenarios. Note that the CMIP5 model ensemble was not designed to span the entire range of uncertainties (cf., Tebaldi and Knutti 2007), yet shows projections for RCP8.5 ranging from as low as 3°C to as high as 6.2°C because of structural differences in the models.

an SCM (Van Vuuren et al. 2008; Rogelj et al. 2011; UNEP 2012). The one overarching feature of these scenarios is that they limit the cumulative amount of global greenhouse gas emissions to a given emissions budget (Meinshausen et al 2009); to not exceed this budget, emissions start declining by 2020 in most of these scenarios (Rogelj et al. 2011).

International climate policy has until now not managed to curb global greenhouse gas emissions on such a declining path, and recent inventories show emissions steadily on the rise (Peters et al. 2013). However, recent high emission trends do not imply high emissions forever (van Vuuren and Riahi 2008). Several studies show that effective climate policies can substantially influence the trend and bring emissions onto a feasible path in line with a high probability of limiting warming to below 2°C even after low short-term ambition (e.g., OECD 2012; Rogelj et al. 2012a; UNEP 2012; van Vliet et al. 2012; Rogelj et al. 2013). Choosing such a path would however imply higher overall costs, higher technological dependency, and higher risks of missing the climate objective (Rogelj et al. 2012a; UNEP 2012). The Global Energy Assessment (Riahi et al. 2012) and other studies (Rogelj et al. 2012a, 2013) also highlight the importance of demand-side efficiency improvements to increase the chances of limiting warming to below 2°C across the board.

The available scientific literature makes a strong case that achieving deep emissions reductions over the long term is feasible

Figure A1.4 As Figure A1.2 for the probability that temperature increase exceeds 1.5 and 2°C

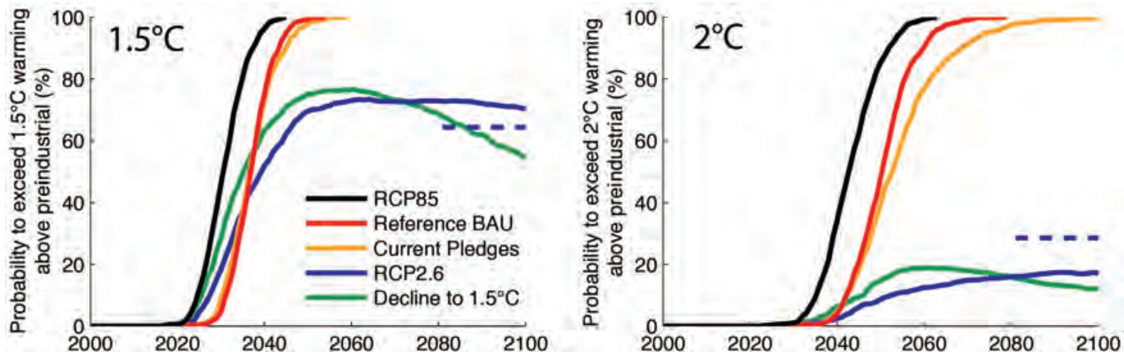


Figure A1.4: As Figure A1.2 for the probability that temperature increase exceeds 1.5 and 2°C. Although 1.5°C is likely to be exceeded even in RCP2.6, the probability is on a downward path by 2100. Still, stronger mitigation efforts than identified in RCP2.6 (see Rogelj et al. 2013) are needed to further bring down the probability of exceeding 1.5°C to below 50 percent by 2100.

(Clarke et al. 2009; Fischedick et al. 2011; Riahi et al. 2012); recent studies also show the possibility together with the consequences of delaying action (den Elzen et al. 2010; OECD 2012; Rogelj et al. 2012a, 2013; van Vliet et al. 2012).

Appendix 2

Methods for Temperature, Precipitation, Heat Wave, and Aridity Projections

Bias Correction for Subset of CMIP5 GCMs as Used Within the ISI-MIP Framework and for Temperature, Precipitation, and Heat Wave Projections in this Report

The temperature, precipitation, and heat wave projections were based on the ISI-MIP global climate database, using the historical (20th century) period and future scenarios RCP2.6 and RCP8.5. The ISI-MIP database consists of 5 CMIP5 global climate models (gfdl-esm2m, hadgem2-es, ipsl-cm5a-lr, miroc-esm-chem, noresm1-m), which were bias-corrected, such that the models reproduce historically observed mean temperature and precipitation and their year-to-year variability. The statistical bias correction algorithm as used by WaterMIP/WATCH has been applied to correct temperature and precipitation values. The correction factors were derived over a construction period of 40 years, where the GCM outputs are compared to the observation-based WATCH forcing data. For each month, a regression was performed on the ranked data sets. Subsequently, the derived monthly correction factors were interpolated toward daily ones. The correction factors were then applied to the projected GCM data (Warszawski et al. in preparation)

Heat Wave Analysis

For each of the ISI-MIP bias-corrected CMIP5 simulation runs, the authors determined the local monthly standard deviation due to natural variability over the 20th century for each individual month. To do so, they first used a singular spectrum analysis to extract the long-term non-linear warming trend (that is, the climatological warming signal). Next, they detrended the 20th century monthly time series 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. In the present analysis, the authors employ the standard deviation calculated for the last half of the 20th century (1951–2010); they found, however, that this estimate is robust with respect to different time periods.

Aridity Index and Potential Evaporation

$$AI = \frac{Pr}{ET_0}$$

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)}$$

With ET_0 in mm day^{-1}, R_n the net radiation at the crop surface [MJ m^{-2} day^{-1}], G the soil heat flux density [MJ m^{-2} day^{-1}], T the mean air temperature at 2 m height [°C], u_2 the wind speed at 2m height [m s^{-1}], e_s the saturation vapor pressure [kPa], e_a the actual vapour pressure [kPa], Δ the slope of the vapor pressure curve [kPa °C–1] and γ psychrometric constant [kPa °C–1].

The authors calculate monthly ET_0 values for each grid point using climatological input from the ISI-MIP database for both the historic period and future scenarios.

Box A2.1 Overview Table of ISI-MIP Models

Sector	Model abbreviation	Full Model name	References to model
Water/Agriculture/ Ecosystems	LPJmL	Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model	Bondeau, A., Smith, P., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B. 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology* 13, 679–706. Rost, S., Gerten, D., Bondeau, A., Lucht, W., Rohwer, J., Schaphoff, S. 2008: Agricultural green and blue water consumption and its influence on the global water system. *Water Resources Research* 44, W09405, doi:10.1029/2007WR006331.
Water/Ecosys-tems	ORCHIDEE	N.A.	Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, P. Ciais, S. Sitch, and I. C. Prentice (2005), A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system, Global Biogeochem. Cycles, 19, GB1015, doi:10.1029/2003GB002199. Piao, S., P. Friedlingstein, P. Ciais, N. de Nolbet-Ducoudré, D. Labat and S. Zaehle (2007) Changes in climate and land use have a larger direct impact than rising CO_2 on global river runoff trends. Proc Natl Acad Sci USA 104:15242–15247.
	JULES	Joint UK Land Environment Simulator	Best, M. J., Pryor, M., Clark, D. B., Rooney, G. G., Essery, R. L. H., Ménard, C. B., Edwards, J. M., Hendry, M. A., Porson, A., Gedney, N., Mercado, L. M., Sitch, S., Blyth, E., Boucher, O., Cox, P. M., Grimmond, C. S. B., and Harding, R. J.: The Joint UK Land Environment Simulator (JULES), model description – Part 1: Energy and water fluxes, Geosci. Model Dev., 4, 677–699, doi:10.5194/gmd–4-677-2011, 2011. Clark, D. B., Mercado, L. M., Sitch, S., Jones, C. D., Gedney, N., Best, M. J., Pryor, M., Rooney, G. G., Essery, R. L. H., Blyth, E., Boucher, O., Harding, R. J., Huntingford, C., and Cox, P. M.: The Joint UK Land Environment Simulator (JULES), model description – Part 2: Carbon fluxes and vegetation dynamics, Geosci. Model Dev., 4, 701–722, doi:10.5194/gmd-4-701-2011, 2011.
Water	VIC	Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model	Lohmann, D., E. Raschke, B. Nijssen and D. P. Lettenmaier, 1998: Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, Hydrol. Sci. J., 43(1), 131–141. Liang, X., Lettennmaier, D. P., Wood, E. F., and Burges, S. J., 1994, A simple hydrologically based model of land surface water and energy fluxes for general circulation models, *J. Geophys. Res.*, 99(D7), 14,415– 14,428 (Nosoc runs/results, Pressoc runs/results) Haddeland, I., T. Skaugen, and D.P. Lettenmaier, 2006, Anthropogenic impacts on continental surface water fluxes, *Geophys. Res. Lett.*, 33(8), Art. No. L08406, doi:10.1029/2006GL026047 (Pressoc runs/results)
	H08	N.A.	Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources - Part 1: Model description and input meteorological forcing, Hydrol. Earth Syst. Sci., 12, 1007–1025, 2008a. Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y., and Tanaka, K.: An integrated model for the assessment of global water resources - Part 2: Applications and assessments, Hydrol. Earth Syst. Sci., 12, 1027–1037, 2008b.
	WaterGAP	Water - Global Analysis and Prognosis	Flörke, M.; Kynast, E.; Bärlund, I.; Eisner, S.; Wimmer, F.; Alcamo, J. (2012): Domestic and industrial water uses of the past 60 years as a mirror of socio-economic development: A global simulation study. Global Environ. Change, doi:10.1016/j.gloenvcha.2012.10.018. Döll, P., Kaspar, F., Lehner, B. (2003): A global hydrological model for deriving water availability indicators: model tuning and validation. Journal of Hydrology, 270 (1–2), 105–134. Döll, P., Hoffmann-Dobrev, H., Portmann, F.T., Siebert, S., Eicker, A., Rodell, M., Strassberg, G., Scanlon, B. (2012): Impact of water withdrawals from groundwater and surface water on continental water storage variations. J. Geodyn. 59–60, 143–156, doi:10.1016/j.jog.2011.05.001

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Box A2.1 Overview Table of ISI-MIP Models

Sector	Model abbreviation	Full Model name	References to model
	Mac-PDM.09	Macro-scale Probability-Distributed Moisture model.09	Gosling SN, Arnell, NW (2011) Simulating current global river runoff with a global hydrological model: model revisions, validation and sensitivity analysis. Hydrological Processes 25: 1129–1145. doi: 10.1002/hyp.7727 Arnell NW (1999) A simple water balance model for the simulation of streamflow over a large geographic domain, J. Hydrol., 217: 314–335
	WBM	Water Balance Model	Vörösmarty, C. J., Peterson, B. J., Lammers, R. B., Shiklomanov, I. A., & Shiklomanov, A.I. (1998). A regional, electronic Hydro-meteorlogical data network for the pan-Arctic Region. Retrieved from http://www.r-arcticnet.sr.unh.edu Wisser, D., Fekete, B. M., Vörösmarty, C. J., & Schumann, A. H. (2010). Reconstructing 20th century global hydrography: A contribution to the Global Terrestrial Network-Hydrology (GTN-H). Hydrology and Earth System Sciences, 14(1),1–24. European Geophysical Society, doi:10.5194/hess-14-1-010
	MPI-HM	Max Planck Institute – Hydrology Model	Hagemann, S. and L. Dümenil Gates, 2003: Improving a subgrid runoff parameterization scheme for climate models by the use of high resolution data derived from satellite observations Clim. Dyn. 21, pp. 349–359 Stacke, T., and S. Hagemann, 2012: Development and validation of a global dynamical wetlands extent scheme. *Hydrol. Earth Syst. Sci., 16, 2915–2933*
	PCR-GLOBWB	PCRaster Global Water Balance	Wada, Y., L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak and M.F.P. Bierkens (2010), Global depletion of groundwater resources, *Geophys. Res. Lett., 37*, L20402, doi:10.1029/2010GL044571. Van Beek, L.P.H., Y. Wada and M.F.P. Bierkens (2011), Global monthly water stress: I. Water balance and water availability, *Water Resour. Res., 47*, W07517, doi:10.1029/2010WR009791. Wada, Y., L.P.H. van Beek, D. Viviroli, H.H. Dürr, R. Weingartner and M.F.P. Bierkens (2011a), Global monthly water stress: II. Water demand and severity of water, *Water Resour. Res.*, *47*, W07518, doi:10.1029/2010WR009792.
	MATSIRO	Minimal Advanced Treatments of Surface Interaction and RunOff	YADU POKHREL et al. (2012) Incorporating Anthropogenic Water Regulation Modules into a Land Surface Model, Journal of Hydrometeorology, Volume 13, Issue 1 (February 2012) Kumiko Takata et al. (2003) Development of the minimal advanced treatments of surface interaction and runoff, Global and Planetary Change, Volume 38, Issues 1–2, July 2003, Pages 209–222
	DBH	Distributed Biosphere-Hydrological Model	Tang, Q., T. Oki, S. Kanae, and H. Hu, 2007. The influence of precipitation variability and partial irrigation within grid cells on a hydrological simulation. Journal of Hydrometeorology, 8, 499–512. Tang, Q., Oki, T., Kanae, S., Hu, H., 2008. Hydrological cycles change in the Yellow River Basin during the last half of the 20th century. Journal of Climate. 21(8), 1790–1806.
Ecosystems	HYBRID4	N.A.	Friend AD, White A. 2000. Evaluation and analysis of a dynamic terrestrial ecosystem model under pre-industrial conditions at the global scale. Global Biogeochemical Cycles 14(4), 1173–1190.
	SDGVM	Sheffield Dynamic Vegetation Model	Le Quere, C., Raupach, M. R., Canadell, et al. Trends in the 5 sources and sinks of carbon dioxide, Nature Geoscience., Vol 2, 831–836, doi: 10.1038/ngeo689, Nov 2009. Woodward F I, Smith T M, Emanuel W R. A global land primary productivity and phytogeography model. Global Biogeochemical cycles, vol. 9, NO. 4, pp 471–490, 1995.

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Box A2.1 Overview Table of ISI-MIP Models

Sector	Model abbreviation	Full Model name	References to model
	JeDi	Jena Diversity Model	Pavlick, R., Drewry, D., Bohn, K., Reu, B., and Kleidon, A.: The Jena Diversity-Dynamic Global Vegetation Model (JeDi-DGVM): a diverse approach to representing terrestrial biogeography and biogeochemistry based on plant functional trade-offs, Biogeosciences Discuss, 9, 4627–4726, 2012.
	ANTHRO-BGC	ANTHRO-BioGeoChemical Cycles	Ma, S., Churkina, G., Wieland, R. & Gessler, A., 2011. Optimization and evaluation of the anthro-bgc model for winter crops in Europe. Ecological Modelling, 222 (20–22), 3662–3679 Available from: http://www.sciencedirect.com/science/article/pii/S0304380011004571 Churkina, G., Brovkin, V., Von Bloh, W., Trusilova, K., Jung, M. & Dentener, F.J., 2009. Synergy of rising nitrogen depositions and atmospheric co2 on land carbon uptake offsets global warming. Global Biogeochemical Cycles, 23, GB4027.
	VISIT	Vegetation Integrative Simulation for Trace gases	Inatomi M, Ito A, Ishijima K, Murayama S (2010) Greenhouse gas budget of a cool temperate deciduous broadleaved forest in Japan estimated with a process-based model. Ecosystems, 13, 472–483. Ito A, Inatomi M (2012) Use and uncertainty evaluation of a process-based model for assessing the methane budget of global terrestrial ecosystems. Biogeosciences, 9, 759–773.
Agriculture	GEPIC	GIS-based agroecosystem model integrating a bio-physical EPIC model (Environmental Policy Integrated Climate) with a Geographic Information System (GIS)	Liu, J. G. Zehnder, A.J.B., Yang, H. 2009. 'Global crop water use and virtual water trade: the importance of green water'. Water Resources Research. 45: doi.10.1029/2007WR006051. Williams, J. R., C. A. Jones, J. R. Kiniry, and D. A. Spanel (1989), The EPIC crop growth model, Trans ASAE, 32, 497–511
	EPIC	Environmental Policy Integrated Climate	Williams, J.R. (1995). The EPIC Model. In: V.P. Singh (eds). Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colorado, 909–1000. Izaurralde, R. C., Williams, J. R., McGill, W. B., Rosenberg, N. J., and Jakas, M. C. Q. (2006). Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecological Modelling, vol. 192, no. 3–4, pp. 362–384, 2006.
	pDSSAT	Productivity – Decision Support System for Agrotechnology Transfer	N.A.
	DAYCENT	Daily derivative of the Century	S. J. Del Grosso, W. J. Parton, A. R. Mosier, M. K. Walsh, D. S. Ojima and P. E. Thornton. 2006. DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. JOURNAL OF ENVIRONMENTAL QUALITY 35 (4): 1451–1460 JUL-AUG 2006 Del Grosso, S.J., D.S. Ojima, W.J. Parton, E. Stehfest, M. Heistemann, B. Deangelo, S. Rose. Global Scale DAYCENT Model Analysis of Greenhouse Gas Mitigation Strategies for Cropped Soils. Global and Planetary Change, 67 (2009) 44–50
	PEGASUS	Predicting Ecosystem Goods And Services Using Scenarios	Deryng et al., GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 25, GB2006, doi:10.1029/2009GB003765, 2011

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Box A2.1 Overview Table of ISI-MIP Models

Sector	Model abbreviation	Full Model name	References to model
	IMAGE	Integrated Model to Assess the Global Environment	MNP (2006) (Edited by A.F. Bouwman, T. Kram and K, Klein Goldewijk), Integrated modelling of global environmental change. An overview of IMAGE 2.4. MNP, Bilthoven, The Netherlands Bouwman AF; Kram T; Klein Goldewijk K (eds): Integrated modelling of global environmental change. An overview of IMAGE 2.4, Report 09.11.2006
	LPJ-GUESS	Lund-Potsdam-Jena General Ecosystem Simulator with managed land	Smith, B., Prentice, C. and Sykes, M.T. 2001. Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. Global Ecology and Biogeography 10:621–637. Sitch, S., B. Smith, I.C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J. Kaplan, S. Levis, W. Lucht, M. Sykes, K. Thonicke, and S. Venevski. 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ Dynamic Vegetation Model. *Global Change Biology* 9:161–185. Lindeskog, M.; Arneth, A.; Bondeau, A.; Waha, K.; Schurgers, G.; Olin, S.; Smith, B. Effects of crop phenology and management on the terrestrial carbon cycle: case study for Africa. Submitted to Earth System Dynamics.
Agriculture/Agro-Economic models	MAgPIE (connected to LPJmL)	Model of Agricultural Production and its Impact on the Environment	Dietrich, J.P., Schmitz, C., Müller, C., Fader, M., Lotze-Campen, H., Popp, A. (2012): Measuring agricultural land-use intensity - A global analysis using a model-assisted approach. Ecological Modelling, Volume 232, 10 May 2012, Pages 109–118, ISSN 0304–3800, 10.1016/j.ecolmodel.2012.03.002. Lotze-Campen et al. 2008. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach, Agricultural economics, VOL 39, 325–338
	GLOBIOM (connected to EPIC)	Global Biosphere Management Model	Havlík, P., Schneider, A.U., Schmid, E., Böttcher, H., Fritz, S., Skalský, R., Aoki, K., de Cara, S., Kindermann, G., Kraxner, F., Leduc, S., McCallum, I., Mosnier, A, Sauer, T. and Obersteiner, M. (2011). Global land-use implications of first and second generation biofuel targets. Energy Policy 39: 5690–5702. doi:10.1016/j.enpol.2010.03.030. Havlík, P., Valin, H., Mosnier, A., Obersteiner, M., Baker, J.S., Herrero, M., Rufino, M.C., Schmid, E. (2013). Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. *American Journal of Agricultural Economics* 95(2): 442–448.
	IMPACT (connected to DSSAT)	International Model for Policy Analysis of Agricultural Commodities and Trade	Nelson, Gerald C. et al. 2010. Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. Washington, D.C.: International Food Policy Research Institute Rosegrant, Mark W, and IMPACT Development Team. 2012. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) Model Description. International Food Policy Research Institute (IFPRI), Washington D.C.
	AIM	Asia-Pacific Integrated Model	Fujimori S., T. Masui and Y. Matsuoka, (2012), AIM/CGE [basic] manual, Discussion Paper Series, No. 2012–01, Center for Social and Environmental Systems Research, NIES.
	GCAM	Global Change Assessment Model	Wise, M., and Calvin, K. 2011. GCAM 3.0 Agriculture and Land Use: Technical Description of Modeling Approach. PNNL-20971, Pacific Northwest National Laboratory, Richland, WA. Available at https://wiki.umd.edu/gcam/images/8/87/GCAM3AGTechDescript12_5_11.pdf Thomson, A., et al. 2011. RCP4.5: a pathway for stabilization of radiative forcing by 2100. Climatic Change 109, 77–94. DOI 10.1007/s10584-011-0151-4.

(*continued on next page*)

Box A2.1 Overview Table of ISI-MIP Models

Sector	Model abbreviation	Full Model name	References to model
	Envisage	The ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model	van der Mensbrugghe, Dominique (2013), "The ENVironmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model: Version 8.0," processed, FAO, Rome. van der Mensbrugghe, Dominique (2013), "Modeling the Global Economy—Forward-Looking Scenarios for Agriculture," Chapter 14 in Dixon, Peter B. and Dale W. Jorgenson, editors, Handbook of Computable General Equilibrium Modeling, North Holland, Elsevier B. V., pp. 933–994.
	FARM	Future Agricultural Resources Model (FARM)	Sands, R.D., H. Förster, K. Schumacher and C.A. Jones (2013) Bio-electricity and Land Use in the Future Agricultural Resources Model (FARM), in review at Climatic Change for special issue on Technology Outcomes and Climate Policy Objectives. Sands, R.D., K. Schumacher, H. Förster and J. Beckman (2013) U.S. CO_2 Mitigation Scenarios in a Global Context: Welfare, Trade and Land Use, in review at The Energy Journal for special issue on US Technology Transitions Under Alternative Climate Policies.
Infrastructure	DIVA	Directions Into Velocities of Articulators	Hinkel, J. and Klein, R.J.T., 2009. The DINAS-COAST project: developing a tool for the dynamic and interactive assessment of coastal vulnerability. Global Environmental Change, 19(3), 384–395. Hinkel, J., Brown, S., Exner, L., Nicholls, R.J., Vafeidis, A.T. and Kebede, A.S., 2011. Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. Regional Environmental Change, Online first.
Health	MARA (Different model setups for malnutrition; heat; Malaria etc.)	a. Empirical statistical model b. Mathematical malaria models	a) Beguin, A., S. Hales, Rocklöv et al. (2011). "The opposing effects of climate change and socio-economic development on the global distribution of malaria." Global Environmental Change-Human and Policy Dimensions 21(4): 1209–1214. b) Gething, P. W., T. P. Van Boeckel, et al. (2011). Modelling the global constraints of temperature on transmission of Plasmodium falciparum and P. vivax. Parasites & Vectors 4.
	WHO CRA Malaria	N.A.	N.A.
	LMM 205	Liverpool Malaria Model	Hoshen, M.B. and Morse, A.P. (2004) A weather-driven model of malaria transmission, Malaria Journal, 3 (32) pp 14. Jones A.E. and Morse A.P. (2010). Application and Validation of a Seasonal Ensemble Prediction System using a Dynamic Malaria Model, Journal of Climate, 23 (15), 4202–4215. DOI:10.1175/2010JCLI3208.1
	MIASMA	Modeling Framework for the Health Impact Assessment of Man-Induced Atmospheric Changes	Van Lieshout, M., Kovats, R.S., Livermore, M.T.J. & Martens, P. (2004). Climate change and malaria: analysis of the SRES climate and socio-economic scenarios. Global Environmental Change, 14(1), 87–99. Martens, P. (1999). MIASMA: Modelling framework for the health Impact Assessment of Man-induced Atmospheric changes. Electronic Series on Integrated Assessment Modeling (ESIAM), Volume 2, February 1999.
	VECTRI	Vector borne disease model of ICTP	Tompkins A.M. and Ermert V., 2012: VECTRI: A dynamical malaria model that accounts for population density and surface hydrology, Submitted to Malaria Journal.

Appendix 3

Methods for Multisectoral Hotspots Analysis

For the hotspots analysis presented in this report, simulations driven by those ISI-MIP GCMs going up to ΔGMT= 5°C have been chosen. These are the RCP8.5 data from HadGEM2-ES, MIROC-ESM-CHEM, and IPSL-CM5A-LR. The analysis covers 11 global hydrological models, seven global gridded crop models, seven biomes models, and four malaria models.

All indicators have annual temporal resolution, neglecting seasonal patterns. For discharge and the Γ-metric, very low values (for the latter of natural vegetation) can lead to spurious effects when looking at changes by amplifying very small changes and overemphasizing those regions (e.g., the Sahara). Therefore, values are set to zero below a lower limit 0.01 $km^2 yr^{-1}$ and a 2.5 percent cover fraction of natural vegetation, respectively (Warszawski et al. in review; von Bloh et al. 2010). The four crops are combined through conversion to energy-weighted production per cell using the following conversion factors for energy content [MJ kg^{-1} dry matter]: wheat – 15.88, rice (paddy) – 13.47, maize – 16.93, and soy – 15.4 (Wirsenius 2000; FAO 2001). Since only negative changes are considered, a possible expansion of cropland to higher latitudes, which is not accounted for because of the masking, is not important. Furthermore, this analysis can only give a limited perspective of agricultural hotspots as for instance millet and sorghum, crops widely grown in Africa, are not included in the analysis. Malaria prevalence, representing the health sector, is only one example of human health effects from climate change—although it is a very relevant one given its potential links to human welfare and economic development (Sachs and Malaney 2002). The impact of climate change on malaria occurrence focuses on changes in length of transmission season. This simple metric represents an aggregated risk factor, since it neglects age-dependent immunity acquisition associated with transmission intensity. Increases in impacts associated with transitions from malaria-free to epidemic conditions are also not considered. Initial areas of endemic malaria vary widely between models and depend on their calibration and focus region.

GMT is calculated from the GCM data before bias correction; change is measured with respect to pre-industrial levels assuming an offset from 0.8°C of the ISI-MIP 1980–2010 baseline.

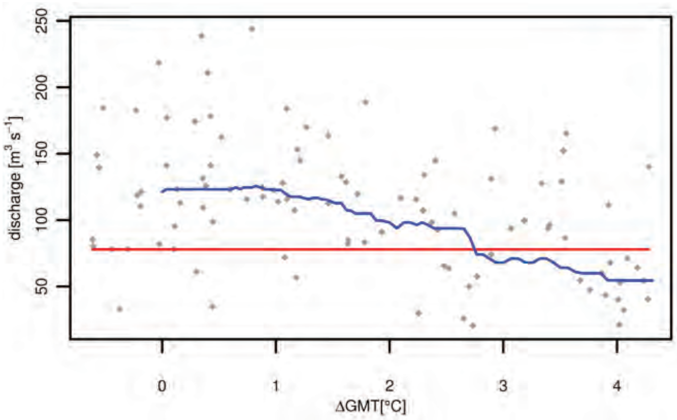
Temperatures are binned at ΔGMT = 1,2,3,4, and 5°C (± 0.5°). If a grid cell is identified as having crossed the threshold, the whole area of the grid cell is assumed to be affected. This neglects, for example, the separation of agricultural and natural vegetation areas in a grid-cell, as such separation is below the resolution of the analysis. The affected population fraction is not very sensitive to applying population distributions for the year 2000 or for 2084, although the total number of affected people would increase, possibly substantially.

Methodology for Sectoral and Multisectoral ISI-MIP Climate Model Projections

Discharge is chosen as a measure for water availability. Food security is represented by crop yields from four major staple crops (wheat, rice, maize, and soy) on current rainfed and irrigated cropland, synthesized by their caloric content. Thresholds are selected to represent severe changes in the average conditions people have experienced in the past. This suggests that impacts would be severe, particularly when occurring simultaneously

For discharge (and cropland), severe changes are assumed when the future projected average discharge (and crop yields) measured over periods of 31 years is lower than today's (1980–2010) 1-in-10-year events. This concept is illustrated in Figure 6.2, and it means

A3.1 Illustration of the method for discharge in one grid cell in Sub-Saharan Africa (longitude = 18.75, latitude = –15.25)



The points are the annual discharge from 1980–2099; the red line is the threshold (the 10th percentile of the reference period distribution, which is the first 31 points); the blue line is the running 31-year median, ranging from 1995 (1980–2010 median) to 2084 (2069–99 median). The crossing temperature would be the temperature where the blue line falls below the red line.

that very low discharge/crop yields would become the norm. The risk of a biome change metric with a severity threshold of 0.3, as introduced in Chapter 6 on "Risk of Terrestrial Ecosystem Shifts", is applied to measure the impacts on ecosystems. Such impacts could severely affect biodiversity and ecosystem services, which would certainly affect livelihoods. Finally, the length of transmission season for malaria is included as an example for impacts of climate change on human health, relevant not only for individuals but also for societies in terms of economic consequences. The selected threshold is a transition from a transmission season shorter than three months to one longer than three months, which is associated with a transition from epidemic to endemic malaria.[133] All the indicators measure potential impacts and do not take into account socioeconomic conditions, livelihood strategies, and a multitude of adaptation options that could mitigate the impacts of the changes. Moreover, no absolute level of impacts is taken into account, merely the crossing of the threshold.

As this analysis is based on multiple impact models per sector, the robustness of results is ensured by requiring at least 50 percent of the models to agree that the threshold has been crossed. A risk estimate is included in the analysis, as the uncertainty stemming from the different impact and climate models turns out to be very large, and a weighting of models is neither possible nor desirable. For that risk estimate, all regions with overlapping impacts are taken into account, without restrictions on the minimum number of models agreeing, and the sectoral crossing temperature is taken as the 10th percentile of all climate-impact-model combinations. The area is estimated in which two, three, and four sectors have crossed their respective thresholds. Note that the maximum area assessed is not equal for all sectors, as crop yields are only considered on present day cropland.

133 This is based on data from the MARA (Mapping Malaria Risk in Africa) Project: www.mara.org.za.

Appendix 4

Crop Yield Changes under Climate Change

Crop yield projections were extracted from the studies listed in the table below. In an attempt to identify a common pattern of the effects of CO_2 fertilization and adaptation measures on crop yield, all crops were gather together and no distinction was made between crop types, irrigation systems, or regions in Asia. Moreover, whenever a study showed a range of GCM models for a specific crop, the average of the models as representative of yield change was considered.

Table A4.1 List of Studies Analyzed in Chapter 5 on "Agricultural Production"

Crop	Author	Description of Results
All crops	Müller et al. (2010)	In absolute numbers, Müller et al. (2010) project mean changes in crop yield (area-weighted mean crop productivity) for South Asia (here also including Afghanistan and Myanmar) for the 10-year period 2046–55 compared to agricultural productivity in the 10-year period 1996–2005 in the range of –18.9 percent (A1B scenario projections ranging from –7.9 percent to –21.9 percent among the five GCMs), –15.3 percent (A2 scenario projections ranging from –9.9 percent to –16.6 percent), and –14.4 percent (B1 scenario projections ranging from –7.2 percent to –17.8 percent) without CO_2 fertilization (+21.3 percent, +24.6 percent, and +14.6 percent with CO_2 fertilization respectively). Estimations are based on the assumption of static production area and adjustment of sowing dates. For wheat, maize, sunflower, and rapeseed, it is additionally assumed that adaption in selecting suitable varieties is undertaken (Müller et al. 2010).
Rice	Nelson et al. (2009, 2010)	A minor increase of 0.1 percent to 2.6 percent (8.5 to 10.2 percent with CO_2 fertilization) is projected for rainfed rice, while irrigated rice yields are expected to decrease significantly by up to 17.5 percent (+1.4 to 2.5 percent with CO_2 fertilization).
	Jalota et al. (2012)	Rice-wheat cropping systems in central India are projected to see a decline in rice yields of –4.6 percent for 2020, –16.1 percent for 2050, and –29.1 percent for 2080 compared to crop yields under the baseline climate of 1989–2009 (estimates averaged over three GCMs for the A2 SRES scenario leading to a global-mean warming of 2.0°C and 3.2°C above pre-industrial levels by 2050 and 2080). Yield declines are found to be smaller (in the range of –2.4 percent, –13.3 percent, and –26.6 percent, when the transplanting date is shifted by +7 days for rice. Jalota et al. (2012) also find a strong correlation between yield declines and the shortening of crop duration under high temperature, whereas shifting the transplanting date seems to be an effective measure to reduce the shortening of crop duration for both crops (Jalota et al. 2012). When assuming that the full benefits of CO_2 fertilization can be realized, declines in yield are again projected to be lower but still smaller than yield levels under the current baseline climate for both crops. Declines in rice yield are estimated to be in the range of –0.2 percent, –7.0 percent, and –17.5 percent, with no adjustment of sowing dates and for the years 2020, 2050, and 2080, respectively (+2.2 percent, –3.8 percent, and 14.6 percent with shifting the transplanting date by +7 days).
	Ruane et al. (2012)	Bangladesh—Boro Rice without CO_2 fertilization (A2 average of GCMs) Bangladesh—Aman (monsoon) Rice without CO_2 fertilization (A2 average of GCMs) Bangladesh—Aus Rice without CO_2 fertilization (A2 average of GCMs)
Wheat	Jalota et al. (2012)	Declines in wheat yields in the range of –8.8 percent for 2020, –22.5 percent for 2050, and –41 percent for 2080 compared to crop yields under the baseline climate of 1989–2009 (estimates averaged over three GCMs for the A2 SRES scenario leading to a global-mean warming of 2.0°C and 3.2°C above pre-industrial levels by 2050 and 2080). Yield declines are found to be smaller (in the range –4.3 percent, –13.6 percent, and –28 percent) when the transplanting date is shifted by +15 days.
	Nelson et al. (2009, 2010)	The impacts on wheat yields are particularly severe. Irrigated wheat is projected to decrease by up to 53.9 percent (–45.8 percent with CO_2 fertilization) by 2050 compared to 2000 levels of crop yields, while rainfed wheat yields may decline by up to 44.4 percent (–28.9 percent with CO_2 fertilization).
	Ruane et al. (2012)	Bangladesh—Wheat without CO_2 fertilization (A2 average of GCMs)
Maize	Nelson et al. (2009, 2010)	Compared to crop yields in 2000, rainfed maize yields are projected to decline by 2.9 percent to 7.8 percent (+0.2 percent to –4.9 percent with CO_2 fertilization), while irrigated maize is projected to decline by 6.4 percent to 5.5 percent (–4.4 percent to –3.6 percent with CO_2 fertilization).

(*continued on next page*)

Table A4.1 List of Studies Analyzed in Chapter 5 on “Agricultural Production”

Crop	Author	Description of Results
Sorghum	Srivastava, Kumar, and Aggarwal (2010)	For a global-mean warming of 2.0°C and 3.2°C above pre-industrial levels by 2050 and 2080 (A2 SRES scenario) and compared to baseline yields for the period 1970–95, HADCM3 projections show a significant decline in sorghum yields in the major sorghum growing areas (Madhya Pradesh, Andhra Pradesh, and Karnataka) in India. With current management practices, the monsoon crop is projected to decline by 16 percent in Madhya Pradesh and Karnataka, and by 3 percent in Andhra Pradesh by 2020. Declines are more severe for the 2050s and 2080s with reductions in yield of up to 17 percent in Madhya Pradesh and Andhra Pradesh and as much as 76 percent in Karnataka. The winter crop is projected to decline, on average, up to 7 percent by 2020, 11 percent by 2050, and 32 percent in 2080 with strongest declines in Karnataka. These projections account for the potential beneficial effect of higher CO_2 levels, although it has to be noted that sorghum is a C4 crop, for which yield effects of CO_2 fertilization are limited (Srivastava, Kumar et al. 2010). Srivastava et al. (2010)[1] also analyze the effects of low-cost adaptation measures, change in crop variety, and shifting sowing dates, on yield. For the monsoon crop, low-cost adaptation measures can reduce the impact on yield by up to 25 percent in Karnataka in 2050, whereas adaptation gains in Madhya Pradesh and Andhra Pradesh are in the order of 2–4 percent in 2020 and 4–10 percent in the 2050s and 2080s. For the winter crop, projected adaptation gains are, on average, 2–4 percent in 2020, 1–11 percent in 2050, and 12–26 percent in 2080. However, even with adaptation, sorghum yields are expected to decrease 1–2 percent in 2020, 3–8 percent in 2050, and 4–9 percent in 2080 in Madhya Pradesh and Andhra Pradesh, while yield reductions in Karnataka are expected to remain at 3–4 percent post-2020 (Srivastava, Kumar, et al. 2010).
Groundnut	Nelson et al. (2009, 2010)	Groundnut crop yields are expected to decline by 8.9 percent (up to +9.1 percent with CO_2 fertilization) for rainfed crops and by up to 10.6 percent (+9.4 percent with CO_2 fertilization) for irrigated crops (Nelson et al. 2009, 2010).
Soybean	Nelson et al. (2009, 2010)	Rainfed and irrigated soybean yields are both projected to decrease without CO_2 fertilization (up to 13.8 percent and 11.5 percent, respectively) while crop yields may increase when the CO_2 fertilization effect is realized (up to + 7.9 and + 12 percent, respectively).

[1] InfoCrop-SORGHUM simulation model.

Table A4.2 The studies depicted in the graph by Müller (2013), in Chapter 3 of this report

Code	Reference
Pae08	Paeth H, Capo-Chichi A, and W. Endlicher. 2008. Climate Change and Food Security in Tropical West Africa—A Dynamic-statistical Modelling Approach. *Erdkunde* 62: 101–15
Seo08	Seo SN and R Mendelsohn. 2008. Measuring Impacts and Adaptations to Climate Change: A Structural Ricardian Model of African Livestock Management. *Agricultural Economics* 38: 151–65
Lau10	Laux P, Jacket G, Tingem RM, and H. Kunstmann. 2010. Impact of Climate Change on Agricultural Productivity under Rainfed Conditions in Cameroon—A Method to Improve Attainable Crop Yields By Planting Date Adaptations. *Agricultural and Forest Meteorology* 150: 1258–71
Gai11	Gaiser T, Judex M, Igué AM, Paeth H, and C Hiepe. 2011. Future Productivity of Fallow Systems In Sub-Saharan Africa: Is the Effect of Demographic Pressure and Fallow Reduction More Significant Than Climate Change? *Agricultural and Forest Meteorology* 151: 1120–30
Sri12	Srivastava AK, Gaiser T, Paeth H, and F Ewert. 2012. The Impact of Climate Change on Yam (Dioscorea Alata) Yield in the Savanna Zone of West Africa. *Agriculture, Ecosystems & Environment* 153: 57–64
Liu08	Liu JG, Fritz S, van Wesenbeeck CFA, Fuchs M, You LZ, et al. 2008. A Spatially Explicit Assessment of Current and Future Hotspots of Hunger in Sub-Saharan Africa in the Context of Global Change. *Global and Planetary Change* 64: 222–35
Lob08	Lobell DB, Burke MB, Tebaldi C, Mastrandrea MD, Falcon WP, and RL Naylor. 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030. *Science* 319: 607–10
Ben08	Benhin JKA. 2008. South African Crop Farming and Climate Change: An Economic Assessment of Impacts. *Global Environmental Change-Human and Policy Dimensions* 18: 666–78
Mue09	Müller C, Bondeau A, Popp A, Waha K, and M. Fader. 2009. *Climate Change Impacts On Agricultural Yields*. Washington, DC: The World Bank.
Nel09	Nelson GC, Rosegrant MW, Koo J, Robertson R, Sulser T, et al. 2009. *Climate Change - Impact on Agriculture and Costs of Adaptation. Rep. 21*, Washington D.C.: International Food Policy Research Institute.
Tho09	Thornton PK, Jones PG, Alagarswamy G, and J. Andresen. 2009. Spatial Variation of Crop Yield Response to Climate Change in East Africa. *Global Environmental Change-Human and Policy Dimensions* 19: 54–65
Tho10	Thornton PK, Jones PG, Alagarswamy G, Andresen J, and M Herrero. 2010. Adapting to climate change: Agricultural system and household impacts in East Africa. *Agricultural Systems* 103: 73–82
Moo12	Moore N, Alagarswamy G, Pijanowski B, Thornton P, Lofgren B, et al. 2012. East African Food Security as Influenced by Future Climate Change and Land Use Change at Local to Regional Scales. *Climatic Change* 110: 823–44
Sch10	Schlenker W, Lobell DB. 2010. Robust Negative Impacts Of Climate Change On African Agriculture. *Environmental Research Letters* 5: 014010
Cli07	Cline WR. 2007. *Global Warming and Agriculture. Impact Estimates by Country*. Washington, DC: Center for Global Development and Peterson Institute for International Economics
Wal08	Walker NJ, and RE Schulze. 2008. Climate Change Impacts on Agro-Ecosystem Sustainability Across Three Climate Regions in the Maize Belt of South Africa. *Agriculture Ecosystems & Environment* 124: 114–24
Igl11	Iglesias A, Quiroga S, and A Diz. 2011. Looking into the Future of Agriculture in a Changing Climate. *European Review of Agricultural Economics* 38: 427–47
Ber12	Berg A, de Noblet-Ducoudré N, Sultan B, Lengaigne M, and M Guimberteau. 2012. Projections of Climate Change Impacts on Potential C4 Crop Productivity over Tropical Regions. *Agricultural and Forest Meteorology*
Seo09	Seo SN, Mendelsohn R, Dinar A, Hassan R, and P Kurukulasuriya. 2009. A Ricardian Analysis of the Distribution of Climate Change Impacts on Agriculture across Agro-Ecological Zones in Africa. *Environmental & Resource Economics* 43: 313–32
Tan10	Tan ZX, Tieszen LL, Liu SG, and E Tachie-Obeng. 2010. Modeling to Evaluate the Response of Savanna-derived Cropland to Warming-drying Stress and Nitrogen Fertilizers. *Climatic Change* 100: 703–15
Tho11	Thornton PK, Jones PG, Ericksen PJ, and AJ Challinor. 2011. Agriculture and Food Systems in Sub-Saharan Africa in a 4°C+ World. *Philosophical Transactions of the Royal Society A Mathematical, Physical & Engineering Sciences* 369: 117–36

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