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# 4° Turn Down the Heat

## Confronting the New Climate Normal

WORLD BANK GROUP

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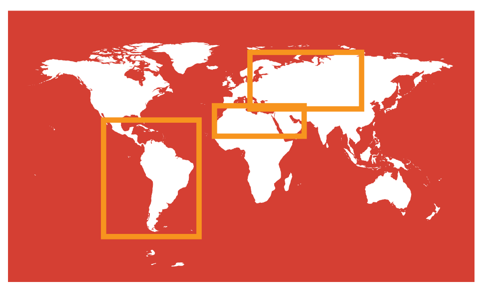

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# Foreword

Dramatic climate changes and weather extremes are already affecting millions of people around the world, damaging crops and coastlines and putting water security at risk.

Across the three regions studied in this report, record-breaking temperatures are occurring more frequently, rainfall has increased in intensity in some places, while drought-prone regions like the Mediterranean are getting dryer. A significant increase in tropical North Atlantic cyclone activity is affecting the Caribbean and Central America.

There is growing evidence that warming close to 1.5°C above pre-industrial levels is locked-in to the Earth's atmospheric system due to past and predicted emissions of greenhouse gases, and climate change impacts such as extreme heat events may now be unavoidable.

As the planet warms, climatic conditions, heat and other weather extremes which occur once in hundreds of years, if ever, and considered highly unusual or unprecedented today would become the "new climate normal" as we approach 4°C—a frightening world of increased risks and global instability.

The consequences for development would be severe as crop yields decline, water resources change, diseases move into new ranges, and sea levels rise. Ending poverty, increasing global prosperity and reducing global inequality, already difficult, will be much harder with 2°C warming, but at 4°C there is serious doubt whether these goals can be achieved at all.

For this report, the third in the *Turn Down the Heat* series, we turned again to the scientists at the Potsdam Institute for Climate Impact Research and Climate Analytics. We asked them to look at the likely impacts of present day (0.8°C), 2°C and 4°C warming on agricultural production, water resources, cities and ecosystems across Latin America and the Caribbean, Middle East and North Africa, and parts of Europe and Central Asia.

Their findings are alarming.

In Latin America and the Caribbean, heat extremes and changing precipitation patterns will have adverse effects on agricultural productivity, hydrological regimes and biodiversity. In Brazil, at 2°C warming, crop yields could decrease by up to 70 percent for soybean and up to 50 percent for wheat. Ocean acidification, sea level rise, tropical cyclones and temperature changes will negatively impact coastal livelihoods, tourism, health and food and water security, particularly in the Caribbean. Melting glaciers would be a hazard for Andean cities.

In the Middle East and North Africa, a large increase in heat-waves combined with warmer average temperatures will put intense pressure on already scarce water resources with major consequences for regional food security. Crop yields could decrease by up to 30 percent at 1.5–2°C and by almost 60 percent at 3–4°C. At the same time, migration and climate-related pressure on resources might increase the risk of conflict.

In the Western Balkans and Central Asia, reduced water availability in some places becomes a threat as temperatures rise toward 4°C. Melting glaciers in Central Asia and shifts in the timing of water flows will lead to less water resources in summer months and high risks of torrential floods. In the Balkans, a higher risk of drought results in potential declines for crop yields, urban health, and energy generation. In Macedonia, yield losses are projected of up to 50 percent for maize, wheat, vegetables and grapes at 2°C warming. In northern Russia, forest dieback and thawing of permafrost threaten to amplify global warming as stored carbon and methane are released into the atmosphere, giving rise to a self-amplifying feedback loop.

*Turn Down the Heat: Confronting the New Climate Normal* builds on our 2012 report, which concluded the world would warm by 4°C by the end of this century with devastating consequences if we did not take concerted action now. It complements our 2013 report that looked at the potential risks to development under different warming scenarios in Sub-Saharan Africa, South East Asia and South Asia, and which warned that we could experience a 2°C world in our lifetime.

Many of the worst projected climate impacts outlined in this latest report could still be avoided by holding warming below 2°C. But, this will require substantial technological, economic, institutional and behavioral change. It will require leadership at every level of society.

Today the scientific evidence is overwhelming, and it's clear that we cannot continue down the current path of unchecked, growing emissions. The good news is that there is a growing consensus on what it will take to make changes to the unsustainable path we are currently on.

More and more voices are arguing that is possible to grow greener without necessarily growing slower. Today, we know that action is urgently needed on climate change, but it does not have to come at the expense of economic growth. We need smart policy choices that stimulate a shift to clean public transport and energy efficiency in factories, buildings and appliances can achieve both growth and climate benefits.

This last report in the *Turn Down the Heat* series comes at a critical moment. Earlier this year, the UN Secretary General's Climate Summit unleased a new wave of optimism. But our reports make clear that time is of the essence.

Governments will gather first in Lima and then Paris for critical negotiations on a new climate treaty. Inside and outside of the conference halls, global leaders will need to take difficult decisions that will require, in some instances, short term sacrifice but ultimately lead to long term gains for all.

At the World Bank Group we will use our financial capacity to help tackle climate change. We will innovate and bring forward new financial instruments. We will use our knowledge and our convening power. We will use our evidence and data to advocate and persuade. In short, we will do everything we can to help countries and communities build resilience and adapt to the climate impacts already being felt today and ensure that finance flows to where it is most needed.

Our response to the challenge of climate change will define the legacy of our generation. The stakes have never been higher.

Dr. Jim Yong Kim
President, World Bank Group

# Executive Summary

# Executive Summary

The data show that dramatic climate changes, heat and weather extremes are already impacting people, damaging crops and coastlines and putting food, water, and energy security at risk. Across the three regions studied in this report, record-breaking temperatures are occurring more frequently, rainfall has increased in intensity in some places, while drought-prone regions are getting dryer. In an overview of social vulnerability, the poor and underprivileged, as well as the elderly and children, are found to be often hit the hardest. There is growing evidence, that even with very ambitious mitigation action, warming close to 1.5°C above pre-industrial levels by mid-century is already locked-in to the Earth's atmospheric system and climate change impacts such as extreme heat events may now be unavoidable.[1] If the planet continues warming to 4°C, climatic conditions, heat and other weather extremes considered highly unusual or unprecedented today would become the new climate normal—a world of increased risks and instability. The consequences for development would be severe as crop yields decline, water resources change, diseases move into new ranges, and sea levels rise. The task of promoting human development, of ending poverty, increasing global prosperity, and reducing global inequality will be very challenging in a 2°C world, but in a 4°C world there is serious doubt whether this can be achieved at all. Immediate steps are needed to help countries adapt to the climate impacts being felt today and the unavoidable consequences of a rapidly warming world. The benefits of strong, early action on climate change, action that follows clean, low carbon pathways and avoids locking in unsustainable growth strategies, far outweigh the costs. Many of the worst projected climate impacts could still be avoided by holding warming to below 2°C. But, the time to act is now.

This report focuses on the risks of climate change to development in Latin America and the Caribbean, the Middle East and North Africa, and parts of Europe and Central Asia. Building on earlier *Turn Down the Heat* reports this new scientific analysis examines the likely impacts of present day (0.8°C), 2°C and 4°C warming above pre-industrial temperatures on agricultural production, water resources, ecosystem services and coastal vulnerability for affected populations.

## Scope of the Report

This third report in the *Turn Down the Heat* series[2] covers three World Bank regions: Latin America and the Caribbean (LAC); the Middle East and North Africa (MENA); and parts of Europe and Central Asia (ECA).[3] The focus is on the risks of climate change to development. While covering a range of sectors, special attention is paid to projected impacts on food and energy systems, water resources, and ecosystem services. The report also considers the social vulnerability that could magnify or moderate the climate

[1] Holding warming to below 2°C and bringing warming back to 1.5°C by 2100 is technically and economically feasible but implies stringent mitigation over the short term. While IPCC AR5 WGIII identified many mitigation options to hold warming below 2°C with a *likely* chance, and with central estimates of 1.5–1.7°C by 2100, only "a limited number of studies have explored scenarios that are *more likely than not* to bring temperature change back to below 1.5°C by 2100". The scenarios in these studies are "characterized by (1) immediate mitigation action; (2) the rapid upscaling of the full portfolio of mitigation technologies; and (3) development along a low-energy demand trajectory".

[2] *Turn Down the Heat: Why a 4°C Warmer World Must be Avoided,* launched by the World Bank in November 2012; and *Turn Down the Heat: Climate Extremes, Regional Impacts, and the Case for Resilience,* launched by the World Bank in June 2013 constitute the first two reports.

[3] The World Bank Europe and Central Asia region in this report includes only the following countries: Albania, Bosnia and Herzegovina, Kazakhstan, Kosovo, the Kyrgyz Republic, the former Yugoslav Republic of Macedonia, Montenegro, the Russian Federation, Serbia, Tajikistan, Turkmenistan, and Uzbekistan.

change repercussions for human well-being. The report complements the first *Turn Down the Heat* report (2012) that offered a global overview of climate change and its impacts in a 4°C world[4] and concluded that impacts are expected to be felt disproportionately in developing countries around the equatorial regions. Also, it extends the analysis in the second report (2013) that focused on the consequences of climate change for present day, 2°C, and 4°C warming above pre-industrial levels in Sub-Saharan Africa, South Asia, and South East Asia and demonstrated the potential of early onset of impacts at lower levels of warming.

This analysis draws on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) Working Group reports released in 2013 and 2014, as well as peer-reviewed literature published after the cutoff dates for AR5. The few cases where there are significant differences in interpretation of projected impacts from the IPCC assessments (such as for sea-level rise and El Niño) are highlighted and explained.

## The Global Picture

This report reaffirms earlier assessments, including the IPCC AR5 and previous *Turn Down the Heat* reports, that in the absence of near-term mitigation actions and further commitments to reduce emissions the likelihood of 4°C warming being reached or exceeded this century has increased. Under current policies there is about a 40 percent chance of exceeding 4°C by 2100 and a 10 percent chance of exceeding 5°C.[5] However, many of the worst projected climate impacts in this report could still be avoided by holding warming below 2°C.

## Selected Key Findings from Across the Regions

At the current level of 0.8°C warming above pre-industrial levels, adverse impacts of climate change have already been observed. Examples include:

- Extreme heat events are occurring more frequently. The occurrence of record-breaking monthly mean temperatures has been attributed to climate change with 80 percent probability.

[4] In this report, as in the previous two reports, "a 4°C world" and "a 2°C world" is used as shorthand for warming reaching 4°C or 2°C above pre-industrial levels by the end of the century. It is important to note that, in the case of 4°C warming, 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. A 2°C world implies stabilization at this level beyond 2100.

[5] IEA (2012) World Energy Outlook 2012. This was reported in the second *Turn Down the Heat* report.

## Box 1: The Case for Immediate Action

**$CO_2$ emissions continue unabated.** Current warming is at 0.8°C above pre-industrial levels. $CO_2$ emissions are now 60 percent higher than in 1990, growing at about 2.5 percent per year. If emissions continue at this rate, atmospheric $CO_2$ concentrations in line with a likely chance of limiting warming to 2°C would be exceeded within just three decades.

**Observed impacts and damages.** Widespread, recently observed impacts on natural and human systems confirm the high sensitivity of many of these systems to warming and the potential for substantial damage to occur at even low levels of warming. Examples include negative impacts on crop yields, the accelerating loss of ice from Antarctica and Greenland, and widespread bleaching of coral reefs. The physical effects of warming to 1.5°C, such as extreme heat events, may be unavoidable.

**21st-century projected impacts.** The projected impacts for the 21st century confirm the scale of the risk to development at 2°C—and the severe consequences of exceeding this level of warming. Even at warming of 1.5°C–2°C, significant, adverse risks are projected for a number of regions and systems, such as the potential for the complete loss of existing long-lived coral reefs, associated marine biodiversity and the livelihoods from tourism and fishing.

**Multi-century consequences of 21st-century emissions.** Scientific evidence is growing of the multi-century consequences of $CO_2$ and other greenhouse gas emissions. Examples include: 'locking-in' a long-term sea-level rise of about two meters per degree Celsius of sustained global mean warming and a multi-century ocean acidification with wide-ranging adverse consequences on coral reefs, marine ecology, and ultimately the planet.

**Risk of large-scale, irreversible changes in the Earth's biomes and ecosystems.** Large scale, irreversible changes in the Earth's systems have the potential to transform whole regions. Examples of risks that are increasing rapidly with warming include degradation of the Amazon rainforest with the potential for large emissions of $CO_2$ due to self-amplifying feedbacks, disintegration of the Greenland and Antarctic ice sheets with multi-meter sea-level rise over centuries to millennia, and large-scale releases of methane from melting permafrost substantially amplifying warming. Recent peer reviewed science shows that a substantial part of the West Antarctic ice sheet, containing about one meter of sea-level rise equivalent in ice, is now in irreversible, unstable retreat.

**Rapidly closing window for action.** The buildup of carbon intensive, fossil-fuel-based infrastructure is locking us into a future of $CO_2$ emissions. The International Energy Agency (IEA) has warned, and numerous energy system modelling exercises have confirmed, that unless urgent action is taken very soon, it will become extremely costly to reduce emissions fast enough to hold warming below 2°C.

- Extreme precipitation has increased in frequency and intensity in many places.
- A robust drying trend has been observed for already drought-prone regions such as the Mediterranean.
- A significant increase in tropical North Atlantic cyclone activity has been observed and is affecting the Caribbean and Central America.

Under future climate change scenarios ***projected*** **impacts** include:

1. ***Highly unusual* and *unprecedented* heat extremes:** State-of-the-art climate modeling shows that extreme heat events increase not only in frequency but also impact a larger area of land under unabated warming**.** The prevalence of *highly unusual* and *unprecedented* heat extremes increases rapidly under an emissions pathway associated with a 4°C world.[6] *Highly unusual* heat extremes are similar to those experienced in Russia and Central Asia in 2010 and the United States in 2012 and *unprecedented* heat extremes refer to events essentially absent under present day climate conditions. *Unprecedented* heat extremes would likely remain largely absent in a 2°C world but in a 4°C world, could affect 70–80 percent of the land area in the Middle East and North Africa and Latin America and the Caribbean and approximately 55 percent of the land area in the parts of Europe and Central Asia assessed in this report.
2. **Rainfall regime changes and water availability:** Precipitation changes are projected under continued warming with substantial, adverse consequences for water availability. Central America, the Caribbean, the Western Balkans, and the Middle East and North Africa stand out as hotspots where precipitation is projected to decline 20–50 percent in a 4°C world. Conversely, heavy precipitation events are projected to intensify in Central and Eastern Siberia and northwestern South America with precipitation intensity increasing by around 30 percent and flooding risks increasing substantially in a 4°C world.
   - In the Western Balkans and Central Asia, water availability becomes a threat as temperatures rise toward 4°C. With earlier glacier melt in Central Asia shifting the timing of water flows, and a higher risk of drought in the Balkans, this carries consequences for crop yields, urban health, and energy generation. In Macedonia, for example, there could be yield losses of up to 50 percent for maize, wheat, vegetables and grapes at 2°C warming. Flood risk is expected to increase slightly along the Danube, Sava and Tisza rivers.
3. **Agricultural yields and food security:** Significant crop yield impacts are already being felt at 0.8°C warming, and as temperatures rise from 2°C to 4°C, climate change will add further pressure on agricultural systems.
   - The risks of reduced crop yields and production losses increase rapidly above 1.5°–2°C warming. In the Middle East and North Africa and the Latin America and the Caribbean regions, without further adaptation actions, strong reductions in potential yield are projected for around 2°C warming. For example, a 30–70 percent decline in yield for soybeans and up to 50 percent decline for wheat in Brazil, a 50 percent decrease for wheat in Central America and the Caribbean, and 10–50 percent reduction for wheat in Tunisia. Projected changes in potential crop yields in Central Asia are uncertain at around 2°C warming. Increasing droughts and flooding events represent a major risk for agriculture in the Western Balkans.
   - While adaptation interventions and $CO_2$ fertilization may compensate for some of the adverse effects of climate change below 2°C warming, this report reaffirms the findings of the IPCC AR5 that under 3–4°C warming large negative impacts on agricultural productivity can be expected. There is some empirical evidence that, despite possible positive $CO_2$ fertilization effects leading to increased productivity, higher atmospheric levels of carbon dioxide could result in lowered protein and micronutrient (iron and zinc) levels of some major grain crops (e.g., wheat and rice).
   - The projected impacts on subsistence and export crops production systems (e.g., soybeans, maize, wheat, and rice) would be felt at the local, national, and global levels. While global trade can improve food security and protect against local shocks, there is a possibility for some regions to become over dependent on food imports and thus more vulnerable to weather events in other world regions and to the interruption of imports because of export bans in those regions.
4. **Terrestrial Ecosystems:** Ecosystem shifts are projected with increasing temperatures and changes in precipitation patterns significantly diminishing ecosystem services. This would

[6] In this report, *highly unusual* heat extremes refer to 3-sigma events and *unprecedented* heat extremes to 5-sigma events. In general, the standard deviation (sigma) shows how far a variable tends to deviate from its mean value, which in this report refers to the possible year-to-year changes in local monthly temperature because of natural variability. For a normal distribution, 3 sigma events have a return time of 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 but will be at least 100 years. Nevertheless, 3-sigma events are extremely unlikely and 4-sigma events almost certainly have not occurred over the lifetime of key infrastructure. A warming of 5 sigma means that the average change in the climate is 5 times larger than the normal year-to-year variation experienced today, and has a return period of several million years. These events, which have almost certainly never occurred to date, are projected for the coming decades.

have major repercussions on, for example, the global carbon cycle. For example:

- Projected increases in heat and drought stress, together with continuing deforestation, substantially increase the risk of large-scale forest degradation (reduction in forest biomass and area) in the Amazon rainforest. This could turn this carbon sink of global importance into a source of carbon; this has already been observed as a consequence of the severe droughts in 2005 and 2010 when scientists estimated that the Amazon faced a decrease in carbon storage of approximately 1.6 Pg carbon (2005) and 2.2 Pg carbon (2010) compared to non-drought years.[7]
- Russia's permafrost regions and boreal forests are sensitive to changes in temperature that could lead to productivity increases. But there is a risk of increasing disturbances, such as fires and pests, leading to widespread tree mortality. Forest dieback and thawing of permafrost threaten to amplify global warming as stored carbon and methane are released into the atmosphere, giving rise to a self-amplifying feedback loop. With a 2°C warming, methane emissions from permafrost thawing could increase by 20–30 percent across boreal Russia.

5. **Marine ecosystems:** Substantial, adverse effects on marine ecosystems and their productivity are expected with rising temperatures, increases in ocean acidity, and likely reductions in available oxygen due to their combined effects. Observed rates of ocean acidification are already the highest in 300 million years and rates of sea level rise are the highest for 6,000 years.

   Projections of coral bleaching indicate that preserving more than 10 percent of these unique ecosystems calls for limiting global warming to 1.5°C. Reef-building corals are critical for beach formation, coastal protection, fisheries, and tourism.

   Physiological changes to fish and fish larvae have been observed and are expected with future ocean acidification. Below 2°C warming and without taking into account changes in ocean acidity, fishery catches in a number of locations are projected to markedly decrease by 2050 as fish populations migrate towards cooler waters.

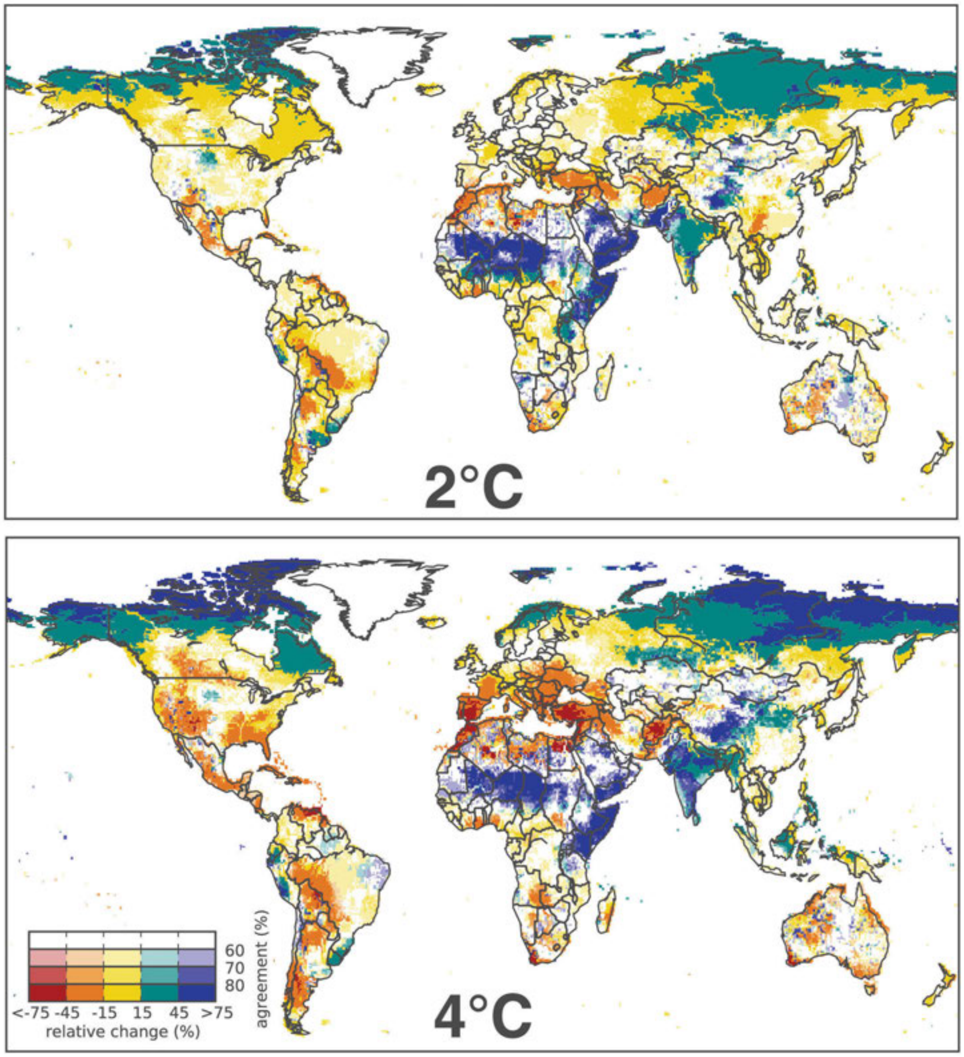
6. **Sea-level rise:** In a 1.5°C world sea level rise is projected to increase by 0.36 m (range of 0.20 m to 0.60 m) and by 0.58 m (range of 0.40 m to 1.01 m) in a 4°C world for the period 2081–2100 compared to the reference period 1986–2005.[8] Due to the time lag in the oceans' response and the long response time of the Greenland and Antarctic ice sheets to atmospheric temperatures (thermal inertia) sea levels will continue to rise for many centuries beyond 2100.
   - Sea-level rise poses a particular threat to urban communities in the Middle East and North Africa and Latin America and the Caribbean, where large urban settlements and important infrastructure are situated along coastlines. The impact of rising sea levels will be particularly severe for the Caribbean island communities as possibilities for retreat are extremely limited. Rising sea levels will substantially increase the risk posed by storm surges and tropical cyclones, in particular for highly exposed small island states and low-lying coastal zones. In addition, rising sea levels could contribute to increased salt-water intrusion in freshwater aquifers (particularly in the Middle East and North Africa), a process made worse by other climate impacts (e.g., reduction in water availability) and other human-induced drivers (e.g., resource overuse).

7. **Glaciers:** A substantial loss of glacier volume and extent has been observed under current levels of warming in the Andes and Central Asia. Increasing glacial melt poses a high risk of flooding and severely reduces freshwater resources during crop growing seasons. It can also have negative impacts on hydropower supply.
   - Tropical glaciers in the Central Andes have lost large amounts of ice volume throughout the 20th century and complete deglaciation is projected in a 4°C world. In Peru it is estimated that a 50 percent reduction in glacier runoff would result in a decrease in annual power output of approximately 10 percent, from 1540 gigawatt hours (GWh) to 1250 GWh.
   - Since the 1960s Central Asian glaciers have reduced in area by 3–14 percent depending on their location. Further substantial losses of around 50 percent and up to 80 percent are projected for a 2°C and a 4°C world respectively. As a result, river flows are expected to shrink

[7] The change in carbon sequestration is caused by the combined effects of reduced uptake of carbon resulting from suppressed tree growth due to the drought, and loss of carbon due to drought induced tree mortality and decomposition over several years.

[8] The sea-level projections presented here follow the methodology adopted in the IPCC AR5 WGI with the important update that more realistic scenario-dependent contributions from Antarctica based on post-IPCC literature are included. Recent publications suggest that IPCC estimates are conservative given the observed destabilization of parts of the West Antarctic Ice Sheet. Note that the regional projections given in this report are also based on this adjustment to the AR5 WGI methodology and do not include land subsidence. Sea-level rise projections presented in this report are based on a larger model ensemble with an ensemble mean warming of less than 1.75°C; as a result, end-of-century sea-level rise in RCP2.6 is classified as 1.5° warming. See Box 2.1 and Section 6.2, Sea-Level Rise Projections for further explanation.

**Figure 1:** Water resources: Relative change in annual discharge for a 2°C and a 4°C world in the 2080s relative to the 1986–2005 period based on an ISI-MIP model inter-comparison.




Colors indicate the multi-model mean change; the saturation of colors indicates the agreement across the model ensemble. More saturated colors indicate higher model agreement. Source: Adjusted from Schewe et al. (2013).

by 25 percent at around 3°C warming during the summer months when water demand for agriculture is highest.

- In Central Asia hydropower generation has the potential to play a major role in the future energy mix however the predicted changes in runoff distribution will mean that there will be less water available for energy generation in summer months when it will compete with demands from agriculture.

8. **Social Vulnerability to Climate Change.** The social impacts of climate change are hard to predict with certainty as they depend on climatic factors and their interaction with wider development trends. However, there is clear evidence that climate change is already affecting livelihoods and wellbeing in parts of the three regions and is likely to do so to a significantly greater extent if more extensive climate change occurs (Box 2). Where governance is weak, or infrastructure

## Box 2: Social Vulnerability Impacts of Climate Change

**Shocks and stresses related to climate change can undermine poverty reduction and push new groups into poverty.** Informal settlements on flood plains and steep hillsides in many Latin American cities and the Western Balkans, for example, have been severely affected by floods and landslides in recent years. While many poor people will be living in isolated, rural areas, continued urban expansion into hazard-prone areas means that a growing proportion of urban populations will be at risk of climate-related extreme events and rising food prices, and thus of increasing poverty levels among urban groups.

**The impacts of climate change will often be most severely felt by poor and socially excluded groups, whose capacity to adapt to both rapid- and slow-onset climate change is more limited.** These include indigenous people and ethnic minorities, migrant workers, women, girls, older people, and children. Although these groups—like their more advantaged counterparts—are already adapting to climatic and other changes, these efforts are often undermined by their limited assets, lack of voice, and discriminatory social norms. For example, increasing water stress, projected for parts of Latin America and low-income Middle East and North Africa countries, can dramatically increase the labor burden associated with fetching water in rural and poor urban environments; and child malnutrition linked to climate change reducing protein and micronutrient contents of staple foods (wheat, rice) could have irreversible, negative life-time consequences for affected children.

**Climate change may lead to displacement and also affect patterns and rates of migration**s. Most displacement related to extreme weather events has, to date, been temporary. However, if climate change renders certain areas uninhabitable (for example, if they become too hot, too dry, or too frequently affected by extreme events—or sea-level rise) such migration may increase in scale and more often lead to permanent resettlement (as already being seen in some water-scarce parts of MENA). Large-scale migration may pose significant challenges for family relations, health, and human security. There is a risk of disadvantaged groups being trapped in adversely affected rural areas as they lack the funds and/or social connections to move.

outdated or insufficient (as in parts of all three regions), this is likely to amplify the social challenges associated with adapting to further climate change.

## Latin America and the Caribbean

The Latin American and the Caribbean (LAC) region is highly heterogeneous in terms of economic development and social and indigenous history with a population of 588 million (2013), of which almost 80 percent is urban. The current GDP is estimated at $5.655 trillion (2013) with a per capita GNI of $9,314 in 2013. In 2012, approximately 25 percent of the population was living in poverty and 12 percent in extreme poverty, representing a clear decrease compared to earlier years. Undernourishment in the region, for example, declined from 14.6 percent in 1990 to 8.3 percent in 2012. Despite considerable economic and social development progress in past decades, income inequality in the region remains high.

At the current 0.8°C warming significant impacts of climate change are being felt throughout the LAC region's terrestrial (e.g. Andean mountains and rainforests) and marine (especially the coral reefs) biomes. As global mean temperatures rise to 2°C and beyond the projected intensity and severity of impacts will increase across the entire region (three significant impacts are described below).

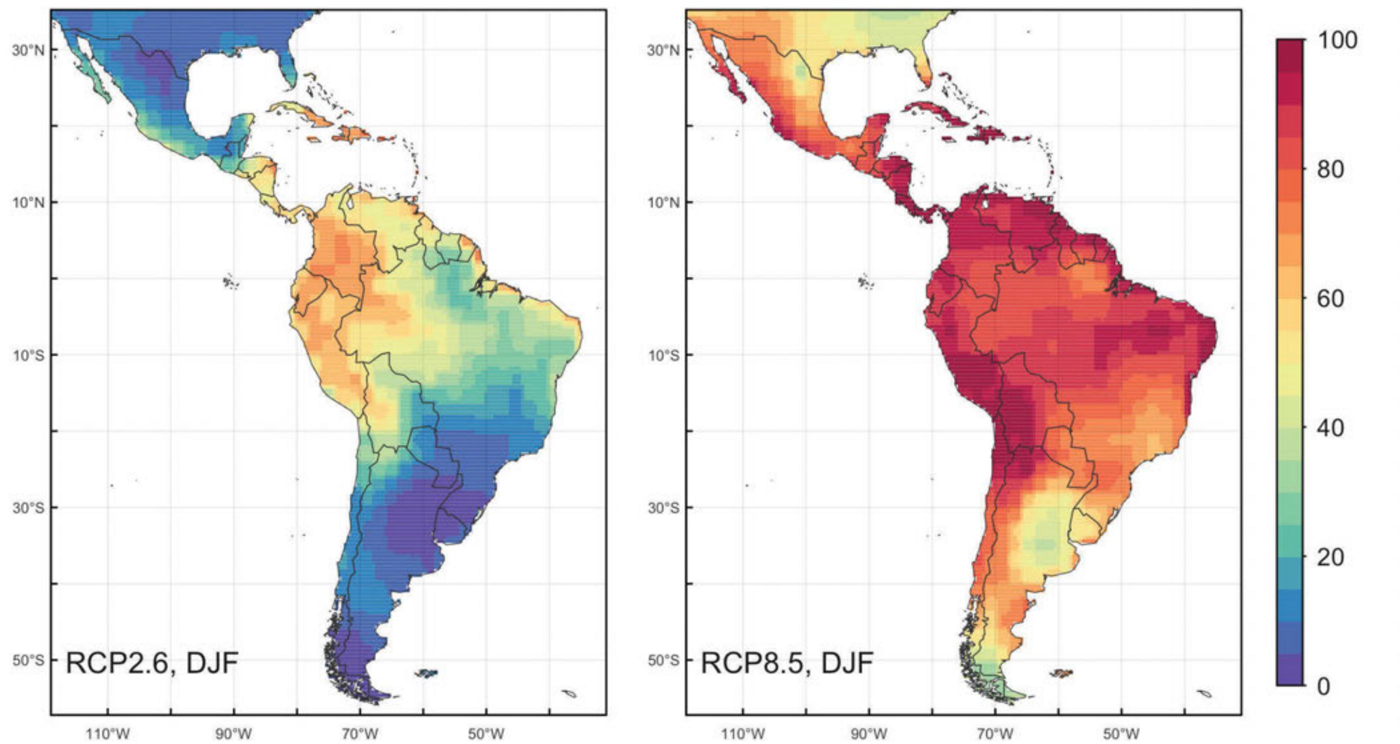
Figure 2 shows the occurrence of highly unusual summer temperatures in a 2°C and 4°C world. Box 3 gives an overview of the climate risks in the region.

### *Changes to the hydrological cycle could endanger the stability of freshwater supplies and ecosystem services.*

Altered precipitation cycles characterized by more intense downpours followed by longer droughts, loss of glaciers, degradation of key ecosystems, and the loss of critical ecosystem services (e.g., water supplies, water buffering, retention, regulation, and soil protection) will impact freshwater supplies regionally and potentially generate upstream-downstream tradeoffs and synergies. A range of impacts are expected to increase in intensity and severity as global mean temperatures rise from 2°C to 4°C.

- **Projections indicate that most dry regions get drier and wet regions get wetter.** Reductions in precipitation are as high as 20–40 percent for the Caribbean, Central America, central Brazil, and Patagonia in a 4°C world. Drought conditions are projected to increase by more than 20 percent. Limiting warming to 2°C is projected to reduce the risk of drought significantly: to a one percent increase of days with drought conditions in the Caribbean and a nine percent increase for South America. At the same time, an increase in frequency and intensity of extreme precipitation events is projected particularly for the tropical and subtropical Pacific coastline and southern Brazil.
- **Massive loss of glaciers is projected in the Andes in a 2°C world (up to 90 percent) and almost complete glacier loss beyond 4°C**. Changes to glacial melt, in response to land surface warming, alter the timing and magnitude of river flows and result in a higher risk of flooding and freshwater shortages and damage to infrastructure assets.

**Figure 2:** Multi-model mean of the percentage of austral summer months (DJF), with highly unusual temperatures (normally unlikely to occur more than once in several hundred years) in a 2°C world (left) and a 4°C world (right) in 2071–2099 and relative to the 1951–1980 base line period.




- **Increased droughts and higher mean temperatures are projected to decrease water supplies and affect most ecosystems and agroecosystems.** The increasing risk of drought will raise the risk of forest fires, large-scale climate-induced forest degradation and the loss of associated ecosystem services.
- **Glaciers will melt at an even faster rate than observed, with a peak in river runoff expected in 20–50 years, and possibly earlier in some watersheds.** Glacial lake outbursts and connected flooding present a hazard for Andean cities. The loss of glaciers will likely impact the *páramos* (Andean, high carbon stock moorlands) which are the source of water for many Andean cities. Moreover, degraded highland ecosystems have less capacity to retain water and intensified downpours will increase erosion with a subsequent increase in siltation and damage to hydropower dams, irrigation works, and hydraulic and river defense infrastructure.
- **The projected trend of more intense rainfall can significantly increase the risk of landslides especially in sloping terrain often occupied by the poorer rural and urban communities.** The major landslides in 2011 in the State of Rio de Janeiro following intense rainfall are a harbinger of the likely severity of projected impacts from more intense rainfall events. Intense rainfall events can quickly overwhelm natural drainage channels in the landscape as well as urban drainage systems that are unlikely to have been designed for the projected more intense future rainfall events and flows.

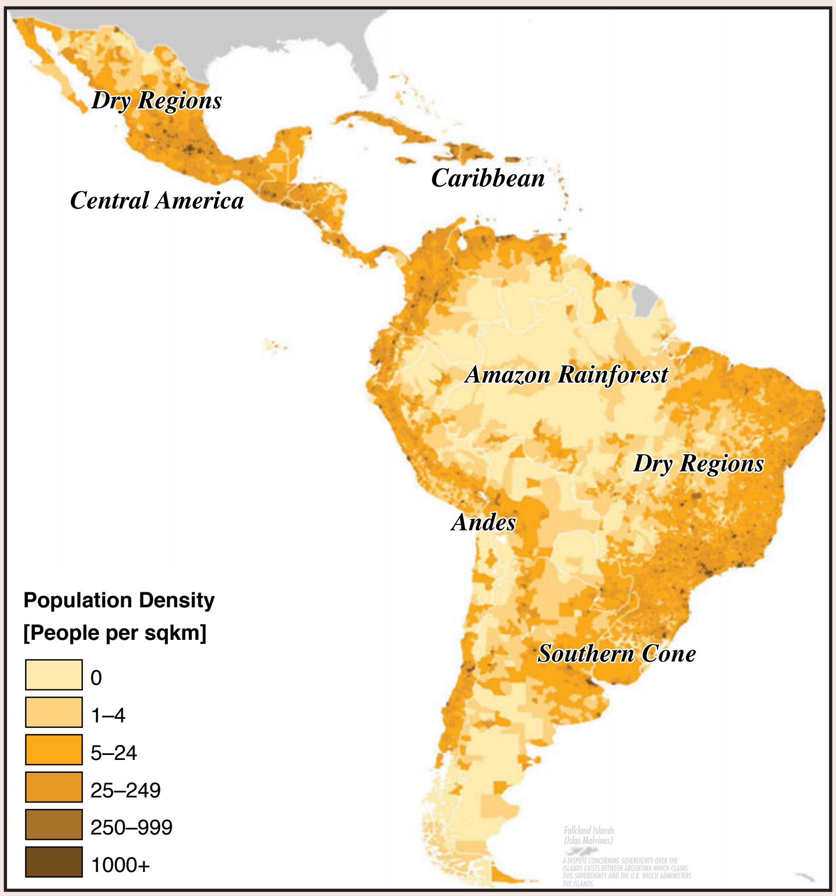
### *Climate change will place at risk small-scale subsistence agriculture and large-scale agricultural production for export*

Agriculture in the Latin America and the Caribbean region is heavily dependent on rain-fed systems for both subsistence and export crops; it is therefore vulnerable to climatic variations such as droughts, changing precipitation patterns, and rising temperatures.

- **Increasing risks for agriculture as warming rises beyond 2°C.** There is a clear negative signal for a large variety of crops with 2°C warming, including soybeans (up to a 70 percent yield decline in some areas of Brazil) and maize (up to a 60 percent yield decline in Brazil and Ecuador) by 2050 relative to a 1989–2009 baseline. Simulated adaptation interventions (e.g. improved crop varieties, improved soil and crop management, and supplementary irrigation) alleviated but did not overcome the projected yield declines from climate change. Other studies

## Box 3: Selected Climate Risks in the Latin America and the Caribbean Region

In a 4°C world, heat extremes, changes in hydrological cycles, tropical cyclones and changes in the El Niño Southern Oscillation (ENSO) are expected to pose severe problems with risks cascading to the agricultural sector, human health, large urban centers and the functioning of critical ecosystem services. At lower levels of warming, glacial melt in the Andes will reduce freshwater and hydropower for communities and large Andean cities during the dry season, while increasing the risks of flooding in the short term and impacting agriculture and environmental services downstream. Severe threats are expected from sea-level rise, damages to low-lying areas and coastal infrastructures. Degrading coral reefs will endanger tourism revenues and undermine biodiversity, fisheries, and the protection of coastal zones thereby negatively impacting livelihoods. For the global community, the potential impact of climate change on the Amazon rainforest is of high relevance. With increasing warming, degradation—if not dieback—of the Amazon rainforest is increasingly possible potentially turning the forest into a large carbon source during dry years and triggering further climate change.




Data sources: Center for International Earth Science Information Network, Columbia University; United Nations Food and Agriculture Programme; and Centro Internacional de Agricultura Tropical—(2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). This map was reproduced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

### Central America & the Caribbean

Higher ENSO and tropical cyclone frequency, precipitation extremes, drought, and heat waves. Risks of reduced water availability, crop yields, food security, and coastal safety.

*Poor exposed to landslides, coastal erosion with risk of higher mortality rates and migration, negative impacts on GDP where share of coastal tourism is high.*

### Amazon Rainforest

Increase in extreme heat and aridity, risk of forest fires, degradation, and biodiversity loss.

*Risk of rainforest turning into carbon source. Shifting agricultural zones may lead to conflict over land. Risks of species extinction threatening traditional livelihoods and cultural losses.*

### Andes

Glacial melt, snow pack changes, risks of flooding, and freshwater shortages.

*In high altitudes women, children, and indigenous people particularly vulnerable; and agriculture at risk. In urban areas the poor living on steeper slopes more exposed to flooding.*

### Dry Regions

Increasing drought and extreme heat events leading to cattle death, crop yield declines, and challenges for freshwater resources.

*Risks of localized famines among remote indigenous communities, water-related health problems. Stress on resources may lead to conflict and urban migration.*

### Southern Cone

Decreasing agricultural yields and pasture productivity, northward migration of agro-ecozones.

*Risks for nutritious status of the local poor. Risks for food price increases and cascading impacts beyond the region due to high export share of agriculture.*

suggest that in a 3°C world, the projected negative impacts on individual crops become stronger. For example up to almost 70 percent decline in wheat in Central America and the Caribbean. This implies that climate change threatens not only smallholder farmers, and rural and indigenous communities but also large-scale commodity (soybeans, maize) producers, ranchers, and agribusinesses—with potential negative repercussions on food security and prices in the region and beyond.

- **Local food security is seriously threatened by the projected decrease in fishery catch potential.** The Caribbean coasts, the Amazon estuaries, and the Rio de la Plata are expected to be particularly affected by declines in catch potential of more than 50 percent as fish stocks migrate in response to warming waters. The Caribbean waters could see declines in the range of 5–50 percent. These estimates are for warming of 2°C by 2050, by which time many of the coral reefs—an important fish nursery and habitat—would be subject to annual bleaching events, further undermining the marine resource base. Ocean acidification could affect fish populations directly, including through physiological damages at early life stages. The effects on the food chain, however, are not yet clear.
- **The Southern Cone (Chile, Argentina, Uruguay, Paraguay, and southern Brazil) as a major grain and livestock producing region is susceptible to climate shocks,** mainly related to changing rainfall patterns and rising heat extremes. This is expected to severely impact maize and soy yields, important export commodities. For example, maize productivity is projected to decline by 15–30 percent in comparison to 1971–2000 levels under warming of 2°C by 2050, and by 30–45 percent under 3°C warming. Strong and/or extreme El Niño events resulting in floods or droughts in the cropping season pose further substantial risks to agriculture in the region.

### *A stronger prevalence of extreme events is projected that would affect both rural and urban communities, particularly on sloping lands and in coastal regions.*

The region is heavily exposed to the effects of more frequent and intense extreme events, such as those that occur during strong El Niño events and tropical cyclones.

- **An increase of approximately 40 percent in the frequency of the strongest north Atlantic tropical cyclones is projected for a 2°C world, and of 80 percent for a 4°C world, compared to present.** In LAC, close to 8.5 million people live in the path of hurricanes, and roughly 29 million live in low-elevation coastal zones. The Caribbean is particularly vulnerable as more than 50 percent of its population lives along the coast, and around 70 percent live in coastal cities. More intense tropical cyclones would interact adversely with rising sea levels, exacerbating coastal flooding and storm surge risks, putting entire economies and livelihoods at risk (particularly for island states).

## Box 4: El Niño Southern Oscillation (ENSO)

**The Latin America and the Caribbean region is particularly exposed to the effects of strong* El Niño and La Niña events,** which are related to the El Niño Southern Oscillation (ENSO). In Central America, El Niño usually results in excessive rainfall along the Caribbean coasts, while the Pacific coasts remain dry. Rainfall increases and floods tend to occur on the coast of Ecuador, the northern part of Peru, and in the southern part of Brazil, Argentina, Paraguay, and Uruguay while drought appears in the Andean zones of Ecuador, Peru and Bolivia and in north eastern Brazil. All these changes can substantially impair livelihoods through impacts on agricultural productivity, critical ecosystems, energy production, water supply, infrastructure, and public health in affected countries. For example, the extreme 1997–98 El Niño event resulted in many billions of dollars in economic damages, and tens of thousands of fatalities worldwide, including severe losses in Latin America. Substantial uncertainties remain regarding climate change impact projections on the intensity and frequency of extreme El Niño events. However, evidence of changes to ENSO-driven precipitation variability in response to global warming has emerged recently and represents an update to the assessment of ENSO projections in the IPCC AR5 report. Recent climate model inter-comparison studies suggest the likelihood of global warming leading to the occurrence of more frequent **extreme** El Niño events over the 21st century.

* "The Oceanic Niño Index (ONI) is the standard that NOAA uses for identifying El Niño (warm) and La Niña (cool) events in the tropical Pacific. It is the running 3-month mean sea-surface temperature (SST) anomaly for the Niño 3.4 region (i.e., 5°N–5°S, 120°–170°W). Events are defined as 5 consecutive overlapping 3-month periods at or above the +0.5° anomaly for warm (El Niño) events and at or below the –0.5 anomaly for cold (La Niña) events. The threshold is further broken down into Weak (with a 0.5 to 0.9 SST anomaly), Moderate (1.0 to 1.4) and Strong (≥ 1.5) events" [Source: http://ggweather.com/enso/oni.htm]

- **Risks associated with El Niño events and tropical cyclones would occur contemporaneously with a sea-level rise of 38–114 cm thus greatly increasing the risks storm surges.** Sea-level rise is projected to be higher at the Atlantic coast than at the Pacific coast. Sea-level rise off Valparaiso, for example, is projected at 0.35 m for a 2°C world and 0.55 m for a 4°C world (medium estimate). Recife sees projections of approximately 0.39 m and 0.63 m respectively, with the upper estimates as high as 1.14 m in a 4°C world—the highest in the region.
- **Extreme events will strongly affect the rural and urban poor who often reside in informal settlements in high-risk areas (e.g., flood plains and steep slopes).** In 2005, the percentage of people living in informal settlements in Latin America was highest in Bolivia (50 percent) and in the Caribbean highest in Haiti (70 percent). The negative effects of extreme events

also affect rural communities as they strongly depend on their environment and its natural resource base.

- **In the Caribbean, substantial adverse impacts on local critical ecosystems, agriculture, infrastructure, and the tourism industry can be expected in a 2°C world.** This is due to loss and/or degradation of important assets from the combined effects of increasing sea levels and associated impacts of saline intrusion and storm surges, ocean acidification, bleaching of coral reefs, and loss of the physical protection afforded to coastlines from dead and degrading reefs. Impacts from these and other climatic changes can be expected to grow substantially with increasing warming, especially given the increasing likelihood of more frequent intense tropical cyclones.

## The Middle East and North Africa

The Middle East and North Africa (MENA) is one of the most diverse regions in the world in economic terms, with per-capita annual GDP ranging from $1,000 in Yemen to more than $20,000 in the Arab Gulf States. Qatar, Kuwait, the United Arab Emirates, Morocco, the Arab Republic of Egypt, and Yemen rank 4, 12, 27, 130, 132, and 151 in GDP per capita on a list of 189 countries. In consequence, adaptive capacity and vulnerability to climate risks varies enormously within the region.

The region's population is projected to double by 2050, which together with projected climate impacts, puts the region under enormous pressure for water and other resources. The region is already highly dependent on food imports. Approximately 50 percent of regional wheat and barley consumption, 40 percent of rice consumption, and nearly 70 percent of maize consumption is met through imports. The region has coped with its water scarcity through a variety of means: abstraction of groundwater, desalinization, and local community coping strategies. Despite its extreme water scarcity, the Gulf countries use more water per capita than the global average, with Arab residential water and energy markets among the most heavily subsidized in the world. The region is very diverse in terms of socio-economic and political conditions. Thus, adaptive capacity and vulnerability to climate risks varies enormously within the region, especially between the Arab Gulf States and the other Middle East and North Africa countries.

The Middle East and North Africa region emerges as one of the hotspots for worsening extreme heat, drought, and aridity conditions. Agriculture, where 70 percent is rain-fed, is highly exposed to changing climatic conditions. Warming of 0.2°C per decade has been observed in the region from the 1961–1990, and since then the region is warming at an even faster rate. Projections indicate that more than 90 percent of summers will have highly unusual heat extremes in a 4°C world compared to between 20–40 percent of summers in a 2°C world (Figure 3).

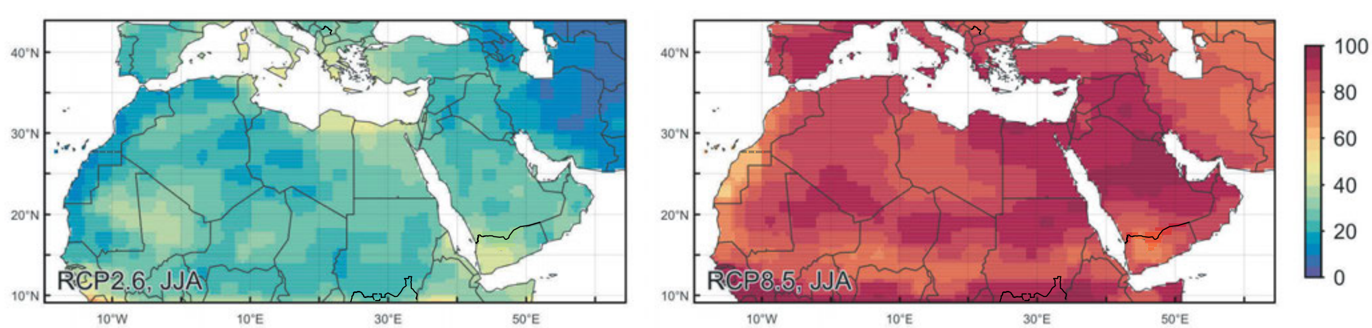
Given its high import dependency, the region is vulnerable to effects beyond its borders. While societal responses to such changes remain hard to predict, it is clear that extreme impacts, such as a more than 45 percent decrease in annual water discharge projected for a 4°C world in parts of the region, would present unprecedented challenges to the social systems affected. Climate change might act as a threat multiplier to the security situation in the region by imposing additional pressures on already scarce resources and by reinforcing pre-existing threats connected to migration following forced displacement. Box 5 gives an overview of the key climate risks in the region.

### *Changing precipitation patterns and an increase in extreme heat pose high risks to agricultural production and regional food security.*

Most agriculture in the region takes place in the semi-arid climate zone, either close to the coast or in the highlands, and is highly vulnerable to the effects of climate change.

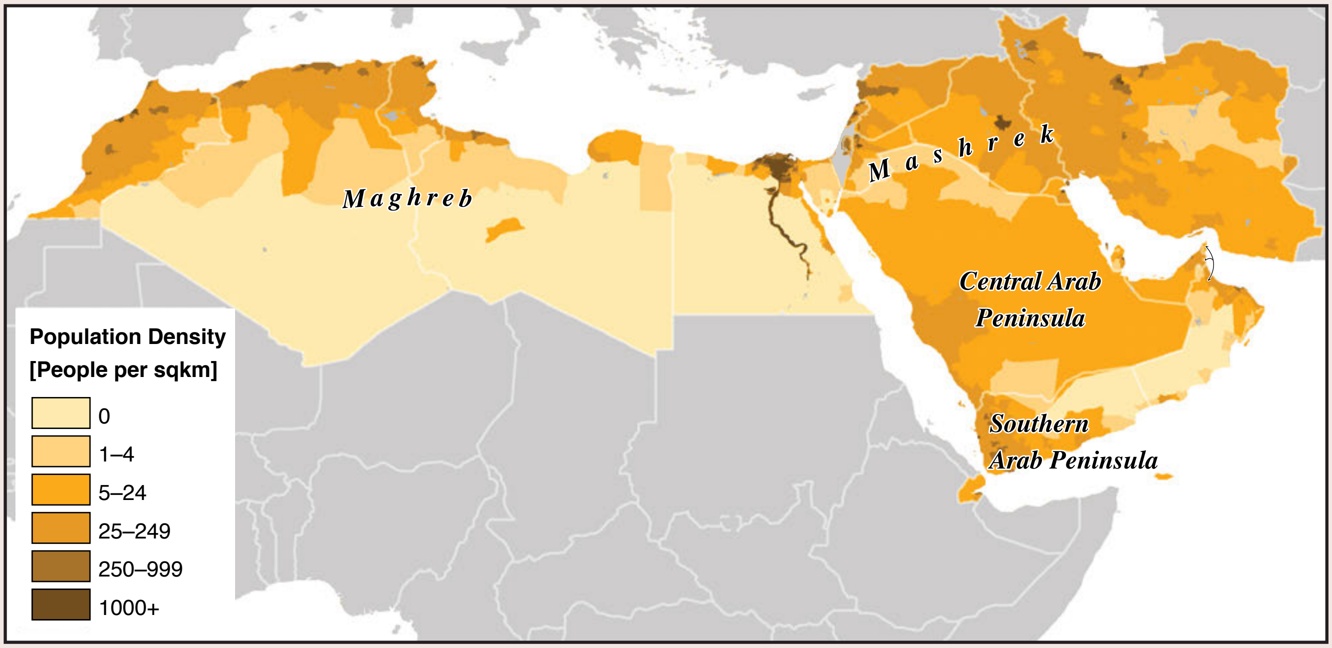
- **Rainfall is predicted to decline by 20–40 percent in a 2°C world and by up to 60 percent in a 4°C world in parts of the region.** Agricultural productivity is expected to drop in parts of the Middle East and North Africa region with increasing

**Figure 3:** Multi-model mean of the percentage of boreal summer months (JJA), with highly unusual temperatures (normally unlikely to occur more than once in several hundred years) in a 2°C world (left) and a 4°C world (right) in 2071–2099 and relative to the 1951–1980 base line period.



## Box 5: Selected Climate Risks in the Middle East and North Africa Region

The region will be severely affected at 2°C and 4°C warming, particularly because of the large increase in projected heat extremes, the substantial reduction in water availability, and expected consequences for regional food security. High exposure to sea-level rise in the coming decades is linked to large populations and assets in coastal areas. In a 2°C world already low annual river discharge levels are projected to drop by more than 15 percent and highly unusual heat extremes are projected to affect about a third of the land. Crop yield declines coupled with impacts in other grain-producing regions could contribute to increasing food prices in the region. The growing food import dependency further exacerbates such risks. Deteriorating rural livelihoods may contribute to internal and international migration, adding further stress on particularly urban infrastructure, with associated risks for poor migrants. Migration and climate related pressure on resources (e.g. water) might increase the risk of conflict.




### Maghreb

Strong warming reduction in annual precipitation, increased water stress and reduced agricultural productivity. Large coastal cities exposed to sea level rise.

*Climate change risks will have severe implications on farmers' livelihoods, country economy, and food security. Exposure of critical coastal assets would have impact on the economy, including tourism. There is risk for accelerated migration flows to urban areas and social conflict.*

### Mashrek and Eastern Parts

Highly unusual heat and decrease in annual precipitation will increase aridity, decrease in snow water storage and river runoff for example in Jordon, Euphrates and Tigris. Adverse consequences for mostly rain-fed agricultural and food production.

*Climate change risks will have severe implications on farmers' livelihoods, country economy, and food security. There is a risk for accelerated migration flows to urban areas and social conflict.*

### Arabian Peninsula

Highly unusual heat extremes in central Arabian Peninsula. In southern parts relative increase in annual precipitation, but uncertain trend of annual precipitation in central part. Sea level rise in the Arabian Sea likely higher than in Mediterranean and Atlantic coasts with risk of storm surges and adverse consequences for infrastructure.

*More heat extremes expected to increase thermal discomfort, posing risk to labor productivity and health.*

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Data sources: Center for International Earth Science Information Network, Columbia University; United Nations Food and Agriculture Programme; and Centro Internacional de Agricultura Tropical—(2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). This map was reproduced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

water scarcity and higher temperatures which are expected to deviate more and more from the temperature optima of several crops (and possibly even exceed their heat tolerance levels).

- **Crop yields in the region may decrease** by up to 30 percent at 1.5–2°C warming in Jordan, Egypt, and Libya and by almost 60 percent (for wheat) at 3–4°C warming in the Syrian Arab Republic. The strongest crop reductions are expected for legumes and maize as they are grown during the summer period.
- **With 70 percent of agricultural production being rain-fed, the sector is highly vulnerable to temperature and precipitation changes and the associated potential consequences for food, social security, and rural livelihoods.** Forty-three percent of the population lives in rural areas and poor rural farmers are particularly vulnerable to hunger and malnutrition as a direct consequence of yield loss and high food prices. In combination with non-climatic pressures the decline in rural livelihood options could trigger further urban migration, potentially exacerbating urban vulnerability and intensifying the potential for conflict.
- **The increase in demand for irrigation water will be difficult to meet due to the simultaneous decrease in water availability** in the Middle East and North Africa countries which have traditionally invested in agriculture to improve the performance in the agriculture sector—about 30 percent of the agricultural land is irrigated whereas agriculture consumes 60 to 90 percent of all water used in the region.
- **Rising food prices that often follow production shocks and long-term declines make the growing number of urban poor increasingly vulnerable to malnutrition**, particularly against the background of increasing local food insecurity. Evidence suggests that child malnutrition could rise in the event of significant food price increases or sharp declines in yields. Child malnutrition is already high in parts of the Middle East and North Africa, with an average of 18 percent of children under age five developmentally stunted. Childhood stunting has been linked to lifelong adverse consequences, including lower economic productivity in adulthood.
- **With its high and growing import dependency the region is particularly vulnerable to worldwide and domestic agricultural impacts and related spikes in food prices.** For example, climatic and hydrological events (droughts and floods), together with global market forces, were contributing factors to high wheat prices in Egypt and affected the price of bread in 2008.

### Heat extremes will pose a significant challenge for human health

People in the region face a variety of health risks, many of which are exacerbated by the hot and arid conditions and relative water scarcity that characterize the region.

- **A substantial rise in *highly unusual* heat extremes is expected in the coming decades.** In a 2°C world, *highly unusual* heat extremes would occur on average in one of the summer months in each year from the 2040s onward. In a 4°C world, this frequency would be experienced as early as the 2030s, and would increase to two summer months by the 2060s and virtually all months by the end of the century. Unprecedented heat extremes are absent in a 2°C world and affect about half the summer months by the end of the century in a 4°C world.
- **The period of consecutive hot days is expected to increase, particularly in cities due to the urban heat island effect**. For example, in a 2°C warmer world the number of consecutive hot days is projected to increase annually from four days to about two months in Amman, from eight days to about three months in Baghdad, and from one day to two months in Damascus. The number of hot days in Riyadh is expected to increase even more—from about three days to over four months. The number of hot days in a 4°C warmer world is projected to exceed the equivalent of four months in most capital cities.
- **Heat stress levels can approach the physiological limits of people working outdoors and severely undermine regional labor productivity, putting a burden on health infrastructure.** High temperatures can cause heat-related illnesses (e.g., heat stress, heat exhaustion, and heat stroke) especially for the elderly, people with chronic diseases or obesity, and pregnant women, children, and people working outside. Climate change is expected to undermine human health in other ways as well. For instance, the relative risk of diarrheal disease as a consequence of climatic changes and deteriorating water quality is expected to increase 6–14 percent for the period 2010–39 and 16–38 percent for the period 2070–99 in North Africa; and 6–15 percent and 17–41 percent, respectively, in the Middle East.

### Sea-level rise will pose serious challenges to the region's coastal population, infrastructure, and economic assets.

The dense concentration of people and assets in coastal cities translate into high exposure to the effects of sea-level rise.

- **Projections show that all coastlines are at risk from sea-level rise.** Depending on the city, sea levels are projected to rise by 0.34–0.39 m in a 1.5°C world and 0.56–0.64 m in a 4°C world (medium estimate), with the highest estimate reaching 1.04 m in Muscat.
- **The Maghreb countries of Egypt, Tunisia, Morocco, and Libya have been identified as among the most exposed African countries in terms of total population affected by sea-level rise.** In Morocco, for example, more than 60 percent of the population and over 90 percent of industry is located in key coastal cities. For example, Alexandria, Benghazi, and Algiers have been identified as particularly vulnerable to a sea-level rise of only 0.2 m by 2050. The United Arab Emirates also

ranks among the ten most vulnerable countries to sea-level rise worldwide.

- **Key impacts of climate change in coastal zones include inundation resulting from slow onset sea-level rise, flooding, and damages caused by extreme events (including storms, storm surges, and increased coastal erosion).** The exposure of critical assets may cause other impacts to have repercussions for the economy (e.g., where tourism infrastructure is exposed). In Egypt, for example, the ocean acidification and ocean warming threatens coral reefs and is expected to place the tourism industry—an important source of income revenue—under severe pressure.
- **Impacts on groundwater levels are significant, with potential negative repercussions on human health for local and migrant populations.** The Nile Delta, home to more than 35 million people and providing 63 percent of Egypt's agricultural production, is especially vulnerable to salinization under changing climate conditions. These impacts will be exacerbated by land subsidence, especially in the eastern part of the delta, and by extensive landscape modification resulting from both coastal modification and changes in the Nile's hydrogeology.

## Europe and Central Asia

Europe and Central Asia (ECA) in this report covers 12 countries[9] within Central Asia, the Western Balkans, and the Russian Federation. The analysis focuses on specific climate challenges related to the agriculture-water-energy nexus in Central Asia; climate extreme in the Western Balkans, and the forests in Russia. While the economic and political profiles of the countries differ greatly, a common denominator is their transition from various types of closed, planned economies to open, market-based systems. The region is characterized by relatively low levels of per-capita annual GDP, ranging from $800 in Tajikistan to $14,000 in Russia. Agricultural production plays an important role in the national economies of the region, particularly those of Tajikistan, the Kyrgyz Republic, Uzbekistan, and Albania. Large portions of the population in Central Asia (60 percent) and the Western Balkans (45 percent) live in rural areas, making them dependent on natural resources for their livelihoods and thus particularly vulnerable to climate change.

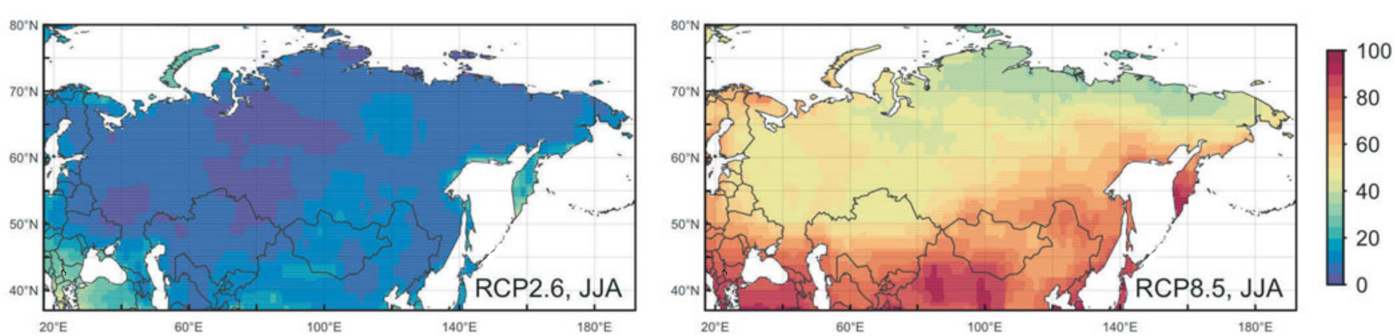
The parts of the Europe and Central Asia region covered by this report are projected to experience greater warming than the global average. The region displays a clear pattern where areas in the southwest are becoming drier and areas further northeast, including most of Central Asia, are becoming wetter as the world warms toward 4°C. The projected temperature and precipitation changes translate into increased risks for freshwater supplies that not only jeopardizes the sustainability of hydropower and agricultural productivity but also negatively impacts ecosystem services such as carbon sequestration for most of the region. A selection of sub-regional impacts is provided in Box 6.

[9] The World Bank Europe and Central Asia region in this report includes only the following countries: Albania, Bosnia and Herzegovina, Kazakhstan, Kosovo, the Kyrgyz Republic, the former Yugoslav Republic of Macedonia, Montenegro, the Russian Federation, Serbia, Tajikistan, Turkmenistan, and Uzbekistan.

### *Water resources in Central Asia increase during the first half of the century and decline thereafter, amplifying the challenge of accommodating competing water demands for agricultural production and hydropower generation.*

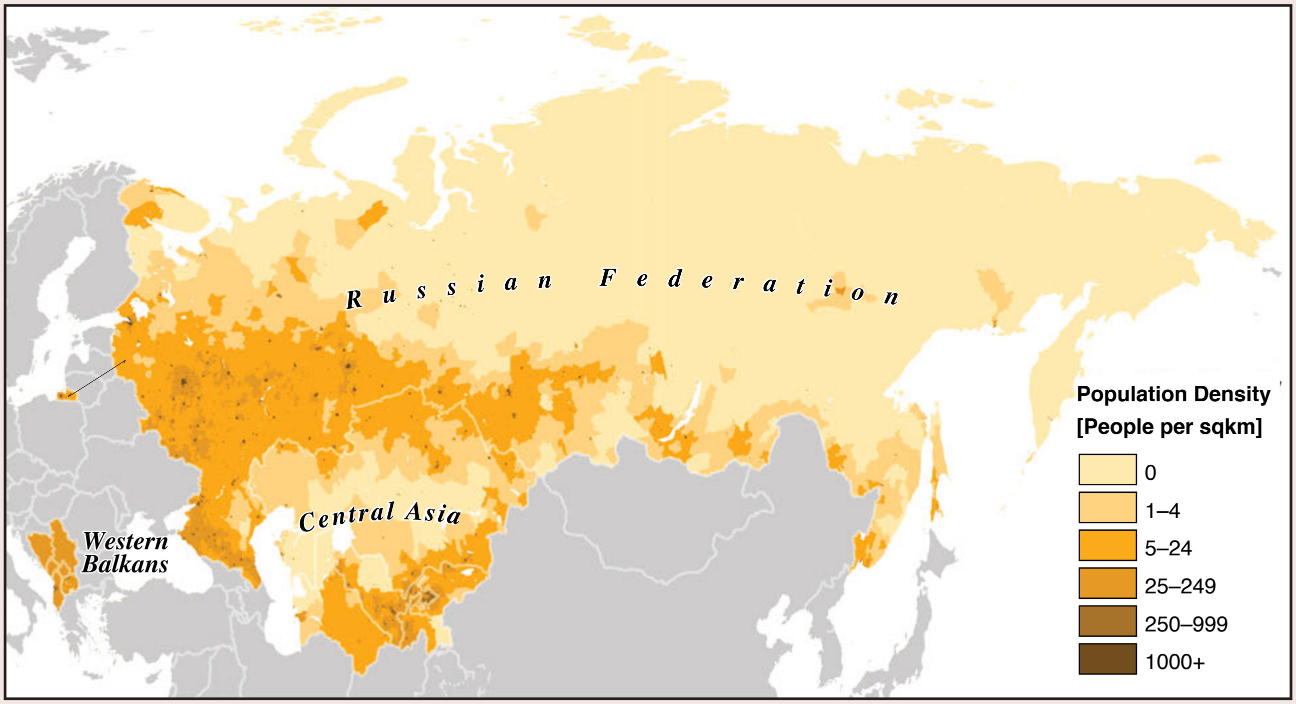
Water resource systems in Central Asia (notably glaciers and snow pack) are sensitive to projected warming; with consequent impacts on water availability in the agriculture and energy sectors.

**Figure 4:** Multi-model mean of the percentage of boreal summer months (JJA) with highly unusual temperatures (normally unlikely to occur more than once in several hundred years) in a 2°C world (left) and a 4°C world (right) in 2071–2099 and relative to the 1951–1980 base line period.



## Box 6: Selected Climate Risks in the Europe and Central Asia Region

Increasing precipitation and glacial melt lead to increased water availability and flood risk in Central Asia in the coming decades. After mid-century and especially with warming leading to a 4°C world, unstable water availability poses a risk for agriculture and competing demands for hydropower generation. In the Western Balkans, extreme heat with a strong decrease in precipitation and water availability are projected to lead to large reductions in crop yields, adverse effects on human health, and increasing risks to energy generation for a 4°C world; but would already be present in a 2°C world. The Russian forests store enormous amounts of carbon in biomass and soils. While their productivity may generally increase with warmer temperatures, large-scale forest dieback and the release of carbon resulting from interacting heat stress, insect spread and fire, have the potential to further affect boreal forests in the second half of the century.




### Western Balkans

Increase in droughts, unusual heat extremes and flooding. High risks for agriculture, human health and stable hydropower generation.

*Risks for human health, food and energy security.*

### Central Asia

Increasing glacial melt alters river runoff. Risks of glacial lake outbursts, flooding and seasonal water shortages. Increasing competition for water resources due to rising agricultural water demand and demand for energy production.

*Risks for poor through rising food prices particularly affecting women, children and the urban poor. Risks for human health due to spreading disease, heat waves and flooding.*

### Boreal Forests of the Russian Federation

Unusual heat extremes and annual precipitation increase, rising risks of forest fires and spread of pests leading to tree mortality and decreasing forest productivity. Possible northward shift of treeline and changes in species composition. Risks of permafrost melt and methane release.

*Risk for timber production and ecosystem services, including carbon capture. Risks of substantial carbon and methane emissions.*

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Data sources: Center for International Earth Science Information Network, Columbia University; United Nations Food and Agriculture Programme; and Centro Internacional de Agricultura Tropical—(2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). This map was reproduced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

Central Asia is increasingly likely to be a hotspot for heat stress for agriculture and human settlements as warming proceeds to 2°C and 4°C especially as temperatures are not moderated by oceanic winds. Since the beginning of the 20th century, Central Asian glaciers have already seen a one-third reduction in glacier volume. Glacier volume is projected to decline by about 50 percent in a 2ºC world, concurrent with a 25 percent decrease in snow cover for the Northern Hemisphere, and by up to 80 percent in a 4°C world. Reductions in water availability are predicted to occur contemporaneously with an increase in demand for irrigation water.

- **River runoff will increase in the coming decades due to enhanced glacial melt rates but flows are expected to decrease for the second half of the century.** By the end of the 21st century a distinct decrease in the water volume of the Syr Darya, and an even more distinct decrease in the Amu Darya River, is expected because of declining glaciers that supply most of its flows. Critically, also the timing of high flow volumes changes. For example, available data for a headwater catchment (Panj) of the Amu Darya River reveal that the timing of peak flows is projected to shift toward spring, leading to a 25 percent reduction in discharge during the mid-summer (July-August) period in a 3°C world. As a result, less water will be available for agriculture during the crop-growing season while at the same time higher summer temperatures lead to higher water demand for plants.
- **Crop productivity is expected to be negatively impacted by increased heat extremes and variability of supply/demand for water that poses substantial risks to irrigated agricultural systems.** Rain-fed agriculture is likely to be affected by uncertain rainfall patterns and amounts, including where irrigation is important, and coupled with rising maximum temperatures can lead to the risk of heat stress and crop failure.
- **Rural populations that are especially dependent on agriculture for food are likely to be increasingly vulnerable** to any reductions in agricultural yields and nutritional quality of their staple food grains.
- **Unstable water availability is likely to increase the challenge of competing requirements for hydropower generation and agricultural production** at times of rising overall demand due to projected population and economic growth in Central Asia. The projected increase in highly unusual and unprecedented heat extremes during the summer months (see Figure 4) can be expected to simultaneously increase energy demand. As the efficiency of hydropower plants depends on inter- and intra-annually stable river runoff, the potential, for example, of installed hydropower plants for small catchments is projected to decrease by 13 percent in Turkmenistan and by 19 percent in the Kyrgyz Republic at around 2°C warming by the 2050s, while an increase of nearly seven percent is projected for Kazakhstan. Overall, energy demand is projected to rise together with population and economic growth.
- Tajikistan and the Kyrgyz Republic, which are located upstream of the Syr Daria and Amu Darya, produce nearly 99 percent and 93 percent, respectively, of the total electricity consumed from hydropower. These upstream countries would have to manage the impact of climate change on their hydropower generation capacity, which is the backbone of their power systems; downstream countries (Kazakhstan, Uzbekistan, and Turkmenistan), meanwhile, would be hit particularly hard by competing demands for agricultural and energy production.

### *Climate extremes in the Western Balkans pose major risks to agricultural systems, energy and human health.*

The Western Balkans are particularly exposed to the effects of extreme events, including heat, droughts, and flooding. Heat extremes will be the new norm for the Western Balkans in a 4°C world. In a 2°C world, highly unusual heat extremes are projected for nearly a third of all summer months compared to virtually all summer months in a 4°C world. Unprecedented heat extremes are projected to occur for 5–10 percent of summer months in a 2°C world compared to about two-thirds of summer months in a 4°C world.

- **The risk of drought is high. Projections indicate a 20 percent increase in the number of drought days and a decrease in precipitation of about 20–30 percent in a 4°C world.** Projections for a 2°C world are uncertain. At the same time, projections suggest an increase in riverine flood risk, mainly in spring and winter, caused by more intense snow melt in spring and increased rainfall in the winter months (precipitation projections are, however, particularly uncertain).
- **Most crops are rain-fed and very vulnerable to projected climate change.** While there are no projections that encompass the entire region, and projections for individual countries remain uncertain, clear risks emerge. For example, projections for FYR Macedonia indicate potential yield losses of up to 50 percent for maize, wheat, vegetables, and grapes for around 2°C global warming by 2050. Pasture yields and grassland ecosystems for livestock grazing may be affected by sustained drought and heat, and decline over large parts of the Western Balkans. The effects of extreme events on agricultural production are mostly not included in assessments, but observations indicate high vulnerability.
- **Energy systems are very vulnerable to extreme events and changes in river water temperatures; changing seasonality of river flows can further impact hydropower production.** Most countries in the Western Balkans depend on hydroelectric sources for at least one-fifth of their electricity production. Reductions in electricity production would be concurrent with

an increase in cooling demand which is projected to increase by 49 percent in a 4°C world.

- **Extreme climate events and the appearance of new disease vectors pose serious risks to human health.** The increased incidence and intensity of extreme heat events could cause the seasonality of temperature-related mortality to shift from winter to summer across continental Europe. Albania and the Former Yugoslav Republic of Macedonia are considered particularly vulnerable to heat waves. The net total number of temperature-related deaths is projected to increase for the period 2050–2100 above 2°C warming levels. Further health risks are likely due to climate change resulting in favorable conditions for the insect vectors transmitting diseases, such as dengue fever and Chikungunya fever.

### *Impacts of projected warming on Russian boreal forests and the permafrost can have severe consequences for forest productivity and global carbon stocks.*

The boreal ecosystems of the Russian Federation that account for about 20 percent of the world´s forest cover large permafrost regions (carbon and methane-rich frozen soil layers) are likely to be quite sensitive to projected warming and heat extremes. Perturbations to the forest or permafrost could result in severe consequences for local ecosystem services and the global carbon budget. Although slightly warmer average temperatures may increase forest productivity, there is a risk of increasing disturbances, such as fires and pests, leading to widespread tree mortality.

Above-average temperature rises and an overall increase in annual precipitation is projected**.** In a 2°C world, highly unusual heat extremes are projected to occur in 5–10 percent of summer months, increasing to 50 percent of all summer months in a 4°C world. Precipitation is expected to increase by 10–30 percent in a 2°C world and by 20–60 percent in a 4°C world. Permafrost in the region is highly vulnerable to warming, with projected permafrost thawing rate of 10–15 percent over Russia by 2050 in a 2°C world.

- **A northward shift of the tree line is projected in response to warming**, causing boreal forests to spread into the northern tundra zone, temperate forests into the present boreal zone, and steppes (grassland plains) into temperate forests. In a 4°C world the Eurasian boreal forest area would reduce around 19 percent and the temperate forest area increase by over 250 percent. With warming limited to around 1.5°C, boreal forests would decrease by around two percent and the temperate forest area would increase by 140 percent. This would lead to a net gain in total temperate and boreal forest area in Eurasia of seven percent in a 4°C world and 12 percent in a 1.5°C world. The potential carbon gains from the expansion of boreal forests in the north are likely to be offset, however, by losses in the south.
- **At lower latitudes the forest is likely to give way to steppe ecosystems**. If (partly uncertain) $CO_2$ fertilization effects do not enhance water-use efficiency sufficiently, the risk of fire, particularly in southern Siberia and Central Yakutia, will increase and could lead to increased carbon emissions. Projections for this area indicate an increase in the annual number of high fire danger days of an average of 10 days in a 3°C world, and 20–30 days in a 4°C world. The effects of heat waves promoting forest fires, and the increasing spread of pests and diseases, as well as the interaction of these factors, may lead to decreased productivity and even increased tree mortality.
- **In a 2°C world, the thawing of the permafrost is projected to increase methane emissions by 20–30 percent**. The projected perturbations to Russian forest ecosystems are of global importance. If pushed beyond critical thresholds and into positive feedback with regional and global warming, large carbon stocks in the boreal forests and methane in the permafrost zones may be released into the atmosphere—with major implications for the global carbon budget.

## Consequences for Development

### *Climate change risks undermining development and poverty reduction for present and future generations*

Climate change poses a substantial and escalating risk to development progress that could undermine global efforts to eliminate extreme poverty and promote shared prosperity. Without strong, early action, warming could exceed 1.5–2°C and the resulting impacts could significantly worsen intra- and inter-generational poverty in multiple regions across the globe.

Severe threats to development outlined in this report are beginning to occur across many sectors in all three regions. The analysis presented in this report reveals that amplified risks are emerging from multi-sectoral impacts in particular connected to food security due to projected large and severe crop yield losses for warming levels above 2°C.

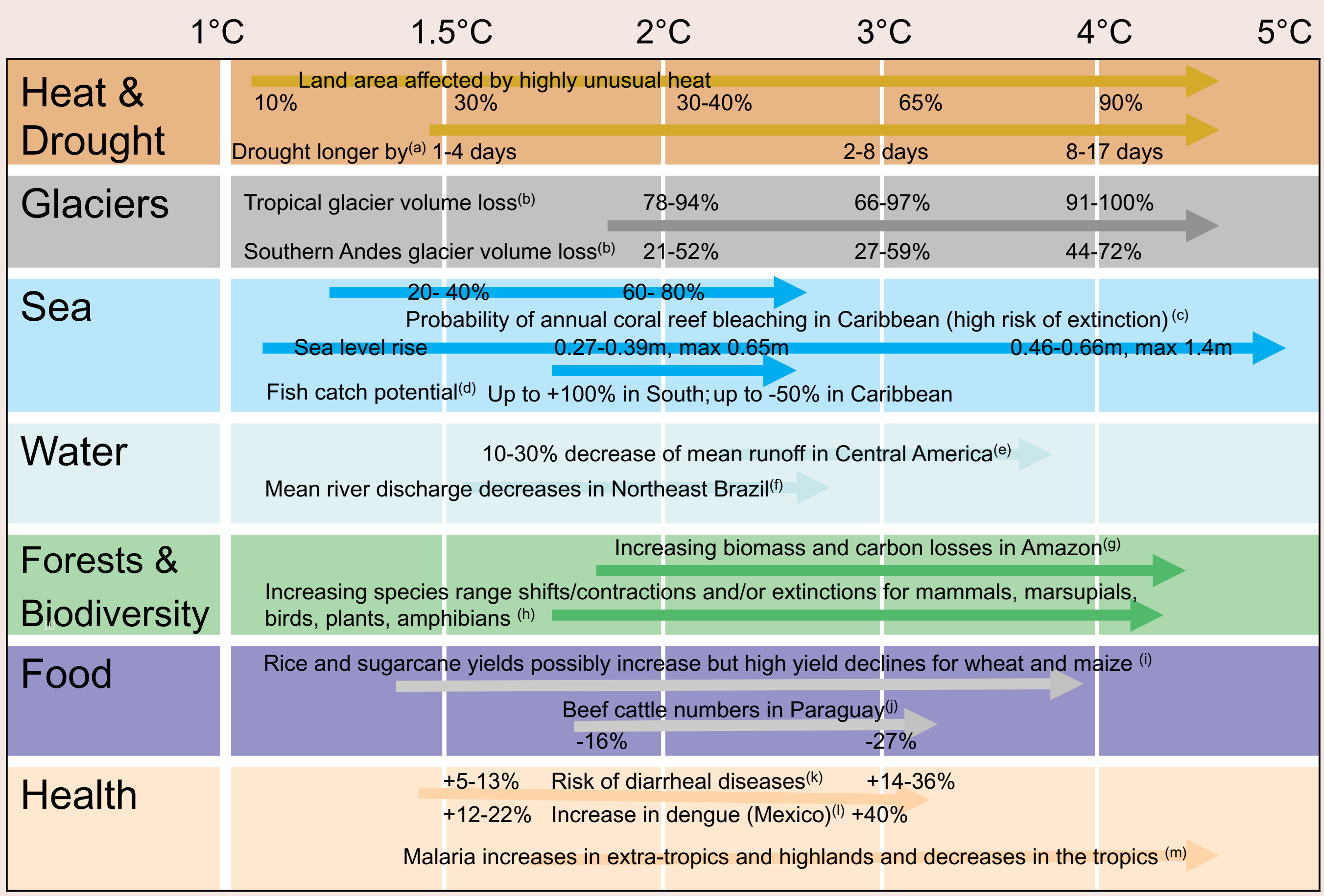
As warming approaches 4°C very severe impacts can be expected to trigger impact cascades crossing critical thresholds of environmental and human support systems. Climatic conditions, heat and other weather extremes considered highly unusual or unprecedented today would become the new climate normal—a world of increased risks and instability.

Every effort must be made to cut greenhouse gas emissions from our cities, land use, and energy systems now and transition to a clean, low carbon pathway. Action is urgently needed on climate change, but it does not have to come at the expense of economic growth. Immediate steps are also needed to help countries build resilience and adapt to the climate impacts being felt today and the unavoidable consequences of a rapidly warming world over the coming decades.

The task of promoting human development, of ending poverty, increasing global prosperity and reducing global inequality will be very challenging in a 2°C world, but in a 4°C world there is serious doubt whether it can be achieved at all. Many of the worst projected climate impacts outlined in this report could still be avoided by holding warming below 2°C. This will require substantial technological, economic, institutional and behavioral change. And, most of all, it will require leadership at every level of society. The time to act is now.

## Box 7: Projected Impacts of Climate Change in Key Sectors in the Latin America and Caribbean Region

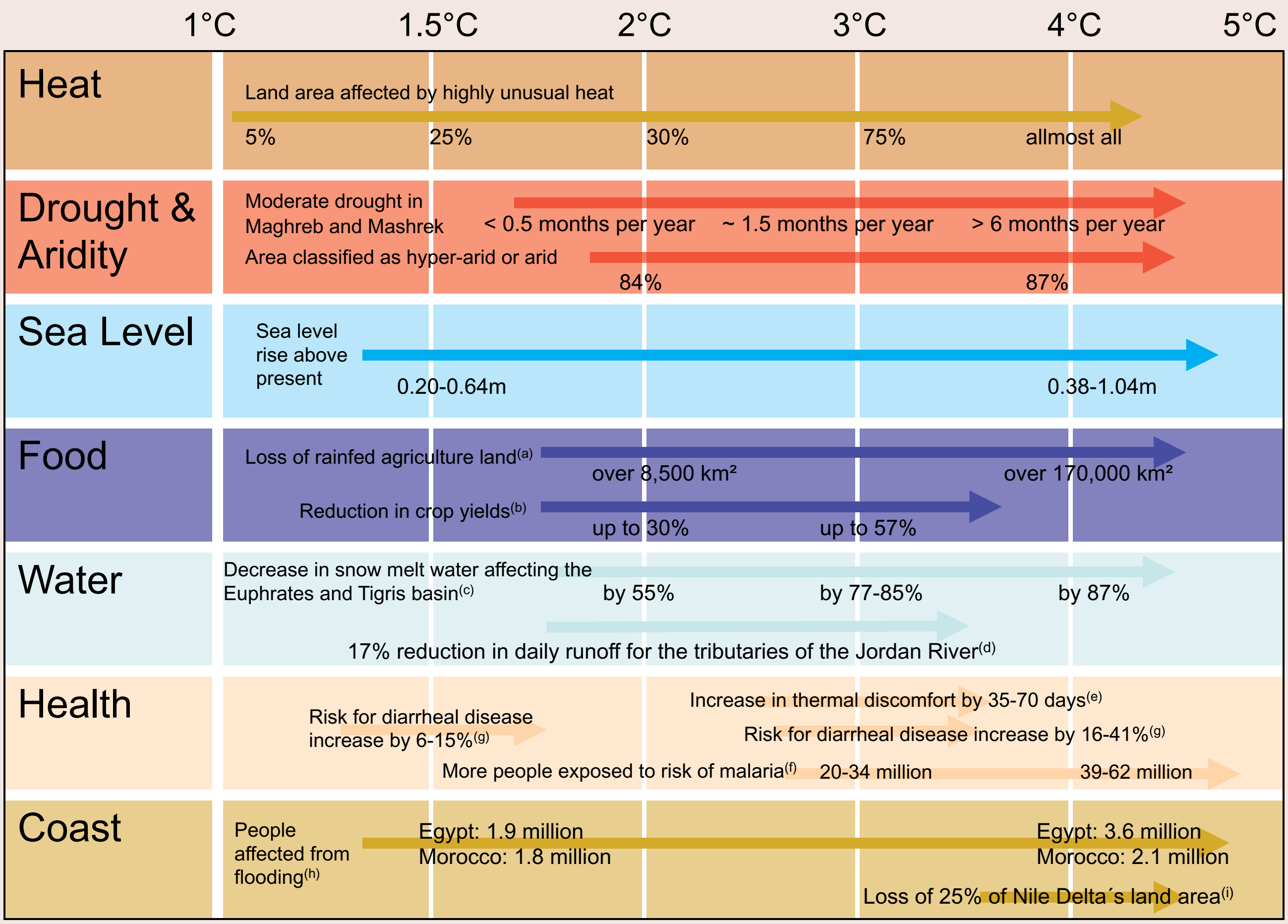
Warming levels are relative to pre-industrial temperatures. The impacts shown here are a subset of those summarized in Table 3.15 of the Main report. The arrows indicate solely the range of warming levels assessed in the underlying studies, but do not imply any graduation of risk unless noted explicitly. In addition, observed impacts or impacts occurring at lower or higher levels of warming that are not covered by the key studies highlighted here are not presented (e.g., coral bleaching already occurs earlier than 1.5°C warming but the studies presented here only start at 1.5°C). Adaptation measures are not assessed here although they can be crucial to alleviate impacts of climate change. The layout of the figure is adapted from Parry (2010). The lower-case superscript letters indicate the relevant references for each impact.[10] If there is no letter, the results are based on additional analyses for this report.




[10] a) Sillmann et al. (2013b); (b) Marzeion et al. (2012); Giesen and Oerlemans (2013); Radic et al. (2013); (c) Meissner et al. (2012); (d) Cheung et al. (2010); (e) Hidalgo et al. (2013); (f) Döll and Schmied (2012); (g) several studies without considering $CO_2$-fertilization, see Table 3.1; (h) several studies, see Table 3.1; (i) several studies, see Table 3.1; (j) ECLAC (2010); (k) Kolstad and Johansson (2011); (l) Colon-Gonzalez et al. (2013); (m) Beguin et al. (2011); Caminade et al. (2014); Van Lieshout et al. (2004).

## Box 8: Projected Impacts of Climate Change in Key Sectors in the Middle East and North Africa Region

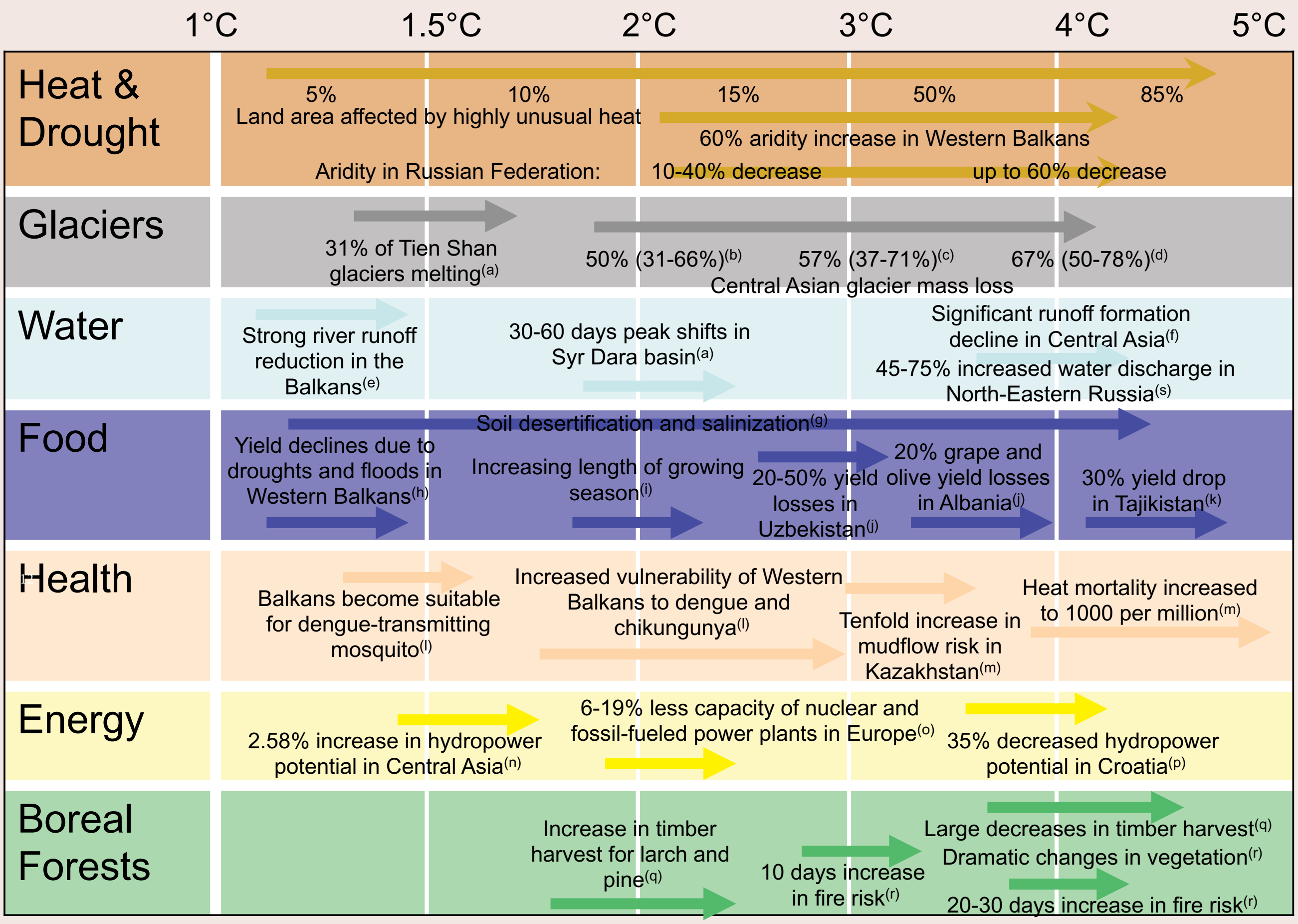
Warming levels are relative to pre-industrial temperatures. The impacts shown here are a subset of those summarized in Table 4.10 of the Main Report. The arrows solely indicate the range of warming levels assessed in the underlying studies; but do not imply any graduation of risk unless noted explicitly. In addition, observed impacts or impacts occurring at lower or higher levels of warming that are not covered by the key studies highlighted here are not presented (e.g., increase in drought and aridity is already observed, but the respective study does not assess impacts below 1.5°C). Adaptation measures are not assessed here although they can be crucial to alleviating the impacts of climate change. The layout of the figure is adapted from Parry (2010). The lower-case superscript letters indicate the relevant references for each impact.[11] If there is no letter, the results are based on additional analyses for this report.




[11] (a) Evans (2008); (b) several studies, see Table 4.1; (c) Bokurt and Sen (2013); (d) Samuels et al. (2010); (e) Giannakopoulos et al. (2013); (f) van Lieshout et al. (2004); (g) Kolstad and Johansson (2011); (h) Brown et al. (2011); (i) Dasgupta et al. (2009).

## Box 9: Projected Impacts of Climate Change in Key Sectors in the Europe and Central Asia Region

Warming levels are relative to pre–industrial temperatures. The impacts shown here are a subset of those summarized in Table 5.7 of the Main report. The arrows solely indicate the range of warming levels assessed in the underlying studies but do not imply any graduation of risk unless noted explicitly. In addition, observed impacts or impacts occurring at lower or higher levels of warming that are not covered by the key studies highlighted here are not presented (e.g., an increase in Tien Shan glacier melt is already observed, but the respective study does not assess the observed impacts). Adaptation measures are not assessed here, although they can be crucial to alleviating the impacts of climate change. The layout of the figure is adapted from Parry (2010). The lower-case superscript letters indicate the relevant references for each impact.[12] If there is no letter, the results are based on additional analyses conducted for this report.




[12] (a) Siegfried et al. (2012); (b) Marzeion et al. (2012); (c) Marzeion et al. (2012); Giesen and Oerlemans (2013); Radic et al. (2013); (d) Marzeion et al. (2012); Giesen and Oerlemans (2013); Radic et al. (2013); (e) Dimkic and Despotovic (2012); (f) Hagg et al. (2013); (g) Thurmann (2011); World Bank (2013f); World Bank (2013d); World Bank (2013a); (h) Maslac (2012); UNDP (2014); (i) Sutton et al. (2013a); Sommer et al. (2013); (j) Sutton et al. (2013a); (k) World Bank (2013m); (l) Caminade et al. (2012); (m) BMU and WHO-Europe (2009); (n) Hamududu and Killingtveit (2012); (o) van Vilet et al. (2012); (p) Pasicko et al. (2012); (q) Lutz et al. (2013b); (r) Tchebakova et al. (2009); (s) Schewe et al. (2013).

# Abbreviations

| | |
|---|---|
| **°C** | degrees Celsius |
| **$** | United States Dollars |
| **AI** | Aridity Index |
| **AOGCM** | Atmosphere-Ocean General Circulation Model |
| **AR4** | Fourth Assessment Report of the Intergovernmental Panel on Climate Change |
| **AR5** | Fifth Assessment Report of the Intergovernmental Panel on Climate Change |
| **BAU** | Business as Usual |
| **$CaCO_3$** | Calcium Carbonate |
| **CAT** | Climate Action Tracker |
| **CMIP5** | Coupled Model Intercomparison Project Phase 5 |
| **$CO_2$** | Carbon Dioxide |
| **DGVM** | Dynamic Global Vegetation Model |
| **DIVA** | Dynamic Interactive Vulnerability Assessment |
| **DJF** | December, January, and February (the winter season of the northern hemisphere) |
| **ECA** | Europe and Central Asia |
| **ECS** | Equilibrium Climate Sensitivity |
| **ENSO** | El-Niño/Southern Oscillation |
| **FAO** | Food and Agricultural Organization |
| **FPU** | Food Productivity Units |
| **GCM** | General Circulation Model |
| **GDP** | Gross Domestic Product |
| **GFDRR** | Global Facility for Disaster Reduction and Recovery |
| **GLOF** | Glacial Lake Outburst Flood |
| **HCS** | Humboldt Current System |
| **IAM** | Integrated Assessment Model |
| **IEA** | International Energy Agency |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ISI-MIP** | Inter-Sectoral Impact Model Intercomparison Project |
| **ITCZ** | Intertropical Convergence Zone |
| **JJA** | June, July, and August (the summer season of the northern hemisphere; also known as the boreal summer) |
| **LAC** | Latin America and the Caribbean |
| **LDC** | Least Developed Countries |
| **MAGICC** | Model for the Assessment of Greenhouse Gas Induced Climate Change |
| **MCMA** | The Mexico City Metropolitan Area |
| **MENA** | Middle East and North Africa |
| **MGIC** | Mountain Glaciers and Ice Caps |
| **NAO** | North Atlantic Oscillation |
| **NDVI** | Normalized Differenced Vegetation Index (used as a proxy for terrestrial gross primary production) |
| **NH** | Northern Hemisphere |
| **NPP** | Net Primary Production |
| **OECD** | Organization for Economic Cooperation and Development |
| **PDSI** | Palmer Drought Severity Index |
| **PgC** | Petagrams of Carbon (1 PgC = 1 billion tons of carbon) |
| **ppm** | Parts Per Million |
| **PPP** | Purchasing Power Parity (a weighted currency based on the price of a basket of basic goods, typically given in US dollars) |
| **RCM** | Regional Climate Model |
| **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 |

**TgC** Teragrams of Carbon (1 TgC = 1 million tons of carbon)
**UNCCD** United Nations Convention to Combat Desertification
**UNDP** United Nations Development Programme
**UNEP** United Nations Environment Programme
**UNFCCC** United Nations Framework Convention on Climate Change
**UNHCR** United Nations High Commissioner for Refugees
**USAID** United States Agency for International Development
**WBG** World Bank Group
**WGI** Working Group I (also WGII, WGIII)
**WHO** World Health Organization

# 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, all of which share the limited range of climatic and environmental conditions within that biome.

**C3/C4 plants:** C3 and C4 refer to two types of photosynthetic biochemical pathways. C3 plants include more than 85 percent of plants (e.g., most trees, wheat, rice, yams, and potatoes) and respond well to moist conditions and to additional $CO_2$ in the atmosphere. C4 plants (e.g., savanna grasses, maize, sorghum, millet, and sugarcane) are more efficient in water and energy use and outperform C3 plants in hot and dry conditions.

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

**$CO_2$ fertilization:** The $CO_2$ fertilization effect refers to the effect of increased levels of atmospheric $CO_2$ on plant growth. It may increase the rate of photosynthesis mainly in C3 plants and increase water use efficiency, thereby causing increases in agricultural productivity in grain mass and/or number. This effect may to some extent offset the negative impacts of climate change on crop yields, although grain protein content may decline. Long-term effects are uncertain as they heavily depend on a potential physiological long-term acclimation to elevated $CO_2$ and other limiting factors, including soil nutrients, water, and light. (See also Box 2.4 on the $CO_2$ fertilization effect on crop productivity.)

**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-projection data. The project provided a framework for coordinated climate change experiments and includes simulations for assessment in the IPCC AR5.

**Development narratives:** Development narratives highlight the implications of climate change impacts on regional development. The *Turn Down the Heat* series, and in particular this report, discuss the potential climate change impacts on particularly vulnerable groups along distinct storylines—the so called development narratives. These development narratives were developed for each region in close cooperation with regional World Bank specialists. They provide an integrated, often cross-sectoral analysis of climate change impacts and development implications at the sub-regional or regional level. Furthermore, the development narratives add to the report by allowing the science-based evidence of physical and biophysical impacts to be drawn out into robust development storylines to characterize the plausible scenarios of risks and opportunities—showcasing how science and policy interface.

**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 forcing (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 100–300 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 product. It is calculated without deductions for depreciation of fabricated assets or for depletion and degradation of natural resources.

**GDP PPP:** This is GDP on a purchasing power parity basis divided by population. Whereas PPP estimates for OECD countries are quite reliable, PPP estimates for developing countries are often rough approximations.

**Highly unusual and Unprecedented:** In this report, *highly 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 depends on the natural year-to-year variability in the base period (1951–1980), which is captured by the standard deviation (sigma). Highly 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 highly 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 over the lifetime of key ecosystems and human infrastructure.

**Hyper-aridity:** This refers to land areas with very low Aridity Index (AI) scores, 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 provide a comprehensive overview of the most recent scientific, technical, and socioeconomic information on climate change and its implications. The Fourth Assessment Report (AR4) was published in 2007. The Fifth Assessment Report (AR5) was published 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 and socioeconomic scenarios. More than 30 models across five sectors (agriculture, water resources, biomes, health, and infrastructure) were incorporated in this modeling exercise.

**Pre-industrial Level (what it means to have present 0.8°C warming):** Pre-industrial level refers to the level of warming before/at the onset of industrialization. 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 the 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 1901–2010 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. However, global greenhouse-gas emissions at the end of the 19th century were still small and uncertainties in temperature reconstructions before this time are considerably larger.

**RCP:** Representative Concentration Pathways 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 such environmental factors 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 inputs for climate modeling. These radiative forcing trajectories are not associated with unique socioeconomic or emissions scenarios; instead, they can result from different combinations of economic, technological, demographic, policy, and institutional futures. RCP2.6, RCP4.5, RCP6 and RCP8.5 refer, respectively, to a radiative forcing of +2.6 $W/m^2$, +4.5 $W/m^2$, +6 $W/m^2$ and +8.5 $W/m^2$ in the year 2100 relative to pre-industrial conditions.

**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 pre-industrial levels. This emissions path is used by many studies that have been assessed for the IPCC 5th Assessment Report and is the underlying low emissions scenario for impacts assessed in other parts of this report. In this report, the RCP2.6 is referred to as a 2°C world (with the exception of sea-level rise, where the subset of model used actually leads to 1.5°C world—see Box 2.1, Definition of Warming Levels and Base Period in this Report).

**RCP8.5:** RCP8.5 refers to a scenario with a no-climate-policy baseline with comparatively high greenhouse gas emissions which is used by many studies that have been assessed for the 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 RCP8.5 is referred to as a 4°C world above the pre-industrial baseline period.

**Severe and extreme:** These terms indicate uncommon (negative) consequences. These terms are often associated with an additional qualifier like "highly unusual" or "unprecedented" that has a specific quantified meaning.

**SRES:** The Special Report on Emissions Scenarios, published by the IPCC in 2000, has provided the climate projections for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change. The scenarios do not include mitigation assumptions. The SRES study included consideration of 40 different scenarios, each making different assumptions about the driving forces determining future greenhouse gas emissions. Scenarios were grouped into four families (A1FI, A2, B1 and B2), corresponding to a wide range of high- and low-emissions scenarios.

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

**Tipping element:** Following Lenton et al. (2008), the term tipping element describes large scale components of the Earth system possibly passing a tipping point. A tipping point "commonly refers to a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system" (Lenton et al. 2008). The consequences of such shifts for societies and ecosystems are likely to be severe.

**Virtual water:** A measure of the water resources used in the production of agricultural commodities. International trade in such commodities thereby implies a transfer of virtual water resources from one country to another embedded in the products.

**WGI, WGII, WG III:** IPCC Working Group I assesses the physical scientific aspects of the climate system and climate change. IPCC Working Group II assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change, and options for adapting to it. IPCC Working Group III assesses the options for mitigating climate change through limiting or preventing greenhouse gas emissions and enhancing activities that remove them from the atmosphere.

# Chapter 1

# Introduction

This report describes the challenges for development and poverty reduction under anthropogenic climate change in Latin America and the Caribbean (LAC), the Middle East and North Africa (MENA), and Europe and Central Asia (ECA). Climate change projections are presented for each region alongside an assessment of the most recent literature on climate change impacts that are expected in key sectors for different warming levels, from the current baseline of 0.8°C through to 2°C and 4°C above pre-industrial levels in 2100. These impacts are then discussed in relation to existing social vulnerabilities to stress the implications of biophysical climate change impacts for development in the different regions. In order to provide a better understanding of how climate change and its expected impacts may affect development, storylines—referred to here as development narratives—are presented. These follow the chain of impacts from the physical to the biophysical and social level and specify how climate change could affect human well-being. Attention is paid to the specific ways in which different population groups are affected. The development narratives stress plausible scenarios and plausible impacts rather than giving probability ranges for the impacts estimated. Following the chain of impacts, the assessment shows that climate change poses severe challenges for human wellbeing and development, with the poor and underprivileged often hardest hit.

The recent publications of the Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) show that greenhouse gas emissions have continued to increase and in fact have accelerated toward the end of the 2000s (IPCC 2014a). Global mean temperature has already increased by 0.8°C from 1880–2012 (IPCC 2013a), and climate change impacts are increasingly being experienced on all continents and across a range of human and natural systems (IPCC 2014b). More severe impacts are projected with further warming, and the resulting challenges for eradicating poverty and promoting human wellbeing could be immense. If efforts and achievements in reducing greenhouse gas emissions continue at the current pace, warming levels of higher than 4°C cannot be ruled out.

Recent efforts to project the effects of current national policies indicate that there is about a 40 percent chance of exceeding 4°C warming above pre-industrial levels by about 2100. Critically, timing is of the essence. With rising temperatures, the risks for human lives and development trajectories increase, and a number of impacts will soon be locked in for decades, if not for centuries to come. For example, if present temperatures were to be maintained, the world would be committed to around 2.3 m of sea-level rise over the next 2,000 years. However sea levels would rise to around 3.6 m under a 2°C warming scenario, and to around 8 m over the same period under a 4°C scenario (Levermann et al. 2013). It is also important to note that greenhouse gas emissions and concentrations leading to a warming of 4°C by 2100 would commit the world to much higher warming levels exceeding 6°C or more in the long term (IPCC 2013b).

This report takes as its starting point the IPCC´s 5th Assessment Reports. In addition it provides regional and sub-regional narratives on the implications of climate impacts on development. The report emphasizes topics that are of particular relevance for the focus regions and considers scientific studies published after the literature cutoff dates of the AR5. It thus takes up the guiding questions of the first two *Turn Down the Heat* reports (World Bank 2012a; 2013) by focusing on three previously not assessed regions and digging deeper into the social and development consequences of climate change for those affected. It does so along the following lines of inquiry:

1. What are the key biophysical climate change impacts in the case study regions under different levels of warming (particularly 2°C and 4°C)?

2. What are the crucial development impacts triggered by the biophysical impacts of climate change within and across sectors?
3. What are the implications of climate change impacts (physical, biophysical, and social) for (differential) social vulnerability within the case study regions?

Through extensive data analysis and literature review, this report shows that the mitigation of greenhouse gas emissions that cause climate change, adaptation to the consequences, and coping with the unavoidable impacts, must be part and parcel of the fight against poverty if risks are to be minimized and benefits promoted. The biogeographic and development context of the three regions defines the nature and extent of climate impacts and the discussion of the development implications. For example:

- **Latin America and the Caribbean** is a highly heterogeneous region in terms of economic development and social and indigenous histories. The rural poor depend on their natural resource base, including subsistence agriculture and ecosystem services. In the Andean region, housing built on steep terrain is critically exposed to heavy precipitation events, landslides, and glacial lake outbursts associated with glacial melt. Coastal livelihoods, particularly in the Caribbean region, face the risks of degrading marine ecosystems and coastal flooding, concurrent with damage to critical infrastructure and freshwater supplies.
- **The Middle East and Northern Africa** relies heavily on agriculture as a source of food and income, not only in the historically important fertile crescent of the Euphrates and Tigris region but also at the Mediterranean coast and along the Nile. At the same time, much of the region is covered by drylands and deserts. Seventy percent of the agricultural production is currently rain-fed, which leaves the region highly vulnerable to the consequences of changes in precipitation patterns and temperature changes—with associated consequences for food security, social security, and rural livelihoods. This, in combination with social changes and strong urbanization rates, marks a very vulnerable future for the region, particularly for both the urban and rural poor.
- **Europe and Central Asia** encompasses a wide terrain of geographic features ranging from the mountainous and partly coastal Western Balkans to the vast plains of Central Asia to the boreal forests of the Russian Federation. In climatic terms the region displays a clear dipole, whereby regions in the southwest are becoming drier and regions in the northeast are becoming wetter as the world warms toward 4°C. The most pronounced warming is expected to occur in two distinct regions: Northern Russia bordering the Barents-Kara Sea, and the Black Sea coastal region, including the Western Balkans. These changing conditions lead to a number of pronounced vulnerabilities, with a high risk of drought in the west and challenges for stable freshwater supplies in the east (where changes in precipitation combine with glacial melt to affect the seasonality of river discharge).

With a deliberate focus on the impacts of climate change, the report frames the critical need for adaptation, but an assessment of climate change adaptation options is outside the scope of this report. It is clear, however, from the evidence presented here that there are a range of low-hanging and no-regret adaptation options that could increase the resilience of natural and social systems across sectors. These include, among others, closing the yield gap between potential and actual agricultural yields through technological changes, climate-smart agriculture, and/or climate-smart urban development, as well as boosting health care systems in developing regions. The IPCC WGII provides a comprehensive review of these and other options (cf. IPCC 2014b).

Although adaptation is crucial to alleviate the impacts of climate change, the potential for additional adaptation, beyond current adaptation, to reduce risks of climate change impacts to low levels is limited even in a 2°C world (IPCC 2014c). In a 4°C world, the effectiveness of adaptation measures is thought to be even more limited for many systems and sectors, which will not be able to minimize risks by simply doubling the effort to adapt to a 2°C world. For example, an increasing severity and frequency in extreme events is likely to severely undermine a population's adaptive capacity for consecutive impacts (World Bank and GFDRR 2013). A 4°C world would also likely mean irreversible changes in the Earth system, with impacts materializing well after warming has stopped. It is thus clear that investments that boost the adaptive capacity of people are a must and it is also evident that climate change mitigation is required. The challenges that climate change poses are the focus of this report.

## 1.1 Development Narratives

Recent work has fostered understanding of what climate change means for development (World Bank 2010a) and decision making in the face of uncertainty (Hallegatte et al. 2012). The *Turn Down the Heat* series, and this report in particular, reports the potential impacts on particularly vulnerable groups along distinct storylines—the so-called development narratives. These development narratives provide an integrated, often cross-sectoral analysis of climate change impacts and development implications at the sub-regional and regional scale. The development narratives also add to the report by allowing the science-based evidence of physical and biophysical impacts to be effectively drawn out into robust development storylines to characterize the plausible scenarios of risks and opportunities—showcasing how science and policy interact. It is widely accepted that climate change affects particular socioeconomic groups, such as the poor, the elderly, children, and women, the hardest (Leichenko and Silva 2014). This report includes a framework for assessing climate change impacts in light of existing social vulnerability (see Box 1.1).

## Box 1.1: Social Vulnerability

Social vulnerability refers to the lack of capability of individuals, groups, or communities to cope with and adapt to external stresses placed on their livelihoods and wellbeing. This is determined by the availability of resources and by the entitlement of individuals and groups to call on these resources (Füssel 2012).

Social vulnerability, and how it differs according to socioeconomic and demographic conditions, is a common denominator in all three regions in this report. Examples of past extreme events expose the uneven distribution of impacts among different populations (IPCC 2014c), such as the impact of Hurricane Katrina in the United States or glacial lake outburst floods in the Peruvian Andes. They show that factors such as socioeconomic class, race, gender, and ethnicity affect the magnitude with which impacts are experienced. Such examples also show that it is the underprivileged in rich nations who bear high burden of climate impacts. In addition, such extremes as hurricanes, floods, and heat waves leave in their wake a trail of damage and human suffering which can extend well beyond the point of impact in terms of both time and space. Damages to supply chains can transmit impacts across an ever more globalized world and have long-lasting economic effects (Levermann 2014). Already under present levels of warming, which have reached about 0.8°C above pre-industrial levels, the number of local record-breaking monthly temperature extremes is around five times higher than would be expected if no warming had occurred (Coumou et al. 2013). As the IPCC WGI AR5 (IPCC 2013b) has shown, and as it is outlined in this report, the likelihood of extreme events is projected to increase under rising temperatures. While large uncertainties exist about the magnitude of the poverty effects of climate change and the scientific debate surrounding the issue is far from settled, the evidence demonstrates a major reason for concern.

## 1.2 Methodological Approach

The projections on changes in temperature, heat extremes, precipitation, aridity, and sea-level rise are based on original analysis of output from state-of-the-art General Circulation Models (GCM) (see Box 1.2 and Appendix). The development narratives combine knowledge that has been gained through large and small scale quantitative and qualitative research. The sectoral analysis for the three regions is based on existing literature. The literature review was almost exclusively conducted in the English language and it followed a prescribed hierarchy of sources: peer-reviewed scientific publications were given most weight, followed by peer-reviewed reports. Where these sources were lacking and additional information was obtainable from other sources, those were used (but least weight was given to them). As the studies assessed were not conducted within an integrated framework, their integration does not allow for a coherent analysis of overall impacts and human consequences. Rather, the causal pathways mapped out in the development narratives present possible scenarios that are based on assumptions drawn from the scientific literature and shaped by the close cooperation with regional development specialists. As a result, it is not feasible to provide uncertainty ranges of the likelihood of the scenarios presented in the development narratives. Rather, a risk-based approach indicating plausible high-impact consequences under 2°C and 4°C global mean warming was chosen to form a basis of further policy and research.

## Box 1.2: Climate Change Projections, Impacts, and Uncertainty

In this report the projections of future climate change and its sectoral impacts are based, necessarily, on modeling exercises. The quantitative 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 a selection of state-of-the-art Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models. Following Hempel et al. (2013), precipitation data was bias-corrected, such that it reproduces the historical mean and variation in precipitation. Results are reported as the mean of the models and their variability. 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, where possible conclusions are drawn from multiple lines of evidence across a range of methods, models, and data sources, including the Intergovernmental Panel on Climate Change Fifth Assessment Report and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC 2012).

## 1.3 Structure of the Report

The report is structured as follows. Chapter 2 explores the probability of warming reaching 4°C above pre-industrial levels and discusses the feasibility 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 first two *Turn Down the Heat* reports (World Bank 2012a; 2013) and provides a framework for the regional case studies. Chapter 2 also presents a framework for how social vulnerability and climate change interact. Chapters 3, 4 and 5 present analyses of climate impacts and the development narratives for the Latin America and the Caribbean, the Middle East and North Africa, and Europe and Central Asia regions respectively.

# Chapter 2

# The Global Picture

The Fifth Assessment Report (AR5) of the IPCC provides a very comprehensive analysis of the physical science basis and the observed and projected impacts of climate change as well as of the economics of climate change mitigation. The following chapter should be read as an addition to the AR5, with emphasis on topics that are of particular relevance for the focus regions of this report and where scientific studies published after the literature cutoff dates of the AR5 led to an update of the findings from IPCC for specific issues.

The IPCC projections always draw on the largest model ensemble available (which differs significantly in size ranging from less than 10 to more than 30 climate models). This report restricts most of the projections presented in this chapter and throughout to five state-of-the-art CMIP5 models that are bias-corrected and used in the ISI-MIP framework (see Appendix). Although the robustness of projections based on smaller ensembles is generally lower, this approach allows for direct comparison between different impacts in an impact cascade (e.g., of changes in precipitation patterns, river discharge, and agricultural impacts).

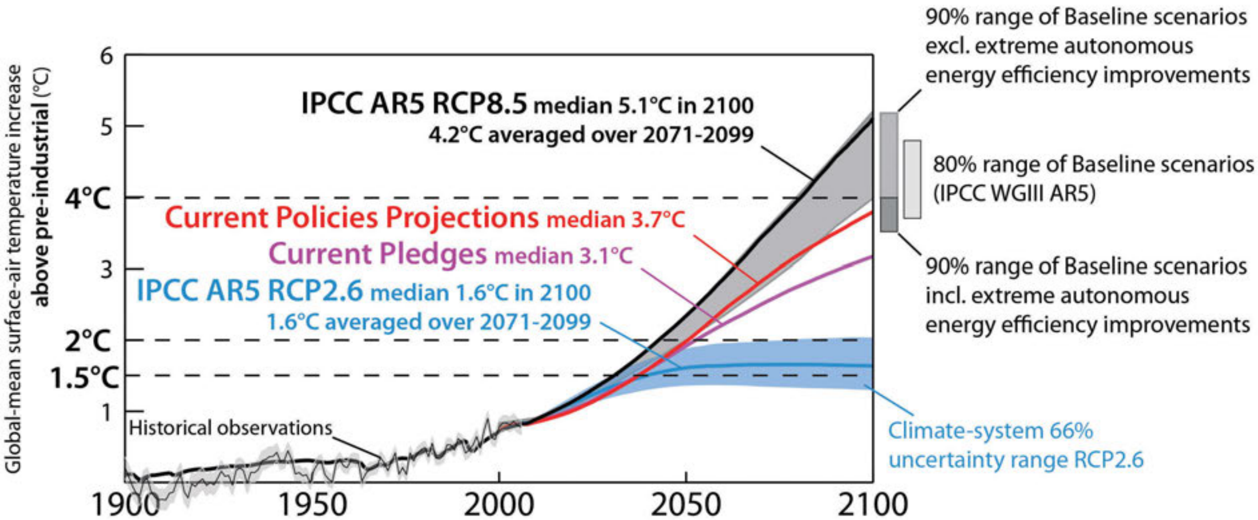
## 2.1 How Likely is a 4°C World?

The previous *Turn Down the Heat* reports estimated that current emissions reductions pledges by countries worldwide, if fully implemented, would lead to warming exceeding 3°C before 2100. New assessments of business-as-usual emissions in the absence of strong climate mitigation policies, as well as recent reevaluations of the likely emissions consequences of pledges and targets adopted by countries, point to a considerable likelihood of warming reaching 4°C above pre-industrial levels within this century.

- Assessments of recent trends and "current policies" in the world's energy system analyzed 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. Another assessment, by Climate Action Tracker, of these trends and policies leads to a warming of 3.7°C, about 0.6°C higher than the median estimate of the effect of the Copenhagen pledges in this assessment.[12] As a consequence, it is projected on the basis of these assessments that under recent trends and current policies there is about a 40 percent chance of exceeding 4°C by 2100 and a 10 percent risk of exceeding 5°C.
- Based on a sample of 114 energy-economic model scenarios estimating emissions in the absence of further substantial policy action (baseline scenarios), climate-model projections reach a warming of 4.0–5.2°C above pre-industrial levels by 2100 (95 percent range of scenarios—grey shaded area Figure 2.1) (Blanford et al. 2014; Kriegler et al. 2013; Kriegler, Tavoni et al. 2014; Kriegler, Weyant et al. 2014; Luderer et al. 2013; Riahi et al. 2013; Tavoni et al. 2014). Only under extreme assumptions regarding autonomous improvements leading to large decreases in energy intensity and an energy demand by 2100 (e.g., 35–40 percent lower than under default assumptions) (Blanford et al. 2014; Kriegler, Weyant et al. 2014) does the lower end of the baselines' 95 percent range decrease to below 4°C (3.5°C) in 2100.
- The IPCC Working Group III Fifth Assessment Report assessment of baseline scenarios leads to a warming of 3.7–4.8°C by 2100 (80 percent range of scenarios; 2.5–7.8°C including climate-system uncertainty), which includes the scenarios with assumptions on autonomous improvements in energy intensity.

[12] http://climateactiontracker.org/news/151/In-talks-for-a-new-climate-treaty-a-race-to-the-bottom.html.

**Figure 2.1:** Projections for surface-air temperature increase, showing the scenarios assessed in this report in the context of baseline projections (no further substantial climate policy from the recent energy-economic model literature).




The medium-dark-grey shaded area (bar on right-hand side indicates year-2100 range) indicates the 90 percent uncertainty range over 114 baseline scenarios from the literature, excluding a class of variants that assume very high autonomous improvements in energy intensity. The dark-grey range on the right-hand side indicates the broadening of the 90 percent scenario range, if one includes these variants. For comparison, the light-grey area indicates the 80 percent range over all scenarios, as assessed in IPCC WGIII AR5 (2014d). The climate model underlying these calculations is the same as applied for all emissions scenarios in the IPCC WGIII AR5 (2014d). The climate-system uncertainty derived from such modeling is depicted for RCP2.6 as the blue-shaded area (66 percent uncertainty). Note that the estimates here are comparable to the full CMIP5 model range, which are slightly cooler at the end of the 21st century than the ISI-MIP subset of CMIP5 models used for most projections in this report (see Appendix). In this subset, the RCP 2.6 scenario represents a 1.8°C warming and the RCP 8.5 represents a 4.6°C warming above pre-industrial levels for the period 2081–2099.

- In relation to the effects of pledges, the updated UNEP Emissions Gap Assessment 2013 (UNEP 2013) assessed present emissions trends and pledges. Global emissions estimated for 2020 are consistent with emissions pathways that reach warming in the range of 3–5°C by 2100,[13,14] and are closest to levels consistent with pathways leading to 3.5–4°C warming by 2100.

On average, the RCP8.5 is illustrative of a range of business-as-usual scenarios,[15] reaching 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 (Figure 2.1). The IPCC AR5 WGI noted that 62 percent of high-complexity climate models exceed 4°C for RCP8.5 by the 2080s,[16] and all model runs exceed 3°C (IPCC 2013b). These AR5 model runs were designed to take into account a fixed pathway of concentrations and do not, therefore, include the effects of carbon-cycle feedbacks on the response of the climate system to $CO_2$ emissions. Including these feedbacks raises the median estimate of warming in RCP8.5 from 4.3 to 4.5°C by the 2080s and widens the total uncertainty, in particular at the high-temperature end, from 3.2–5.3°C to 3.1–6.2°C by that time, relative to pre-industrial levels (Collins et al. 2013).

### 2.1.1 Can Warming be Held Below 2°C?

Climate policy has not to date succeeded in curbing global greenhouse gas emissions, and emissions are steadily rising (Peters et al. 2013). However, recent high-emissions trends do not imply a lock-in to a high-emitting pathway (van Vuuren and Riahi 2008) if there is a move toward rapid, technically and economically feasible mitigation. As was confirmed in the 2013 UNEP Emissions Gap Report (UNEP 2013) and in successive International Energy Agency Assessments (International Energy Agency 2013), there are many measures that could close the gap between estimated global

[13] The Climate Action Tracker projections of the effects of pledges if fully implemented is about 3.1°C warming by 2100 (median estimate)—i.e., at the lower end of this range.
[14] This applies to the "unconditional pledges, strict rules" case.
[15] Not including those with extreme assumptions on autonomous improvements in energy intensity.
[16] A probability of >66 percent is labeled "likely" in IPCC's uncertainty guidelines adopted here.

## Box 2.1: Definition of Warming Levels and Base Period in This Report

This report and the previous *Turn Down the Heat* reports reference future global warming levels against the pre-industrial period 1850–1900 consistent with the IPCC WGI AR5.

To study the impacts of climate change at different levels of global mean warming in this report, the literature and present climate impacts for different warming levels above the pre-industrial period were reviewed using the following classification:

| WARMING CATEGORY | OBSERVED | 1°C | 1.5°C | 2°C | 3°C | 4°C |
|---|---|---|---|---|---|---|
| **Range [°C]** | <0.8 | 0.8–1.25 | 1.25–1.75 | 1.75–2.25 | 2.25–3.5 | >3.5 |

Given the diversity of different base periods for projections, emissions scenarios, and models or model ensembles used, this report adopts a standardized approach to convert any given warming level with any given base period to its corresponding warming level relative to the pre-industrial period (see Appendix). This allows, within limits, for a classification of climate impacts independent of the underlying emissions scenario and model or model ensemble used. This stringent approach of classifying warming levels is new in this *Turn Down the Heat* report and allows for a consistent comparison of climate change impacts across studies and sectors.

Median warming for the full CMIP5 model ensemble under the RCP2.6 is about 1.6°C (and therefore on the border between the 1.5° and 2°C warming categories presented above); 22 percent of the models nonetheless projecting a warming above 2°C. For the estimation of heat extremes, precipitation, and aridity, this report uses a subset of the CMIP5 models (as in the ISI-MIP project) showing a median warming of 1.8°C above pre-industrial levels by 2081–2100 for the RCP 2.6 scenario. As in the earlier reports, impacts in a "2°C world" refer to the impacts assigned to the 2°C warming category. Where the results of the ISI-MIP ensemble for RCP 2.6 are used to describe a 2°C world, readers need to be aware that this is at the low end of the 2°C impact category. Sea-level rise projections presented in this report are based on a larger model ensemble with an ensemble mean warming of less than 1.75°C; as a result, end-of-century sea-level rise in RCP2.6 is classified as 1.5° warming.

The "4°C world" refers to impacts assigned to the 4°C category as described above. The median warming of the RCP8.5 CMIP5 ensemble for the period 2081–2100 is 4.3°C, whereas the projected warming for the ISI-MIP ensemble (used to project heat extremes, precipitation, and aridity) is 4.6°C above pre-industrial levels (and thus at the high end of the 4°C warming category). Impacts shown in tables refer to the exact warming category above pre-industrial levels, as they allow for more detail than the stylistic futures drawn at 2°C and 4°C global mean warming.

The terms "2°C world" and "4°C world" always refer to end-of-21st-century impacts' for impacts referring to earlier time periods the convention of "2°C warming by 20xx" is chosen.

greenhouse gas emissions levels by 2020 and levels consistent with pathways that keep warming below 2°C. The required emission reductions over the 21st century, were estimated by IPCC WGIII AR5 to lead to an annualized reduction in consumption growth limited to 0.04–0.14 percentage points, relative to baseline growth of 1.6–3 percent per year (IPCC 2014d). This does not include the co-benefits, including for example health and environmental benefits from reduced co-emited air pollutants, fuel poverty reductions and net employment gains (IPCC 2014d). Delaying additional mitigation increases mitigation costs in the medium- to long-term.

The recent IPCC AR5 WGI (summary for policymakers) showed that "warming is unlikely to exceed 2°C for RCP2.6" and "likely to exceed 1.5°C . . . for all RCP scenarios except RCP2.6" (IPCC 2013a). The energy-economic modeling behind the RCP2.6 emissions scenario (van Vuuren et al. 2011) shows that large-scale transformations in the energy system are feasible to achieve the low emissions levels of RCP2.6 and net-negative global energy-related $CO_2$ emissions by the 2070s. The IPCC WGIII AR5 showed that there is a broad category of low-emissions mitigation scenarios that reach emissions levels comparable to or lower than RCP2.6 (IPCC 2014d). On average, these scenarios also reach net-zero $CO_2$ emissions by 2070 [2060 to 2080]. The lowest published emissions scenarios in recent literature (Luderer et al. 2013; Rogelj et al. 2013a; Rogelj et al. 2013b) lead to warming projected to peak at around 1.5°C and decline to a median level of 1.3°C above pre-industrial by 2100.

## 2.2 Climate Sensitivity and Projected Warming

Although the past decade has been the warmest on record globally, observations suggest that the rate of warming during the last decade has been slower than earlier decades. This has led to discussions of a so-called "warming hiatus", for example in the IPCC AR5 WGI:

> "In summary, the observed recent warming hiatus, defined as the reduction in GMST trend during 1998–2012 as compared to the trend during 1951–2012, is attributable in roughly equal measure to a cooling contribution from internal variability and a reduced trend in external forcing (expert judgment, medium confidence)." (Stocker et al. 2013, Box TS.3)

Slower and faster decades of warming occur regularly, related to variations in forcing (e.g., volcanic eruptions, solar activity) and to internal redistribution of heat in the oceans driven by large-scale patterns of climate variability (including the El Niño/La Niña-Southern-Oscillation—see also Section 2.3.2) causing natural variations of surface warming (Balmaseda et al. 2013; England et al. 2014; Foster and Rahmstorf 2011).[17] An additional factor is data uncertainty. Without taking data uncertainties or the physical explanation of a remaining "hiatus" into account, 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. IPCC AR5 WGI estimated equilibrium climate sensitivity (ECS) at 1.5–4.5°C, which has a lower low-end estimate than the IPCC AR4 at 2–4.5°C. On the contrary, values substantially higher than 4.5°C still cannot be ruled out.

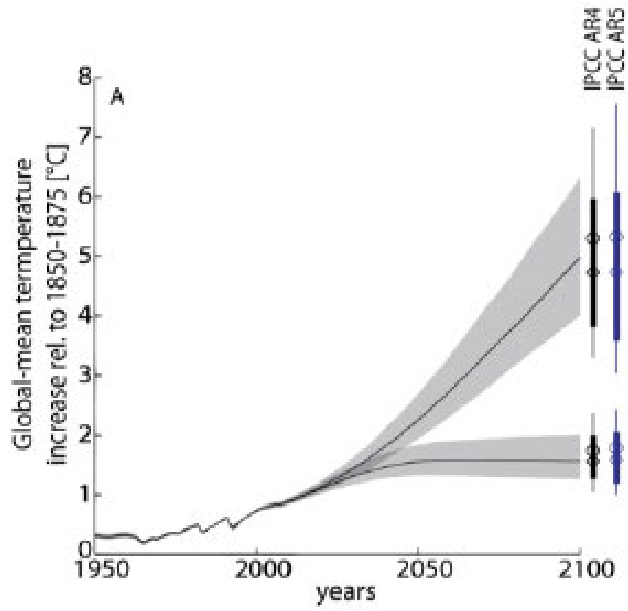
Climate projections for the 21st century are, however, not highly sensitive to *equilibrium* warming estimates. Rogelj et al. (2014) evaluated the implications of both AR4 and AR5 assessments of ECS in a climate-model framework. While the uncertainty ranges of global-mean temperature increases by 2100 for RCP2.6 and RCP8.5 are slightly wider for the AR5 than for the AR4 model version, the difference is small and the median estimates are virtually unaffected (Figure 2.2). Hence, a change in estimated equilibrium climate sensitivity, among others informed by a recent warming hiatus, has no significant effect on the climate projections presented in this report.

## 2.3 Patterns of Climate Change

This report gives an update of the projected patterns of climate change presented in the earlier *Turn Down the Heat* reports with a particular focus on temperature and precipitation extremes as well as changes in droughts and river runoff.

[17] This can be explained by natural external forcings, like those of solar and volcanic origin, and physical mechanisms within the climate system itself. This includes a large role played by the El Niño/La Niña-Southern-Oscillation, 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 datasets before comparing with model results.

**Figure 2.2:** Climate-model projections of global-mean surface-air temperature for RCP2.6 (lower curves) and RCP8.5 (top curves).

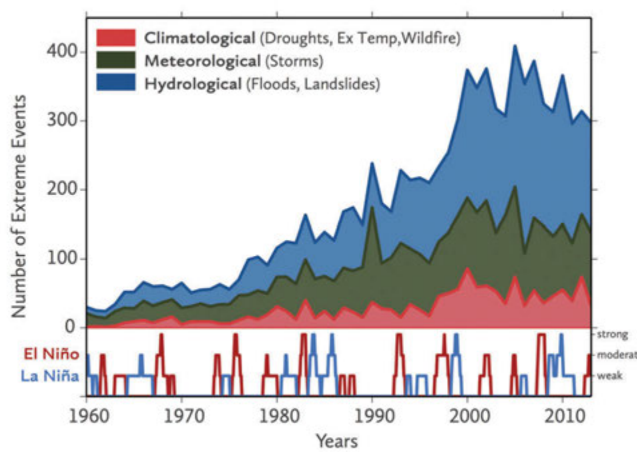



Lines indicate median estimates, grey shaded areas 66 percent uncertainty ranges, consistent with the AR4 assessment of equilibrium climate sensitivity (2–4.5°C). On the right-hand side, the increases averaged over the years 2081–2100 are shown for both the model version constrained by a representation of the AR4 assessment and the AR5 (blue) assessment (1.5–4.5°C). Bold right-hand side columns show a 66 percent uncertainty range, thin columns a 90 percent range, diamonds median estimate, circles mean estimates (higher than the median, because of skewed probability distributions due to significant likelihood of very high climate sensitivity values). Source: Rogelj et al. (2014).

### 2.3.1 Observed Trends in Extreme Events

Since the 1960s, a robust increase in the number and magnitude of hot temperature extremes is observed globally that is consistent with the increase in global mean temperature over the same time period (Donat, Alexander et al. 2013; Seneviratne et al. 2012). Consequently, the recent IPCC AR5 assesses a human contribution to this trend as very likely (IPCC 2013a). Coumou et al. (2013) find that new record-breaking monthly mean temperatures can be attributed to climate change with an 80 percent probability. Despite a decade of slowed-down global mean temperature increase, the number of observed hot temperature extremes is continuously on the rise—with a trend that is strongest for the most extreme events (Seneviratne et al. 2014; Sillmann et al. 2014). At the same time, an increase in frequency and duration of heat waves has been

**Figure 2.3:** ENSO and extreme events.




Upper panel: Number of climate-related disasters from 1960–2013 (based on the EM-DAT database[18]). A robust increase in all types of climate-related disasters is observed. Lower panel: El Niño and La Niña events identified on the basis of the Niño 3.4 sea-surface temperature index.[19]

observed globally, although trends differ strongly among regions (Donat, Alexander et al. 2013; IPCC 2013a, Table SPM.1).

Unlike the patterns of change for extreme temperature indices, changes in extreme precipitation appear to be more heterogeneous. Significant increases both in frequency and intensity of heavy precipitation events are observed over eastern North America, large parts of Eastern Europe, Asia, and South America; a decrease is reported for the Mediterranean, South East Asia, and the northwestern part of North America (Donat, Alexander et al. 2013). While being spatially heterogeneous, most areas of the globe experience an increase in precipitation extremes—and a human contribution to this increase can be clearly identified (IPCC 2013a, Table SPM.1; Min et al. 2011). The median intensity of extreme precipitation is found to increase by about 6–8 percent per degree rise in global mean temperature (Kharin et al. 2013; Trenberth 2011; Westra et al. 2013). Figure 2.3 illustrates the increase in precipitation-related disasters recorded in the EM-DAT database since the 1960s.

While the observed changes in heavy precipitation are statistically robust and the level of agreement between different studies and datasets is high for most world regions (Donat et al. 2014), this is not the case for dry spells and droughts (Dai 2012; Donat, Alexander et al. 2013; Sheffield et al. 2012; Trenberth et al. 2014). Although global trends remain uncertain, robust drying signals emerge from the observational record (e.g., for the Mediterranean) (Donat, Peterson et al. 2013; Hoerling et al. 2012; Sousa et al. 2011). Additionally, a strengthening in the seasonal cycle and regional contrast has been observed, meaning that the strongest increase in heavy precipitation events has been found during wet seasons of already wet regions, while the strongest drying signals emerge during the dry season of already dry areas (Chou et al. 2013); this further amplifies flood and drought risks in the respective regions.

Despite a substantial increase in meteorological disasters recorded in the EM-DAT database (compare Figure 2.3) that are related to tropical and extra-tropical storms, confidence in large-scale trends in meteorological indices remains low for extra-tropical storms and tropical cyclones as well as for such small-scale meteorological events as hail and thunderstorms (Stocker et al. 2013, TS.2.7.1). For tropical cyclones, however, a robust global trend in poleward migration is observed (Kossin et al. 2014). At the same time, the frequency and intensity of the strongest tropical cyclones have increased significantly in the North Atlantic since the 1970s (Grinsted et al. 2012; IPCC 2013a, Table SPM.1; Kossin et al. 2013) with profound consequences for the Caribbean, Central America, and southeastern-North America.

A steep rise in climate-related disasters by one order of magnitude from about 30 in the early 1960s to more than 300 in the early 21st century (trend: approximately 70 events per decade from 1960–2014) is apparent from the EM-DAT database (see Figure 2.3). The absolute values of this increase should be interpreted with caution, since this signal is distorted by an increase in climate-related disaster reporting over the same time frame that is very difficult to quantify. Still, this increase in climate-related disaster reporting is assumed to have happened predominantly before the mid-1990s (and the advent of modern information technology); while the number of disasters counted nearly doubled between the mid-1990s and 2010–2014.

Although not necessarily as strong as for climate-related disasters, such an increase in reporting is also assumed to be responsible for the observed increase in geophysical disasters (volcanic eruptions and earthquakes). This trend, however, is an order of magnitude smaller than what has been observed for climate-related extremes (about 6.5 events per decade over 1960–2014). A robust trend also

[18] EM-DAT: The OFDA/CRED International Disaster Database. Available at www.emdat.be.

[19] Following NOAA guidelines, the index is derived based on running-mean 3-month SST anomalies in the Niño 3.4 region (5°N–5°S, 120°–170°W)]. At least five consecutive overlapping 3-month periods above 0.5°C (below –0.5°C) are identified as El Niño (La Niña) events. El Niño events are classified as weak (moderate) if at least three consecutive overlapping 3-month periods exceed 0.5°C (1°C) and as strong if they exceed 1.5°C. La Niña events are similarly classified. Source: NOAA, Oceanic Niño Index (ONI).

emerges from the analysis for severe climatological disasters, for which a reporting bias can be assumed to be absent. Thus, the increase in climate-related disasters in the EM-DAT database can be attributed in part to climate change, but the exact influence of increased reporting cannot be quantified. The lower panel of Figure 2.3 depicts the time series of the El Niño Southern Oscillation index highlighting low, moderate, and strong El Niño and La Niña events that have a profound imprint on the tropical climate regime and extreme events statistics globally.

## 2.3.2 El-Niño/Southern Oscillation

One of the largest sources of climate variability in terms of scale and impact is the El Niño/Southern Oscillation (ENSO). ENSO is a coupled atmosphere-ocean phenomenon in the tropical Pacific region and the dominant global mode of variability on an interannual timescale. Although substantial uncertainties remain with respect to how ENSO will respond to rising atmospheric temperature, recent model intercomparison studies suggest a trend toward more extreme El Niño events over the 21st century (Cai et al. 2014; Power et al. 2013).

During El Niño events, the heat that is stored in the ocean is released into the atmosphere, leading to changes in the tropical atmospheric circulation (see Box 2.2) and, consequently, to variations in weather patterns around the world. Anomalous El Niño-type conditions are related to disastrous flooding events in Latin America and droughts in Australia and large areas of South East Asia, and can have far-reaching effects on the Atlantic hurricane activity and the global monsoon system (e.g. Donnelly and Woodruff (2007); Kumar et al. (2006)). All these changes can substantially impair livelihoods (e.g., through impacts on agricultural productivity, infrastructure, and public health) (Kovats et al. 2003; Wilhite et al. 1987). For example, the extreme El Niño of 1997–98 resulted in billions of dollars of economic damages and tens of thousands of fatalities worldwide, with severe losses in Latin America in particular (McPhaden et al. 2006; Vos et al. 1999). Recent research has also suggested an ENSO influence on the risk of civil conflict around the world (Hsiang et al. 2011).

### *2.3.2.1 Observed Changes in ENSO*

It seems unlikely that a complex system consisting of numerous feedback mechanisms would not be affected by anthropogenic global warming (Collins et al. 2010). The amplitude, frequency, seasonal timing, and spatial pattern of ENSO events, as well as their links to weather patterns around the world, might all be altered in what could potentially be one of the most prominent manifestations of climate change (Guilyardi et al. 2012; Vecchi and Wittenberg 2010). But the instrumental record is short and so far yields no clear indication of a climate change effect on ENSO, even though such an effect may already be occurring but obscured by natural inter-decadal variability (Christensen et al. 2013; Latif and Keenlyside 2009; Stevenson et al. 2012; Wittenberg 2009). A tree-ring-based reconstruction of ENSO strength suggests that ENSO over the past 700 years has never been as variable as during the last few decades, and that the ENSO cycle thus may have intensified due to global warming (Jinbao et al. 2013).

### *2.3.2.2 ENSO Projections*

Despite model uncertainties, there is high confidence that the mean climate in the tropical Pacific will change under global warming. It is likely that these changes will affect ENSO through one or several of the associated atmospheric or oceanic feedbacks; but models disagree on the exact nature of the ENSO changes (Collins et al. 2010; Guilyardi et al. 2012; Latif and Keenlyside 2009; Power et al. 2013).

Some robust evidence of changes to ENSO-driven precipitation variability in response to global warming has emerged recently, and it represents an update to the assessment of ENSO projections in the IPCC AR5. A majority of GCMs shows that the rainfall anomalies associated with El Niño events in the tropical Pacific (i.e., dry conditions in the west and more abundant rainfall in the central and eastern Pacific) will become stronger (Power et al. 2013) and impacts of El Niño thus more intense. This result is consistent with another study showing a major increase in the frequency of extreme El Niño events (Cai et al. 2014). These particularly strong events have caused devastating impacts (recent examples include the 1982–83 and the 1997–98 El Niño events) and GCMs that are able to simulate such events project approximately a doubling in frequency in a 4°C world (Cai et al. 2014).

## 2.3.3 Projected Changes in Extreme Temperatures

Figure 2.5 depicts projected regional boreal summer (JJA) warming by 2071–2099 for a 4°C world (RCP8.5) and a 2°C world (RCP2.6). The upper panels show the northern hemisphere summer temperature anomalies relative to the 1951–1980 base period for the 4°C world (RCP8.5) and the 2°C world (RCP2.6). In a 2°C world, summer warming anomalies exceed 2°C for large areas of the Northern Hemisphere; this regional warming is enhanced disproportionally for some regions in a 4°C world, where up to 8°C boreal summer warming is reached in northern central Russia and in the western United States. In addition, the Mediterranean appears as a warming hotspot; so do Northern Africa and Central Asia, which is likely due to regional amplification as a result of a drying trend in these regions.

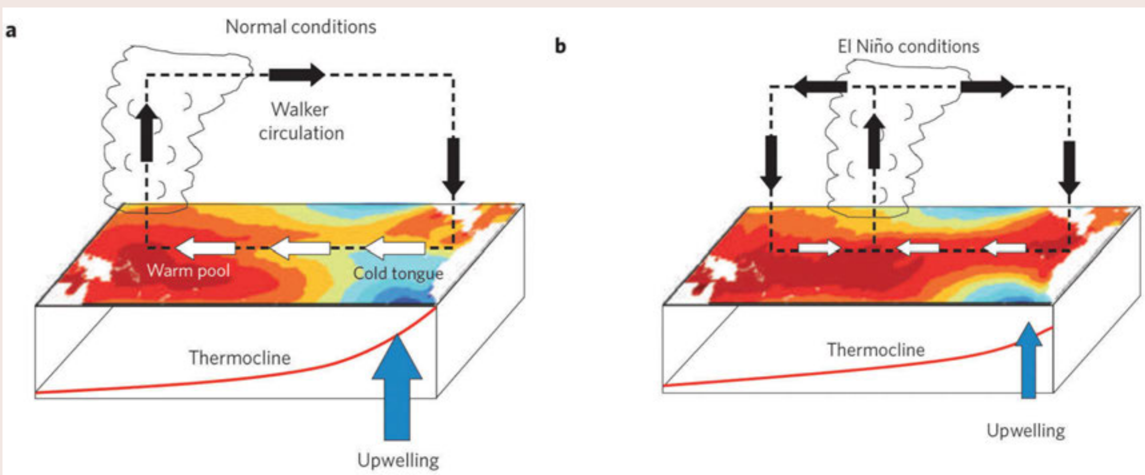
The lower panels of Figure 2.5 illustrate the projected warming in terms of regional climate variability relative to the 1951–1980 base period (Hansen et al. 2012). The local absolute warming is

## Box 2.2: Mechanisms Behind the El-Niño/Southern Oscillation

In simple terms, the oceanic part of ENSO is characterized by the movement of a pool of warm surface water in an east-west direction along the equator. In the mean state, this warm pool is confined to the western tropical Pacific, whereas in the Eastern Pacific, sea surface temperatures (SST) are much cooler and the surface water layer, separated from the cold, deep ocean by the so-called thermocline, is shallower (see Figure 2.4 a). In the west, the warm surface water facilitates strong atmospheric convection and resulting precipitation; together with sinking motion over the colder East Pacific and easterly surface winds that follow the SST gradient an overturning movement of air is formed—the so-called Walker circulation. This wind pattern, in turn, drives upwelling of cold deep water in the East Pacific and reinforces the concentration of warm surface water in the west.

This positive feedback between oceanic and atmospheric processes renders the mean state unstable. Small fluctuations in a part of the system are amplified into oscillations of the entire system. Every couple of years, when the easterly surface winds weaken and the warm water from the West Pacific extends so far to the east that it approaches the American coast, it creates an El Niño event, with a characteristic pattern of positive SST anomalies in the central and eastern tropical Pacific (see Figure 2.4 b). In some years the pendulum swings the other way, and easterly winds strengthen and the warm water pool gets concentrated further in west than on average. This is called a La Niña event. Both El Niño and La Niña events occur every 2–7 years and with varying magnitudes.

**Figure 2.4:** Idealized schematic showing atmospheric and oceanic conditions of the tropical Pacific region and their interactions during normal conditions, El Niño conditions, and in a warmer world.

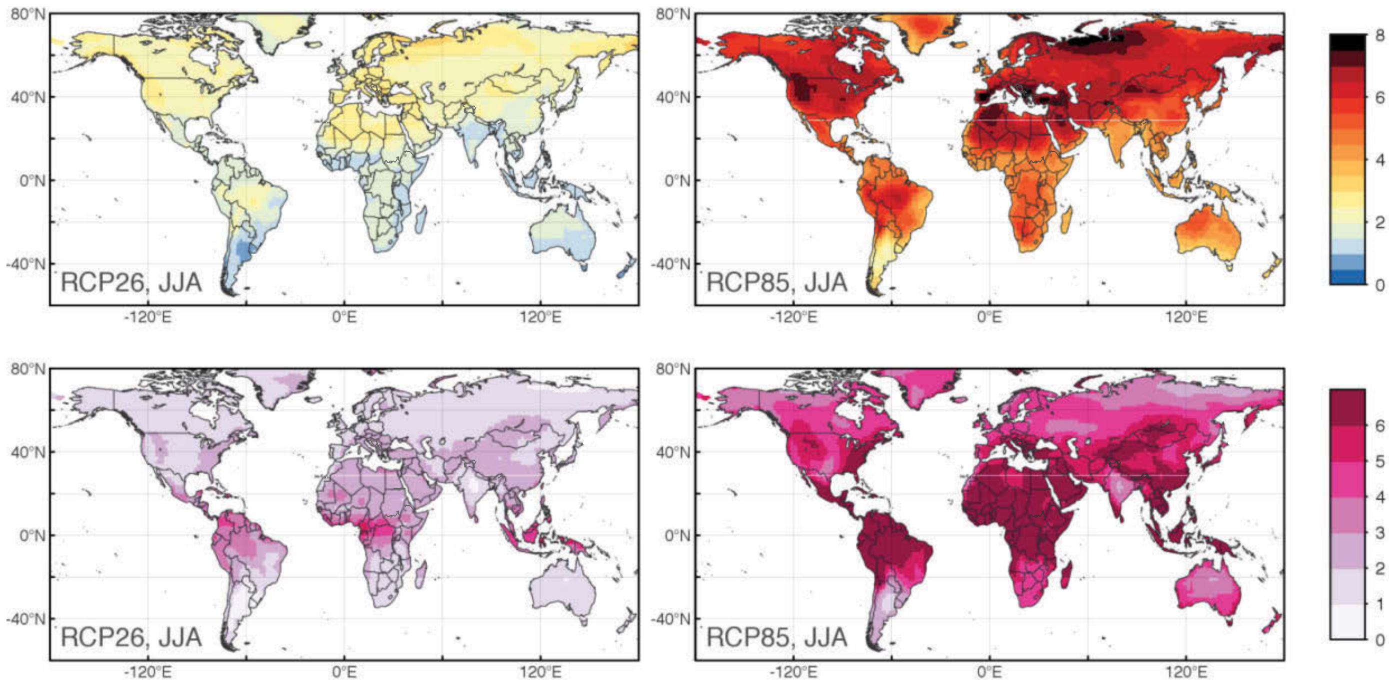



**(a),** Mean climate conditions in the tropical Pacific, indicating sea-surface temperatures (SSTs), surface winds and the associated Walker circulation; the mean position of atmospheric convection over the Western tropical Pacific; the mean oceanic upwelling in the Eastern tropical Pacific; and the position of the oceanic thermocline separating surface and cooler nutrient rich deep ocean waters. **(b),** Typical conditions during an El Niño event. SSTs are anomalously warm in the east; convection moves into the central Pacific; the trade winds weaken in the east and the Walker circulation is disrupted; the thermocline flattens; and the upwelling is reduced. Source: Collins et al. (2010).

divided (normalized) by the standard deviation (sigma) of the local monthly temperature dataset over the reference period, which represents the normal year-to-year changes in monthly temperature because of natural variability (see Box 2.3). Since ecosystems and humans are adapted to local climatic conditions and infrastructure is designed with local climatic conditions and its historic variations in mind, this approach helps to highlight regions most vulnerable to warming.

A 3-sigma deviation (see Box 2.3) would be considered a very rare extreme month under present conditions and a deviation by five sigma (or more) unprecedented. Since natural variability is lower in the tropics, the same change in absolute temperature is much stronger relative to natural variability in this region, posing a potential threat to ecosystems even under low levels or warming. Under a 4°C warming scenario (RCP8.5), about 50 percent of the global land surface is projected to be covered on average by

**Figure 2.5:** Multi-model mean global temperature anomaly for RCP2.6 for (2°C world, left) and RCP8.5 (4°C world, right) for the boreal summer months (JJA).




Temperature anomalies in degree Celsius (top row) are averaged over the time period 2071–1999 relative to 1951–1980. The bottom row offers a different perspective on these changes by depicting them relative to a measure of currently normal variations in monthly temperature (standard deviation)–a factor of 2 indicates that projected changes in boreal summer temperature are twice as large as currently occurring variations in summer temperatures across different years.

## Box 2.3: Heat Extremes

This report defines two types of monthly temperature 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). While there is a range of impact relevant temperature extreme measures on a daily or multi-daily basis, this report focuses on monthly data.

### *3-sigma Events—Three Standard Deviations Outside the Normal*

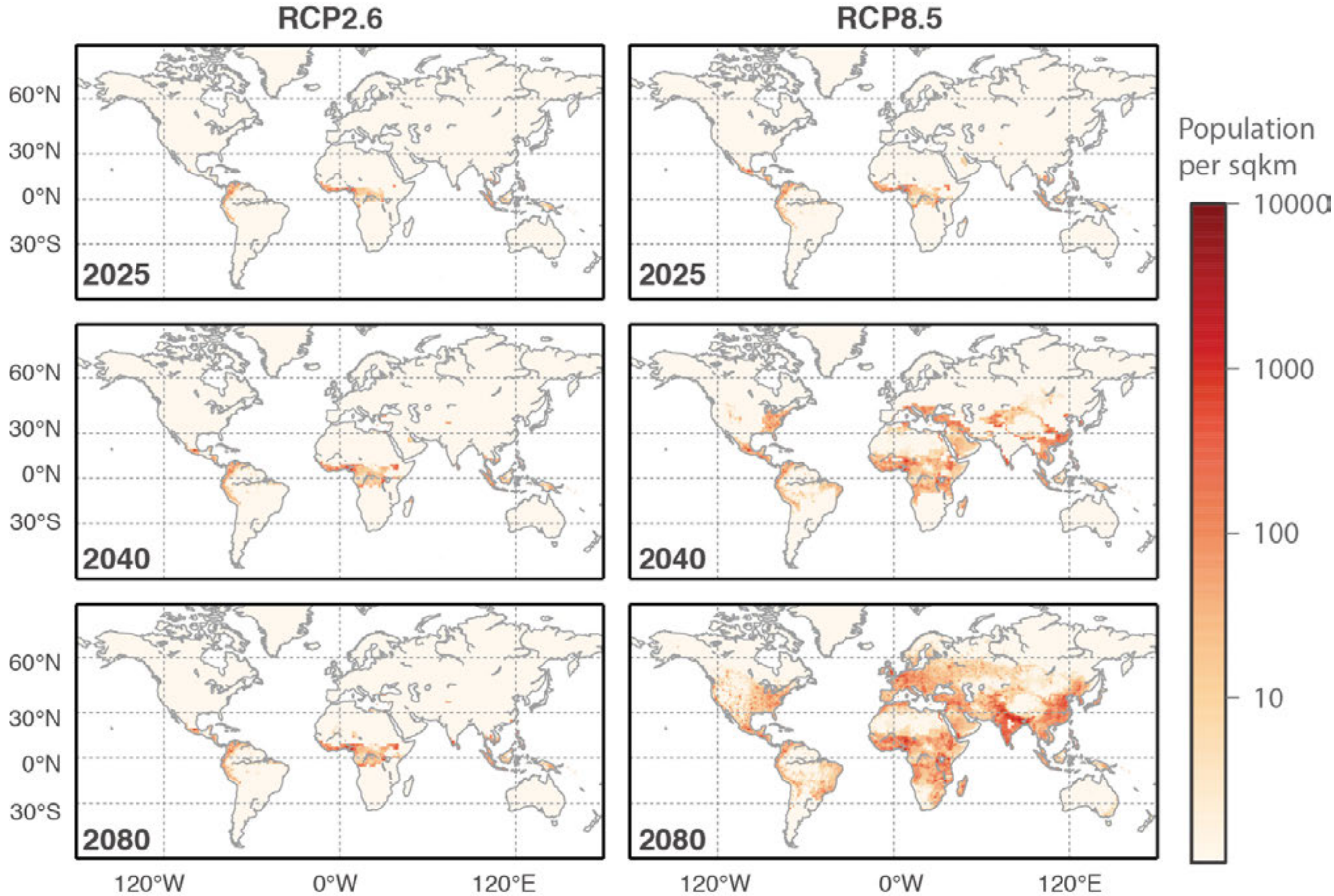
- *Highly Unusual* at present
- *Extreme* monthly heat
- Projected to become the norm over most continental areas by the end of the 21st century

### *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 mid-latitudes during summertime

Assuming a normal distribution, 3-sigma events would 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 and Robinson 2013). 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.

**Figure 2.6:** Estimates of world population experiencing highly unusual monthly boreal summer temperatures (JJA, averaged over centered 20-year time intervals) for the RCP2.6 (2°C world, left panel) and the RCP8.5 (4°C world, right panel). Population estimates are based on the Shared Socioeconomic Pathway 2 (SSP2) and shown in terms of population density.[20]




highly unusual heat extremes by 2050; this number increases to 90 percent by the end of the century. The departure from the historical climate regime (which means that the coldest month will be warmer than the warmest month during the 1860–2005 reference period) for large parts of the tropics is projected to happen by the 2050s–2060s under such a scenario (Mora et al. 2013). Also in a 4°C world, about 60 percent of the global land surface is projected to be covered on average by unprecedented heat extremes by the end of the century. This implies a completely new climatic regime posing immense pressure globally on natural and human systems.

In a 2°C world (RCP2.6), the projected land area experiencing highly unusual heat extremes is limited to about 20 percent and constrained to the tropical areas of South America, Africa, and South East Asia—with unprecedented heat extremes being rare.

Using population estimates from the intermediate Shared Socioeconomic Pathway 2 (SSP2), the population affected by extreme heat can be approximated over the 21st century. It is important to highlight that these population estimates are based on a range of assumptions about societal development that cannot be constrained. Unlike physically based projections (e.g., temperature projections), these population estimates should be interpreted merely as a possible future, not claiming any kind of predictive skill.

The policy choices made with respect to a pathway toward a 4°C or 2°C world will make a fundamental difference in terms of the population affected by heat extremes in the 2020s and thereafter. In 2025, about 17 percent of the world's population is estimated to experience highly unusual monthly summer temperatures for a 4°C world (and 11 percent of the population for a 2°C world), mostly located in tropical regions (compare Figure 2.6, upper panel). Heading toward a 4°C world (RCP8.5),

[20] The basis for the gridded population estimates is the National Aeronautics and Space Administration GPWv3 y-2010 gridded population dataset, which is linearly scaled up on a country basis to match the SSP projections, thus neglecting population redistribution within countries. The SSP2 population estimates on country basis with 5-year time steps were obtained from the SSP database as in Schewe et al. (2013).

the affected population increases to about 50 percent in 2040, including some of the most densely populated areas in South East Asia, the Americas, and the Mediterranean. By 2080, 96 percent of the global population is projected to experience highly unusual summer temperatures and 71 percent to experience unprecedented extreme temperatures (meaning that this would be the new norm for more than two-thirds of global population). Estimates are considerably lower for a 2°C world (RCP2.6), where highly unusual summer temperatures are projected to affect about 25 percent of the global population in 2080 and unprecedented summer temperatures would be very rare.

### 2.3.4 Projected Changes in Extreme Precipitation

A warming of the lower atmosphere is expected to strengthen the hydrological cycle. The increase in extreme precipitation event intensity over the 21st century is found to be about six percent per °C for the CMIP5 model ensemble and thus about three times stronger than the increase in mean precipitation of about 1.5–2.5 percent per °C (Kharin et al. 2013). A widely used indicator for persistent heavy rain conditions (and, as such, for potential flood risk) is the annual maximum 5-day precipitation accumulation (RX5day). The RX5day is found to intensify by about six percent for RCP2.6, but the change exceeds 20 percent for RCP8.5 for the 2080–2100 period. While heavy precipitation events become more intense, they are also projected to increase in frequency.

Kharin et al. (2013) find that annual extremes of daily precipitation that are estimated to have a return time of 20 years during 1986–2005 will be about 3–4 times as common by the end of the 21st century in a 4°C world. In a 2°C world, such events are projected to occur 25 percent more often.

### 2.3.5 Aridity and Water Scarcity

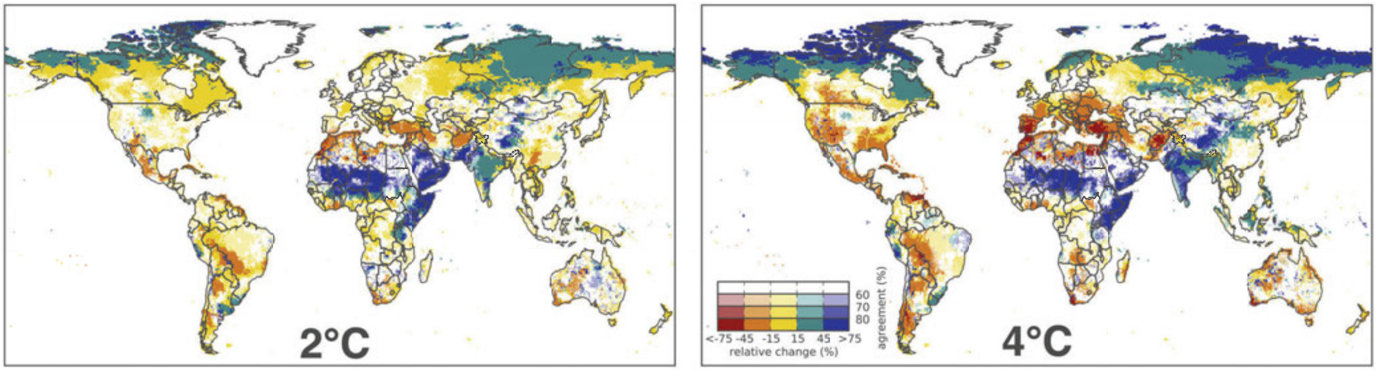
As mean precipitation over large regions of land is increasing, so is evaporation, since higher temperatures provide more energy for evaporation. Under a changing climate, the land surface warming will be particularly pronounced and the saturated water vapor concentration will increase in the lower atmosphere over land surface. If this saturated water vapor concentration exceeds the growth in actual water vapor concentration, this may result in a drying trend even though absolute precipitation increases.

A drying trend over land has been observed globally; this is strongly heterogeneous, however, with some regions experiencing profound wetting. This is in agreement with Feng and Fu (2013), who report an increase in global dry land area of about 10 percent in a 4°C world by the end of the century relative to the 1961–1990 baseline. The patterns emerging from the analysis in this report are broadly consistent with the overall "wet gets wetter" and "dry gets drier" trend under climate change noted in the previous *Turn Down the Heat* reports. The subtropical regions, particularly those in the northern hemisphere, stick out as aridity hotspots. This broad global trend does not apply to all regions equally, however. One notable exception is the Amazon, which is projected to experience drying despite its very humid present-day climate; another exception is East Africa, where wetting is projected. Southern Europe, especially the Balkans and the eastern Mediterranean, are expected to experience aridity index (AI) changes of up to –60 percent in a 2°C world; an AI increase of about 30 percent is projected for large parts of Siberia. These trends are strongly amplified in a 4°C world. While regional precipitation projections are very sensitive to the underlying model ensemble, the subtropical drying trend and the Siberian wetting trend are consistently found in a wide range of climate models and model generations (Knutti and Sedláček 2012).

These trends in aridity also lead to changes in annual water discharge that can be taken as a first-order approximation of the water resources available to humans. Figure 2.7 shows the relative changes in annual water discharge for a 2°C versus a 4°C world based on Schewe et al. (2013). Profound changes in river runoff are already evident for a 2°C world. A robust reduction in discharge in the subtropical regions (including Meso-America and the Caribbean, parts of central and southern South America, Southern Africa, Western Australia, and the Mediterranean) between 15–45 percent relative to the 1986–2005 reference period is projected. On the contrary, an increase in water availability is projected for the high northern latitudes, parts of South and South East Asia (due to an intensification of the Indian Monsoon system), and parts of central and eastern Africa. However, some of the strongest relative increases are plotted relative to a very low baseline precipitation (e.g., the Sahara desert or the Arabian Peninsula), which means that these regions will remain very dry.

The changes in projected precipitation patterns for a 4°C world are not simply a linear extrapolation of the patterns observed for a 2°C world. While, for a 2°C scenario, discharge changes for central and Eastern Europe and North America are inconclusive, a robust drying of 15–45 percent is projected for a 4°C world for the southeast, west, and north central North America and for most parts of central and Eastern Europe and the Balkans. Interestingly, only a slight increase or even decrease in discharge is projected for central and eastern Africa and the Arabian Peninsula, with some countries (e.g., Pakistan) exhibiting a robust increase in discharge under a 2°C warming scenario that is reduced to zero or even negative in a 4°C world.

**Figure 2.7:** Relative change in annual water discharge for a 2°C world and a 4°C world.




Relative to the 1986–2006 period based on an ISI-MIP model intercomparison using climate projections by CMIP5 GCMs as an input for global hydrology models (GHMs)[21] (adjusted from Schewe et al. 2013). Colors indicate the multi-model mean change, whereas the saturation indicates the agreement in sign of change over the ensemble of GCM—GHM combinations.

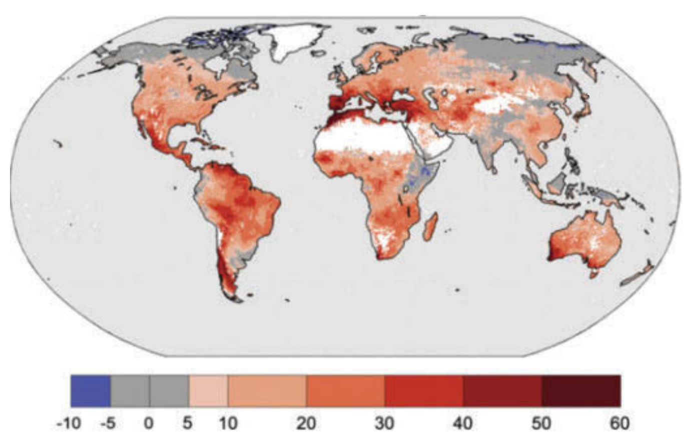
Other features present already for a 2°C world (e.g., the subtropical drying trend) get more pronounced, reaching reductions in annual mean discharge of up to 75 percent in the Mediterranean. In addition, the high-latitude discharge is robustly projected to increase further for a 4°C world, dominated by an increase in winter precipitation. A warming of about 3°C is found to lead to an increase in the number of people living under absolute water scarcity (which means less $< 500$ $m^3$ per capita per year); 40 percent higher than projected due to population growth alone (Schewe et al. 2013).

## 2.3.6 Droughts

While an upward trend for extreme temperature and heavy precipitation events can be clearly deduced from the observational record, there is still considerable debate as to whether or not there is a trend in global drought in recent decades (Dai 2012; Sheffield et al. 2012). Drought projections depend strongly on the underlying methodology, the applied indicators, and the reference periods used (Trenberth et al. 2014). In accordance with the overall drying trend in several world regions, an increase in intensity and duration of droughts is estimated to be likely by the end of the 21st century (IPCC 2013a, Table SPM.1).

Figure 2.8 shows the relative increase in the number of days under drought conditions for a 4°C world relative to the 1976–2005 baseline (Prudhomme et al. 2013). The subtropical and tropical regions in the Mediterranean, Meso-America, Caribbean, southern South America, and Australia are projected to experience the strongest increase in

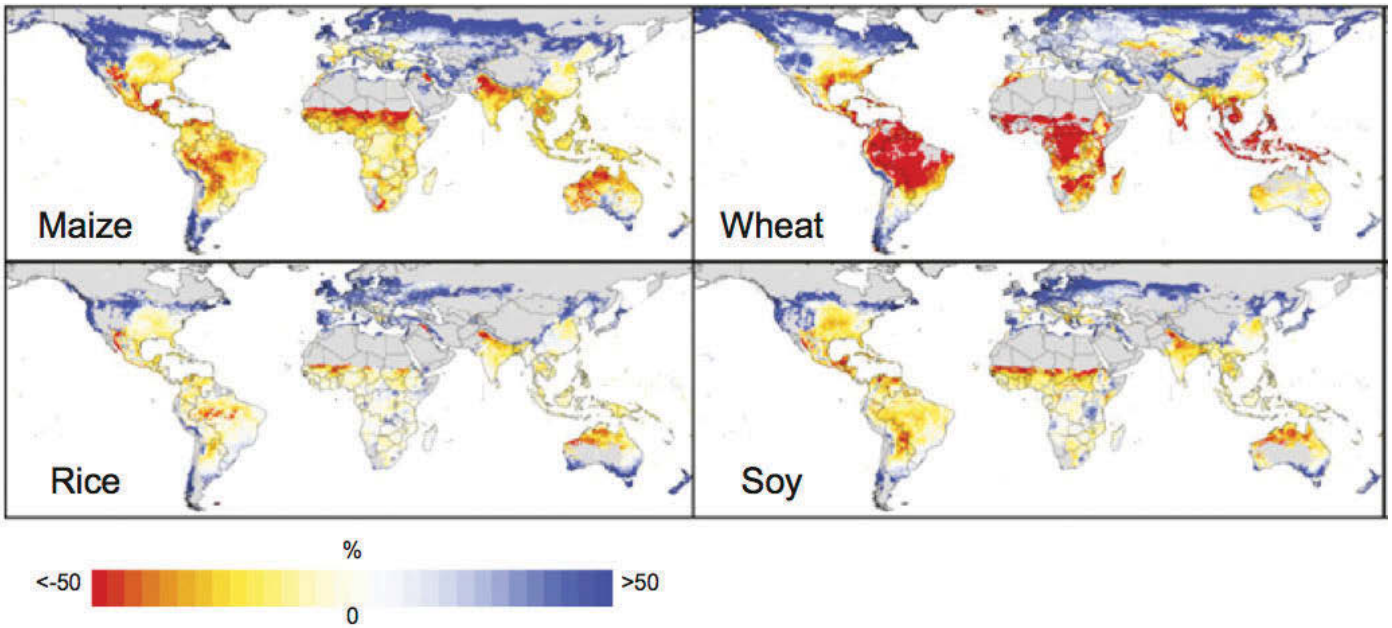
**Figure 2.8:** Percentile change in the occurrence of days under drought conditions by the end of the 21st century (2070–2099) in a 4°C world relative to the 1976–2005 baseline.




White regions: Hyper-arid regions for which runoff is equal to zero more than 90 percent of the time in the reference and future periods. Reprinted from Prudhomme et al. (2013).

[21] Please note that not all models of the ISI-MIP ensemble reach 4°C in the 21st century, which is why these projections are just based on three CMIP5 GCMS, namely HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM. As in Schewe et al. (2013), these GCM projections are then combined with 11 global hydrology models.

**Figure 2.9:** Median yield changes (%) for major crop types in a 4°C world relative to the 1980–2010 baseline from the AgMIP (Rosenzweig et al. 2013a). Please note that this projection only considers global gridded crop models that explicitly account for $CO_2$ effects and nitrogen stress.




days under drought conditions. In fact, more than six months per year on average is projected under at least moderate drought conditions for the Mediterranean over the 2080–2100 period in a 4°C world compared to less than a month in a 2°C world (Orlowsky and Seneviratne 2013). Substantial drought risk also emerges for large parts of South America, including the Amazon (representing a considerable threat to the Amazonian rainforest (see chapter 3.4.5)).

## 2.3.7 Agricultural Yields

The impacts of climate change on agricultural production have been observed for different crops. The recent IPCC AR5 Working Group II report states with medium confidence that wheat and maize production has been affected negatively in many regions and at a globally aggregated level (IPCC 2014c).

Even though projected warming and drying trends present a major threat to agriculture, in particular in tropical and sub-tropical regions, there remains substantial uncertainty in the projections of agricultural yields over the 21st century. This is due to uncertainties in climatological forcing as well as in the response of the agricultural models used and their representation of carbon dioxide, nitrogen, and high temperature-related effects on agricultural yields (Asseng et al. 2013; Rosenzweig et al. 2013b; see Box 2.4 for a discussion of the $CO_2$ fertilization effect).

Recent model intercomparison projects and the meta-analysis studies which provide the basis for the analysis in this report provide a clearer picture of agricultural impacts and risks than was previously possible. Figure 2.9 shows end of 21st century (2070–2099) changes in yield projections relative to the 1980–2010 base period from the AgMIP project (Rosenzweig et al. 2013a) for models that explicitly account for $CO_2$ and nitrogen effects, thus including the most important processes influencing yield dynamics (although the magnitude and the interplay of these effects are highly uncertain) (see Box 2.4).

While gains in agricultural yields are projected for the high latitudes, substantial losses are projected for the tropical and subtropical regions and all major crop types. For wheat and maize, losses may even exceed 50 percent on average for large parts of the tropical land area. This is consistent with a meta-analysis of more than 1,700 published studies on agricultural yield changes under climate change that found robust indications for a reduction in wheat, rice, and maize production for a local warming of 2°C in both temperate and tropical regions without adaptation (Challinor et al. 2014). All studies show a downward trend at local warming levels of 1°–3°C for both temperate and tropical regions if no adaptation is taken into account. The strongest results (40 percent yield decreases under 5°C local warming) were found for wheat in tropical areas. Notably, this decrease is still projected to be about 30 percent for wheat in tropical regions when adaptation measures are considered. The results indicate significant negative aggregate impacts of 4.9 percent yield losses per degree of warming.

## Box 2.4: The $CO_2$ Fertilization Effect

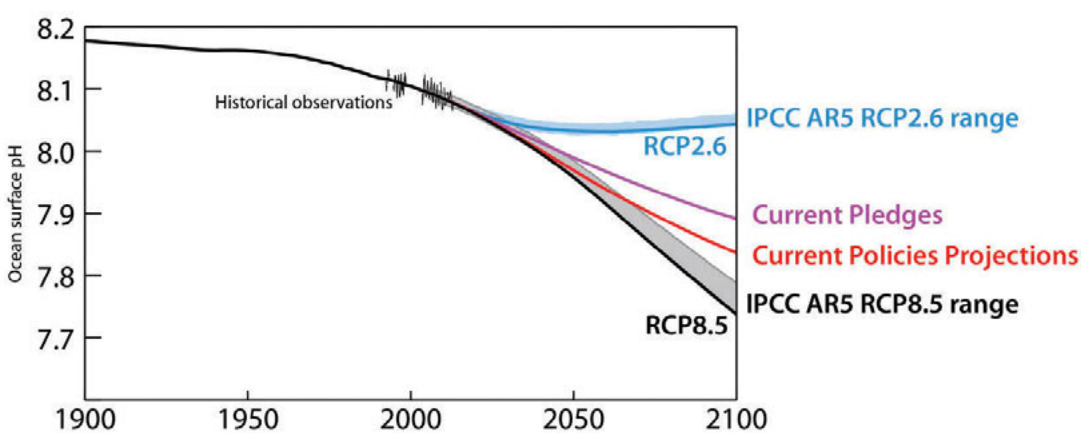
Increasing carbon dioxide concentrations in the atmosphere lead not only to higher air temperatures due to the greenhouse effect but also affect plant productivity and vegetative matter (Ackerman and Stanton 2013). Higher $CO_2$ concentrations also lead to improved water use efficiency in plants through reducing transpiration by decreasing the plant's stomatal conductance (Hatfield et al. 2011).

Plants can be categorized as C3 and C4 plants according to their photosynthetic pathways. Maize, sorghum, sugar cane and other C4 plants use atmospheric $CO_2$ more efficiently, which means that C4 plants do not benefit as much as C3 plants from increasing $CO_2$ concentrations except during drought stress (Leakey 2009). C3 plants, including wheat, rice, and soybeans, use atmospheric $CO_2$ less efficiently and therefore profit from increasing $CO_2$ concentrations (Ackerman and Stanton 2013; Leakey 2009); this possibly attenuates the negative effects of climate change for C3 plants.

The degree to which the $CO_2$ fertilization effect will increase crop yields and compensate for negative effects is uncertain, as differing experimental designs have shown. For example, Free-Air $CO_2$ Enrichment (FACE) experiments suggested a 50-percent lower $CO_2$ fertilization effect than enclosure studies (Ackerman and Stanton 2013; Long et al. 2006).* Moreover, the yield response to elevated $CO_2$ concentrations seems to be plant and genotype specific and depends on the availability of water and nutrients (Porter et al. 2014). It seems certain, however, that water-stressed crops benefit stronger from elevated $CO_2$ concentrations, and thus rain-fed cropping systems could benefit more than irrigated systems (Porter et al. 2014). A debate is ongoing over whether results from FACE experiments, laboratory experiments, or modeling approaches are closest to reality and results among the different approaches differ greatly (Ainsworth et al. 2008; Long et al. 2006; Tubiello, Amthor et al. 2007). For this reason, many climate impact studies include a scenario with the $CO_2$ fertilization effect and one scenario without considering the fertilization effect. Elevated $CO_2$ concentrations are thought to positively influence future food security through faster plant growth, but they could also have a negative impact through a change in the grain's protein concentration (Pleijel and Uddling 2012; Porter et al. 2014). This change comes about when the increased biomass accumulation happens faster than the corresponding nitrogen or nitrate uptake, leading to increasing yields but reduced protein concentration; this is also known as growth dilution (Bloom et al. 2010; Pleijel and Uddling 2012). This decrease in grain protein concentration, which in experiments with wheat ranged from 4–13 percent (and 7.9 percent in FACE experiments), and with barley ranged from 11–13 percent, is assumed to have negative effects on the nutritional quality of grains (Bloom et al. 2010; Erbs et al. 2010; Högy et al. 2013; Pleijel and Uddling 2012; Porter et al. 2014). In addition, elevated $CO_2$ concentrations are associated with significant decreases in the concentrations of zinc and iron in C3 grasses and legumes (Myers et al. 2014).

*The study by Long et al. (2006) triggered a debate and resulted in a critical response by Tubiello et al. (2007) which in turn was answered by the original authors in Ainsworth et al. (2008).

**Figure 2.10:** Global ocean acidification as expressed by a gradual decrease of ocean surface pH (indicating a higher concentration of hydrogen ions—or acidity).




Projections for scenarios in this figure are produced by a simple model (bold lines) derived from one of the complex models that is included in the range of projections from IPCC AR5 WGI (shaded ranges). Also indicated is a local historical measurement series at Aloha normalized to (global) model levels. Source: Methodology in Bernie et al. (2010) combined with climate projections as in Figure 2.1; IPCC data WGI IPCC (2013); observed data Dore et al. (2009).

Although crop-level adaptation is found to increase simulated yields by 7–15 percent, there are still substantial climate-related threats to regional and global crop production. These threats represent a major reason for concern about global food security, particularly given population (and food demand) increases.

### 2.3.8 Ocean Acidification

Rising atmospheric $CO_2$ concentrations not only cause land surface and sea-surface temperatures to rise but also leave their imprint on ocean chemistry. In order to restore the balance between the atmosphere's and the ocean's $CO_2$ concentration, the oceans absorb additional $CO_2$ as atmospheric concentrations rise. The oceans have taken up approximately 25 percent of anthropogenic $CO_2$ emissions in the period 2000–06 (Canadell et al. 2007). $CO_2$ dissolves in seawater and eventually forms a weak acid—a process known as ocean acidification (Caldeira and Wickett 2003).

The increase in $CO_2$ concentrations to the present-day value of 396 ppm has caused the ocean surface pH to drop by 0.1 from pre-industrial days (Raven 2005), equivalent to a 30 percent increase in ocean acidity. In fact, current rates of ocean acidification appear unprecedented over the last 300 million years (WMO 2014). A 4°C or higher warming scenario by 2100 corresponds to a $CO_2$ concentration above 800 ppm and will lead to a further decrease of pH by another 0.3, equivalent to a 150 percent acidity increase over pre-industrial levels (World Bank 2012a). Such changes in ocean chemistry will induce dramatic, though uncertain biological responses. A recent meta-analysis of biological responses suggests that the effects are likely to interact with other changes, including rising temperatures (Harvey et al. 2013).

An important effect of the reaction of $CO_2$ with seawater is the reduction of carbonate ions available for skeleton- and shell-forming organisms in the form of calcium carbonate ($CaCO_3$). Surface waters are usually super-saturated with aragonite, which is a mineral form of $CaCO_3$. In the case of coral reefs, decreasing availability of carbonate ions is expected to increase vulnerability to the effects of rising temperatures and to hinder recovery following hurricanes and other extreme events (Dove et al. 2013).

In combination with warming waters and other anthropogenic stresses, including overfishing and pollution, ocean acidification poses severe threats to marine ecosystems. Section 3.4.6 provides an overview of some of the most recent scientific publications on the expected impacts. While those impact projections are focused on Latin America and the Caribbean, this does not imply that they are not expected to occur in other regions. In fact, the levels of acidification are projected to be above average in cold waters at higher latitudes.

## 2.4 Sea-Level Rise

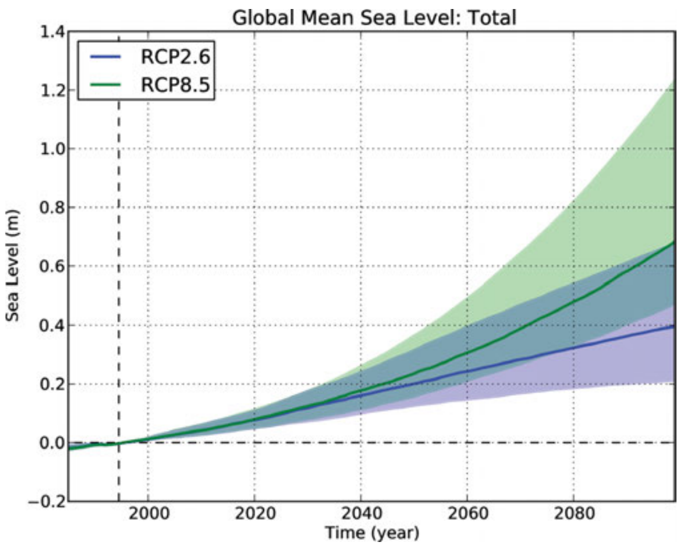
Sea-level rise is one of the main consequences of global warming with direct and fundamental impacts on coastal regions. Many low-lying coastal regions are particularly densely populated and are expected to experience further population increases. The density of people living in flood prone, coastal zones and megacities may increase by about 25 percent until 2050 (Aerts et al. 2014). Since the potential impacts of fast-rising seas will be severe for both the built and natural environments in these regions, avoiding sea-level rise is a strong reason to engage in mitigation efforts.

Paleo-reconstructions show that sea levels were significantly higher during warmer periods of earth history. The rate of sea-level rise increased from tenths of mm per year in the stable climate of the last 5,000 years to 1.7 mm per year during the 20th century—and 3.2 mm per year from 1993–2010 (Church et al. 2013). The present rate of sea level rise is the highest in recent history, i.e. higher than all rates within the past 6,000 years as inferred from proxy records (Lambeck et al. 2014). Sea-level rise is the result of the thermal expansion of sea water and melting of land ice from glaciers and ice sheets, with an increasing contribution from the latter in the past 20 years. In its latest assessment report, the IPCC projects rates of up to 16 mm per year by the end of the 21st century (Church et al. 2013).

Projections of global and regional sea-level rise in this report are draw upon the IPCC AR5 WGI report (Masson-Delmotte et al. 2013) and more recent estimates of the Antarctic contribution (Bindschadler et al. 2013; Hinkel et al. 2014; Levermann et al. 2014) (see methods in Appendix). This report follows a process-based approach based on the outcome of physical models. This differs from the earlier *Turn Down the Heat* reports (World Bank 2012a, 2013), where semi-empirical methods (Rahmstorf 2007; Schaeffer et al. 2012) were applied due to the lack of sufficient progress at the time in developing and validating process-based models. The adoption of process-based estimates in this report is the result of recent advances in modeling and the narrowing gap between process-based estimates and observations (Church et al. 2013; Gregory et al. 2013). Compared to the IPCC AR5, the projections for Antarctica in this report are scenario-dependent and yield higher upper bounds (up to about 0.2 m higher) as they explicitly account for different levels of ocean warming and resulting ice sheet melt (see discussion in Appendix).

It is important to note that large uncertainties remain in predicting future sea-level rise and, in particular, the contribution from potentially unstable regions of marine ice in Antarctica (Church et al. 2013). The results in this report incorporate the direct effect of Southern Ocean warming on ice-shelf basal melting and related ice stream acceleration in Antarctica; as in the IPCC AR5, however, they do not include amplifying feedbacks responsible for marine ice sheet instability. In light of model shortcomings and increasing evidence of marine ice sheet instability, this report cannot provide a *very likely* range for sea-level rise from Antarctica. This report thus follows the IPCC AR5 approach and assesses the model-based, 90 percent range as a *likely* (67 percent) range only. This applies not only to Antarctica but to all sea-level rise contributions (see

**Figure 2.11:** Global mean sea-level rise projection within the 21st century.




Time series for sea-level rise for the two scenarios RCP2.6 (1.5°C world, blue) and RCP8.5 (4°C world, green). Median estimates are given as lines and the lower and upper bound given as shading (likely range[23]). The estimate includes contributions from thermal expansion, glaciers and ice caps, and the Greenland and the Antarctic ice sheet, but not from anthropogenic groundwater mining (estimated to 0.04 +/– 0.05 m by the IPCC AR5 over the projection period). The estimates are skewed toward high values mainly because of a possible, yet less probable, large Antarctic contribution to sea-level rise. The sea-level rise baseline is 1986–2005, which represents a sea level of about 0.2 m higher than pre-industrial levels.

**Table 2.1:** Sea-level rise projections to 2081-2100 above the 1986–2005 baseline, in meters (unless indicated otherwise).

| | RCP2.6 (1.5°C WORLD) | RCP8.5 (4°C WORLD) |
|---|---|---|
| Steric | 0.13 (0.1, 0.18) | 0.27 (0.2, 0.32) |
| Glacier | 0.12 (0.07, 0.17) | 0.18 (0.13, 0.27) |
| Greenland | 0.07 (0.02, 0.12) | 0.11 (0.06, 0.21) |
| Antarctica | 0.04 (–0.01, 0.19) | 0.04 (–0.03, 0.3) |
| SLR in 2081–2100 | **0.36 (0.20, 0.60)** | **0.58 (0.40, 1.01)** |
| SLR in 2046–2065 | 0.22 (0.14, 0.35) | 0.27 (0.19, 0.43) |
| SLR in 2100 | 0.4 (0.21, 0.67) | 0.68 (0.48, 1.23) |
| Rate of SLR in 2046–2065 (mm/yr) | 4.2 (2.2, 7.8) | 7.1 (5.3, 12.9) |
| Rate of SLR in 2081–2100 (mm/yr) | **3.9 (1.3, 7.2)** | **10.8 (7.5, 21.9)** |

The lower and upper bounds are shown in parentheses (*likely* range[24]). The sum of median contributions is not exactly equal to the total due to rounding. The upper and lower bounds of the total sea-level rise (SLR) are smaller than the sum of each contribution's upper and lower bound because errors are not necessarily correlated (see methods in Appendix). Note that the land-water contribution is not included.

methods in Appendix). The lower and upper bounds can thus be interpreted as *likely* ranges. Note also that sea-level rise contributions not related to climate warming, such as resulting from groundwater mining, are not included and should be added on top of our global projections.

This report projects 0.58 m of globally averaged sea-level rise in a 4°C world (RCP8.5) for the period 2081–2100 compared to the reference period 1986–2005,[22] with the low and high bounds being 0.40 and 1.01 m (Figure 2.11).

For the scenario RCP2.6 (classified as a 1.5°C world for the model ensemble used here, see Box 2.1) this report projects 0.36 m of sea-level rise (0.20 m–0.60 m) for the same period, a reduction of almost 40 percent compared to RCP8.5. This potential for sea-level rise mitigation is broadly consistent with median IPCC AR5 estimates and emphasizes a larger benefit than previously estimated from emissions reductions.

Even when global mean temperatures stabilize, as in the RCP2.6 scenario, sea level is projected to continue to rise beyond 2100. The slow response of sea levels also explains the small difference between the RCP2.6 and RCP8.5 sea-level rise estimates in 2100 relative to the seemingly much larger divergence in global mean temperature projections (Table 2.1). The effect of a large proportion of 21st century emissions on sea-level rise will only become visible in the decades and centuries beyond 2100, when sea level projections diverge more strongly between the RCP2.6 and RCP8.5 scenarios (Church et al. 2013).

The future divergence is foreshadowed by the difference in the rates of sea-level rise toward the end of the century. For RCP2.6, this report projects a rate of 3.9 (1.3–7.2) mm per year as the mean over the 2081–2100 period, which is comparable with the present-day rate of 3 mm per year. This is in strong contrast to the report's projections for RCP 8.5, where the rate of sea-level rise, at 10.8 (7.5–21.9) mm per year, is two to three times higher. In addition, this report projects the risk of a rate of sea-level rise higher than 20 mm per year in a 4°C world toward the end of the century. Sea-level rise is projected to continue for centuries to millennia to come. Based on paleo-evidence as well as model results, Levermann et al. (2013) estimate the sea-level commitment over the next 2000 years to be about 2.3 m per degree of global mean temperature warming.

[22] The 1986–2005 baseline period is about 0.2 m higher than pre-industrial times.
[23] The *likely* range (67 percent) is computed from the model-based 90-percent range.
[24] The *likely* range (67 percent) is computed from the model-based 90-percent range.

### 2.4.1 Marine Ice Sheet Instability

Post-IPCC literature provides further evidence of marine ice sheet instability (Mercer 1978; Oppenheimer 1998) in both West and East Antarctica (Joughin et al. 2014; Mengel and Levermann 2014). Marine ice sheets predominantly rest on solid rock below sea level. Rapid disintegration of the ice sheets can be triggered by oceanic melting underneath the floating ice shelves surrounding the ice sheets and is associated with a self-enforcing dynamic feedback mechanism, where the retreat of the grounding line[25] being exposed to warming waters accelerates poleward on downward-sloping bedrock. This rapid retreat of the grounding line is currently being observed for several large glacier systems in West Antarctica, including the Pine Island and Thwaites glacier (Rignot et al. 2014), and numerical models indicate that a collapse of these glaciers might already be underway (Favier et al. 2014; Joughin et al. 2014). If this proves to be true, it would result in an irreversible additional sea-level rise of about one meter on multi-centennial time scales with the potential for a destabilization of the entire West Antarctic ice sheet (containing ice that is equivalent to about 4 m of sea-level rise). In East Antarctica, Mengel and Levermann (2014) identified a potential marine ice sheet instability of the Wilkes basin (3–4 m sea-level equivalent).

The potential of warm water intrusion has been shown for at least one large ice shelf cavity (Hellmer et al. 2012). However, the skill of climate models in predicting the oceanic dynamics surrounding the ice sheets is still low; as a result, it is very uncertain how and at what levels of global warming disintegration of this ice sheet could be triggered. At the same time, new insights into the bed topography of the Greenland ice sheet reveal deeply incised submarine glacial valleys that control about 88 percent of total ice discharge from Greenland into the ocean; this indicates a much greater sensitivity of the ice sheet to oceanic melt than previously thought (Morlighem et al. 2014).

### 2.4.2 Regional Distribution of Sea-Level Rise

Sea-level rise is not distributed equally across the globe. This is clearly visible in satellite observations (Meyssignac and Cazenave 2012) and tide-gauge reconstructions (Church and White 2011), and this inequality is projected to be amplified under future sea-level rise (Perrette et al. 2013; Slangen et al. 2011). Recent sea level trend patterns have been dominated by thermal expansion of the oceans (Lombard et al. 2009), where additional heat from global warming is not stored equally. Associated density changes (steric changes) are further modulated by salinity changes, for example freshening in high latitudes from increased precipitation, runoff, and ice melt (Bamber et al. 2012; Durack et al. 2012; Pardaens et al. 2011).

Wind patterns are also critical in redistributing the heat and shaping the sea surface (Timmermann et al. 2010). They are responsible for strong natural, cyclical variability such as related to the Pacific Decadal Oscillation, where high sea levels in the Eastern Pacific occur along with low sea levels in the Western Pacific (e.g. Bromirski et al. 2011), and inversely. Sustained changes in wind-induced sea level trends are also expected as the climate warms. The ocean dynamical response to changing density and atmospheric conditions is complex and GCMs show a large spread (Pardaens et al. 2011; Yin 2012). A well-known example of dynamic-steric sea-level rise is a projected 10–30 cm additional rise in the northeastern coast of the United States associated with a slowing down of the Atlantic meridional overturning circulation (Schleussner et al. 2011; Yin and Goddard 2013; Yin et al. 2009). Signs of such an accelerated sea-level rise at this coastline are already visible in the tide gauge record (Sallenger et al. 2012).

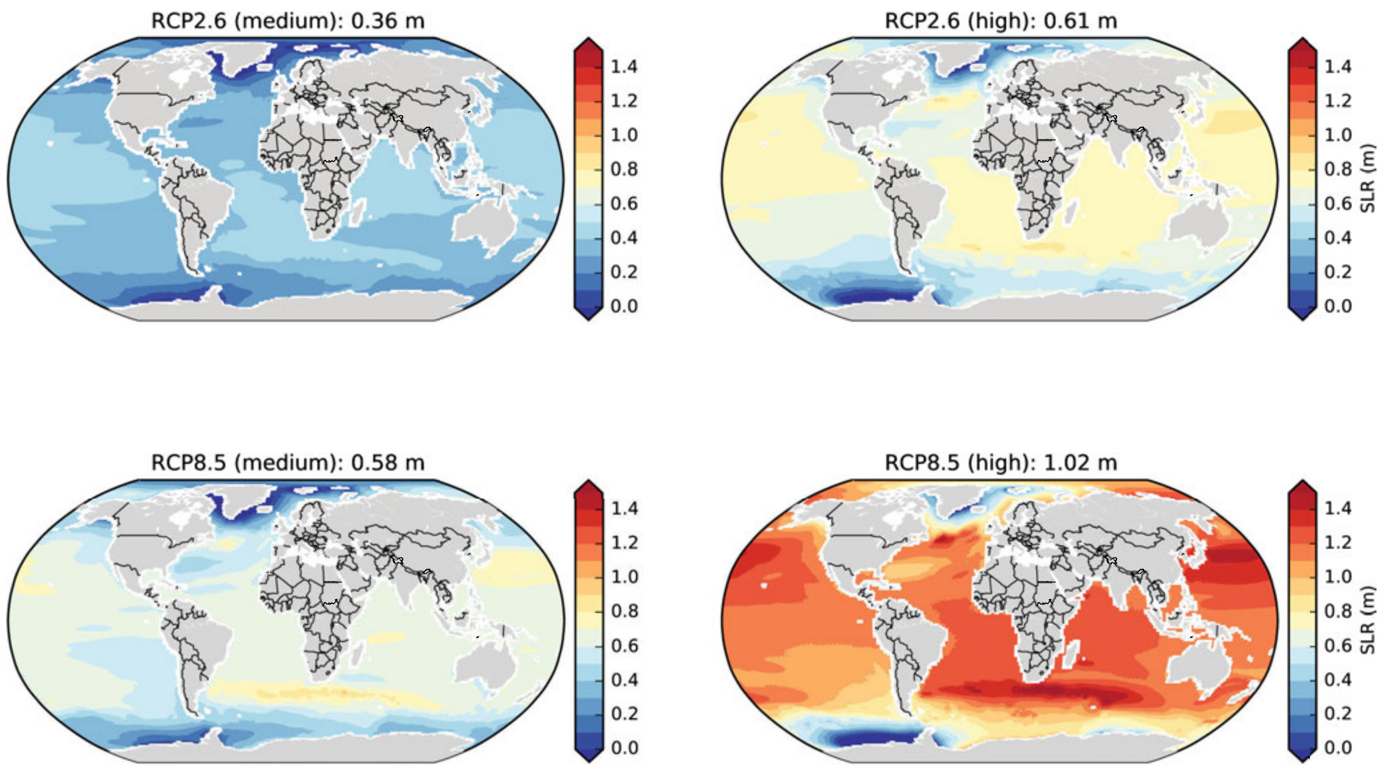
In addition to ocean circulation and density changes, melting glaciers and ice sheets induce a redistribution of mass as melt water spreads into the oceans, reducing the gravitational pull of the formerly glaciated regions and potentially causing local land uplift (Bamber et al. 2009; Mitrovica et al. 2001). This results in above-average sea levels far away from melting ice masses and below-average rise or even relative drops in sea levels drop in their proximity.

In the projections in this report, these processes are accounted for by analyzing steric-dynamic GCM outputs and combining projections for glacier and ice sheet contributions with regional fingerprints (see Appendix). This is similar to previous *Turn Down the Heat* reports. This report focuses on long-term changes and thus does not attempt to predict natural, up to multi-decadal, variability in sea levels. Consistent with the previous *Turn Down the Heat* reports, this report only includes climate-related contributions to sea-level rise and omits such other, more local contributions as ongoing glacial isostatic adjustment since the last glacial ice age (Peltier and Andrews 1976), sediment transport—especially in river deltas (Syvitski et al. 2009), and local mining (Poland and Davis 1969).

These local factors may provoke vertical land movement and contribute to enhanced (in case of subsidence) or reduced (in case of uplift) relative sea-level rise at the coasts. They should be accounted for by local planners, for example by using Global Positioning System measurements (Wöppelmann and Marcos

[25] The point at where the ice sheet is grounded on solid rock, marking the transition from the floating part that already contributes to global sea levels (ice shelf) to the grounded ice sheet that does not.

**Figure 2.12:** Patterns of regional sea-level rise.



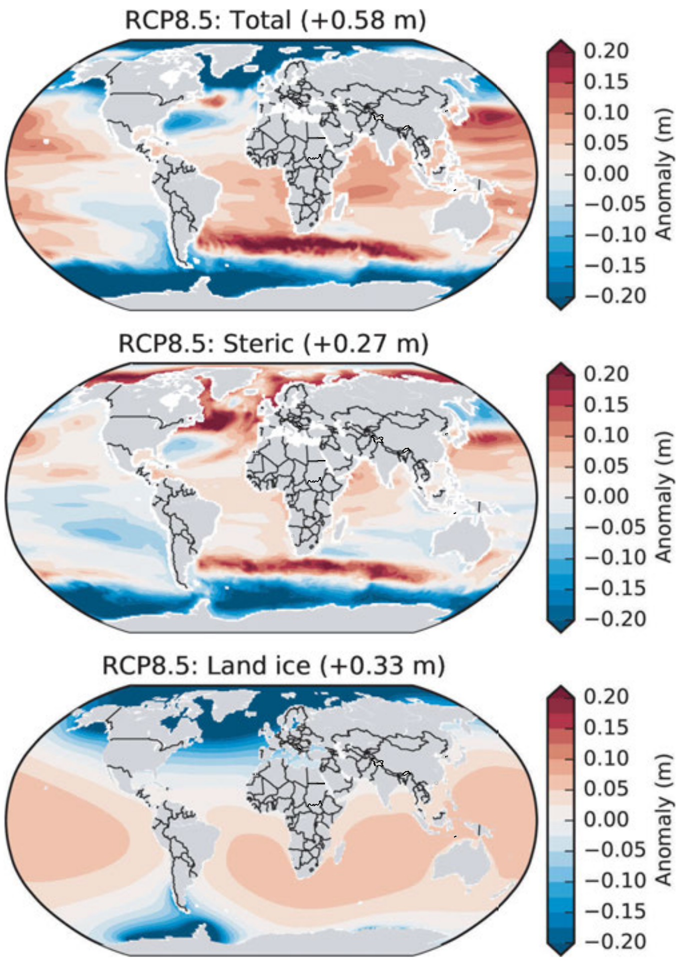

Median (left column) and upper range (right column) of projected regional sea-level rise for the RCP2.6 scenario (1.5°C world, top row) and the RCP8.5 scenario (4°C world, bottom row) for the period 2081–2100 relative to the reference period 1986–2005. Associated global mean rise are indicated in the panel titles, consistent with Table 2.1.

2012). Another limitation of the projections in this report results from the poor skills of global models at representing local oceanic processes, especially in semi-enclosed basins such as the Mediterranean Sea.

Regional sea-level rise is projected to exceed the global mean at low latitudes (Figure 2.12). Since the ice sheets are concentrated near the poles and melting is projected to increase significantly toward the end of the century, their decreasing gravitational pull piles up water in the low latitudes (Figure 2.13, bottom). This effect is stronger than freshening-induced steric rise in the Arctic (Figure 2.13, middle). Due to the large contribution of the Antarctic ice sheet in this report's high estimate, sea-level rise at low latitudes will exceed the global average (Figure 2.12, right column). Therefore, large ice sheet melt should have strongest impacts at the tropical coastlines.

Near-polar regions are projected to experience sea-level rise below the mean, with sea-level fall occurring at the coasts very close to the mass losses of the big ice sheets. A map of regional anomalies from the global mean rise shows that, in most coastal areas away from the poles, sea-level rise tends to remain within +/– 10 cm of the global mean rise of 0.58 m (Figure 2.13, top). In these areas, uncertainty in global mean sea-level rise dominates the total uncertainty (excluding local, non-climatic processes). It is also clear from Figure 2.12 that global sea level uncertainty is comparable in magnitude to differences between emissions scenarios, but both the "medium" and "high" scenarios in this report indicate a mitigation potential of about 40 percent in sea-level rise between RCP8.5 and RCP2.6. A more detailed analysis is conducted for each region covered in this report.

**Figure 2.13:** Regional anomaly pattern and its contributions in the median RCP8.5 scenario (4°C world).




Total sea-level rise (top), steric-dynamic (middle), and land-ice (bottom) contributions to sea-level rise, shown as anomalies with respect to the global mean sea-level rise. Global mean contributions to be added on top of the spatial anomalies are indicated in the panel titles (see also Table 2.1).

## 2.5 Social Vulnerability to Climate Change

People's vulnerability to climate change, their capacity to adapt, and their resilience in the face of its impacts reflect a combination of geographical exposure to hazards and varied demographic, socioeconomic, and political factors (Beck 2010; Hewitt 1997; Ribot 2010; Wisner et al. 2004). For the first time, the most recent report of the IPCC WGII includes a chapter on the livelihoods and poverty dimensions of climate change (Olsson et al. 2014). Figure 2.14 presents a framework for understanding key factors leading to social vulnerability to climate change, based on an extensive literature review in the three focus regions and beyond (see Appendix, Summary of Evidence Concerning Social Vulnerability, and Table 2.2). Chapters 3–5 draw on elements of this framework as they highlight the potential social impacts of climate change in the three focus regions.

### 2.5.1 Interaction of Key Current and Future Development Trends with Climate Change

Looking toward the late 21st century and the possible consequences of up to 4°C global warming, changes in demographic, economic, technological, sociocultural, and political conditions are likely to profoundly shape the vulnerability and adaptive capacity of societies and particular social groups (Hallegatte et al. 2011). Key development trends include population dynamics, migration, and urbanization; overall economic development, which will influence both patterns of emissions and the resources at different social groups' disposal to respond to threats to their livelihoods and wellbeing; and the availability of and demand for natural resources. Adaptation and mitigation policies will also significantly influence different social groups' vulnerability to the effects of climate change. These trends will both affect and be affected by the impacts of climate change.

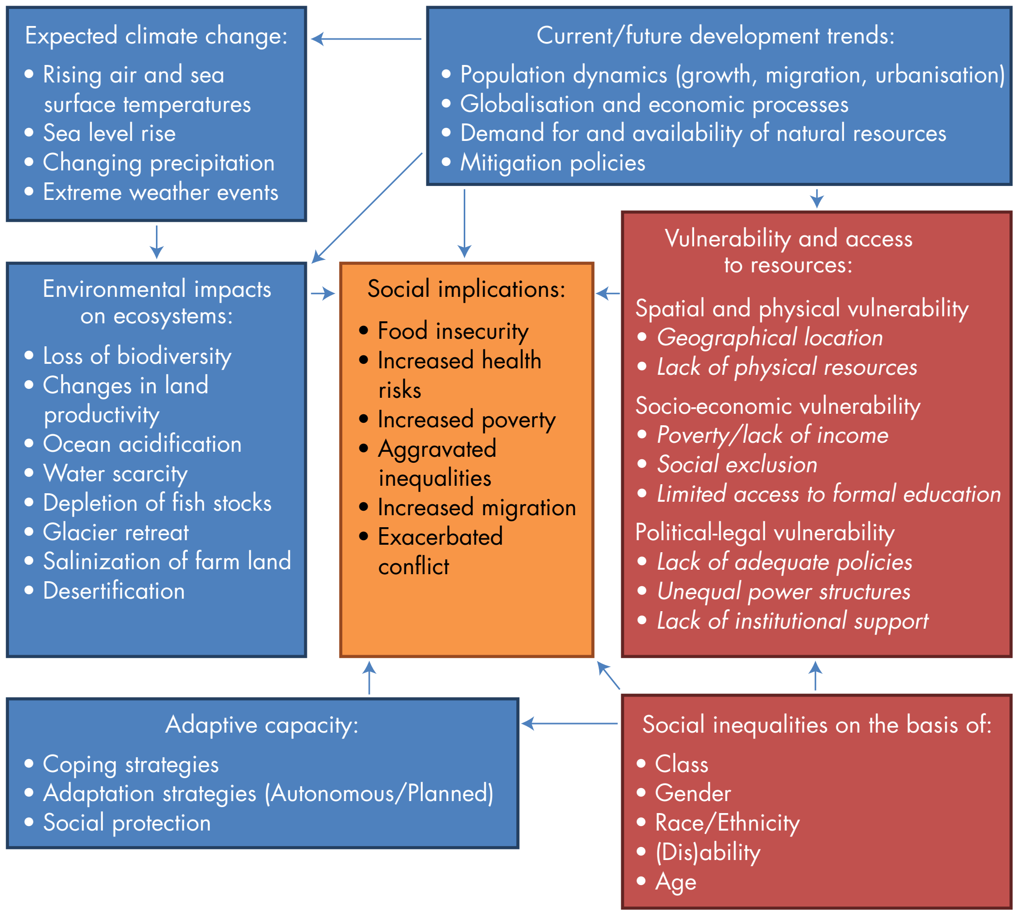
### 2.5.2 Understanding Vulnerability, Adaptive Capacity, and Resilience

How different groups experience climate change is strongly influenced by their capacity to adapt, which itself depends largely on access to resources (Moser et al. 2010; Wisner et al. 2012)—economic assets and incomes, natural and physical resources, social networks, cultural knowledge, and access to political power (Chambers and Conway 1991). Processes underpinning inequality and social exclusion (related for example, to ethnicity or class) frequently lead to increased exposure to hazards and prevent certain groups from acquiring the resources needed to protect themselves and recover from shocks (i.e., to become resilient to climate change). The typology developed by Moser et al. (2010) defines three key elements of vulnerability: spatial and physical vulnerability, socioeconomic vulnerability, and political/legal vulnerability.

### 2.5.3 Spatial and Physical Vulnerability

Coasts and deltas, tropical forests, mountainous regions, arid and semi-arid areas and the Arctic are all identified as geographical regions particularly sensitive to climate change (IPCC 2014a; World Bank 2012a). Within these regions, vulnerabilities vary considerably. Typically people living in areas that are prone to hazards,

**Figure 2.14:** Framework for understanding social vulnerability to climate change




Source: Adapted from Verner (2010).

such as flooding, landslides or cyclones, and in areas affected by drought or heat extremes are most likely to be negatively affected by climate change. Loss of ecosystem services, related for example to loss of forest cover, reduction in overall water supply or increased salinity, is likely to put increasing stress on livelihoods and wellbeing in affected areas, such as, for example, growing pressures on water availability in many Latin American cities. There is a strong (but not complete) overlap between geographical and economic vulnerability—with a growing risk of people being 'trapped' in climatically stressed areas because they lack the financial capital or social connections to move, and are unable to diversify into more resilient livelihood activities (Black et al. 2011). Likewise, poorer people often have no choice but to live in hazard-prone locations, where housing is cheaper (Winchester 2000). For example, many of the victims of Saudi Arabia's 2009 floods were migrant workers who lived in poorly constructed, informal shanty houses in the *wadi* (natural drainage) area (Verner 2012).

## 2.5.4 Socioeconomic Vulnerability

### *2.5.4.1 Poverty*

Economically and socially marginalized people's access to resources to adapt to anticipated environmental stresses such as slow-onset climatic change, and to cope with extreme events, is often impeded because their needs are overlooked or due to discrimination (Wisner et al. 2012; Tanner and Mitchell 2009). Economic and social marginalization, in turn, reinforces geographical vulnerability. Thus, for example, over one million people live in Rio de Janeiro's favelas that sprawl over the slopes of the Tijuca mountain range, making them particularly at risk from mudslides (Hardoy and Pandiella 2009).

Poorer people often take longer to bounce back after such shocks as flooding and cyclones, reflecting their more limited physical, financial, human, and social assets. After Hurricane Mitch in Honduras, for example, many poor people took 2–3 years longer than better-off people to rebuild their livelihoods (Carter et al. 2007). In Mexico, meanwhile, Hurricanes Stan and Wilma had much longer-lasting effects in Chiapas (a poorer state) than the similarly affected but better off Yucatan (Rossing and Rubin 2010).

Poorer people's livelihoods often depend on sectors such as agriculture, forestry, fishing, and pastoralism that are particularly sensitive to the effects of slow-onset climatic changes (Leichenko and Silva 2014). Poor people's adaptive capacity is often undermined by lower education levels, limited alternative livelihood options, discriminatory social norms that affect their access to labor markets and decent work, and a lack of long-term institutional planning, policy, and programmatic support for resilience-strengthening activities (UNISDR 2009). Although significant reductions in extreme poverty are projected by 2030–50,[26] up to 325 million extremely poor people will be living in the 45 countries most exposed to drought, extreme temperatures, and flood hazards in 2030. Most of these people will reside in isolated rural areas in South Asia, Sub-Saharan Africa, and Central America and the Caribbean (Shepherd et al. 2013). As a result, poverty and geographical exposure to climate change are likely to continue to reinforce one another in the medium term.

#### *2.5.4.2 Gender Dimensions of Vulnerability*

Different gender roles and norms mean that men, women, girls, and boys are likely to be affected in different ways by climate change (Demetriades and Esplen 2009; Denton 2002). For example, water scarcity can lead to particular challenges for women and girls, who in many cultures have primary responsibility for obtaining water for domestic use, and for cooking, laundry, and bathing of young children. In contexts where much subsistence farming is carried out by men, and social norms concerning masculinity frame men as breadwinners, boys and men are more likely to migrate for work if climate-related stresses on agriculture undermine livelihoods.

Rural women's access to land, property rights, financial resources, and representation in decision-making processes is also often restricted compared to men's access (Agarwal 1994; Brody et al. 2008). This constrains women's capacity to diversify into alternative livelihoods in the event of climate or other stresses (Demetriades and Esplen 2009; Verner 2012) and to anticipate and prepare for disasters and environmental stresses (Enarson 2003; Fordham 2012). Furthermore, in some contexts (e.g., in parts of the Middle East and North Africa, and in areas of Latin America) social norms restrict girls from learning important survival skills (e.g., swimming). This is one reason why women are typically more likely than men to die as a result of climate related disasters.

Where gender relations are more egalitarian, differentials in disaster mortality are much lower. In some contexts, however, norms of masculinity that mandate heroic behavior can lead to greater death rates among men. This was seen, for example, in Central America after Hurricane Mitch (Neumayer and Plumper 2007; Bradshaw and Fordham 2013). Both disasters and daily pressures can increase the work needed to ensure basic survival, which can disproportionately affect women if household tasks become more time consuming. Additionally, they can also exacerbate stress factors and may increase violence against women and girls (Azad et al. 2014; Brody et al. 2008; Enarson 2003).

There is increasing evidence that promoting gender equality is an important component of an effective strategy for developing resilience to climate change, since gender differentials in education, access to and control of assets, access to information and social networks can all limit disadvantaged women's adaptive capacity (Ahmad 2012; Verner 2012; World Bank 2011), and thus undermine overall resilience.

#### *2.5.4.3 Vulnerability Related to Age and Disability*

Age greatly influences people's ability to face climate-related threats. During extreme climatic events, older people's reduced mobility, strength, and health; impaired eyesight and hearing; and greater vulnerability to heat and cold can restrict their ability both to cope and to escape danger (HelpAge International 2012). Thus, for example, the European heat wave of 2003 (Vandentorren et al. 2006) and the 2013 heat wave in Pudong, China (Sun et al. 2014) led to disproportionate death rates among older people. In both cases, people over 80 were among the most affected. In France, both older people from poorer socioeconomic groups and people with more limited social networks were disproportionately affected (Vandentorren et al. 2006). Similarly death rates during Chicago's 1995 heat wave were lower in more socially connected neighborhoods (Klinenberg 2002).

Poorer older people face particular challenges in adapting their housing to cope with changing climates; in the absence of effective social protection systems they may also be unable to afford to purchase food, fuel, and water as prices rise. This can make them reliant on farming and ecosystem services, and consequently even more vulnerable to climate change (Wang et al. 2013). Globally, the number of older people is expected to triple by 2050, accounting for one-third of the population in developed regions and one-fifth of the population in developing countries (UN 2010). The combination of aging and urbanization could lead to a significant increase in the number of people vulnerable to climate-related stresses.

Disabled people, are often more dependent on household and community members to fulfill their daily basic needs; they are

[26] This is expected to be a result of growth in emerging economies (Dadush and Stancil 2010; Edward and Sumner 2013), but these projections do not typically take into account the effects of climate change. As a result, they may underestimate climate-change-related impoverishment.

thus at higher risk if supportive infrastructures and social relationships are strained or limited. Disabled people are over-represented among the very poor in low-income countries and face greater risk of death, injury, discrimination, and loss of autonomy (Priestley and Hemingway 2006). Moreover, they are often ignored in preparedness, recovery and adaptation planning.

Children are also disproportionately affected by climate change (O'Brien et al. 2008; UNICEF 2008). Food insecurity can have particularly negative effects on their development (Bartlett 2008; Shepherd et al. 2013). Children are also at greater risk than adults of mortality and morbidity from malnutrition, disasters and their consequences, and from diseases (e.g., malaria and waterborne diseases) that may become more widespread as a result of climate change. An additional challenge is that some family coping strategies, such as withdrawing children from school or marrying off daughters to reduce the number of mouths to feed (or to being new assets into the household) end up jeopardizing the wellbeing of children (Brown et al. 2012).

Lost human development opportunities in childhood can have lifetime consequences. Evidence from Zimbabwe, for example, indicates that children affected by drought and food insecurity in infancy never catch up on lost growth (Hoddinott and Kinsey 2001). If these negative consequences (e.g., increased rates of malnutrition, lost educational opportunities) become more common, climate change could lead to an increase in intergenerational poverty cycles (Harper et al. 2003)—thus compounding vulnerability to climate change.

### *2.5.4.4 Ethnicity and Belonging to Minority Groups*

Indigenous and minority groups disproportionately live in areas already affected by climate change where livelihoods are increasingly undermined—including the Amazon (Kronik and Verner 2010), the Andes (Hoffman and Grigera 2013), and dryland areas (Macchi et al. 2008). They are typically more likely than majority groups to be poor and to have limited access to public services, employment, education, and health care (UNPFII 2009; Care 2013; World Bank 2014). In addition, indigenous and minority groups often have less access to early warning systems; likewise, they are often excluded from or underrepresented in decision-making processes (Abramovitz 2011; Salick and Ross 2009; Vásquez-Léon 2009). Research with Aymara villagers in Bolivia found, for example, that stresses related to the impact of the retreat of the Mururata glacier on water supply were accompanied by historical marginalization due to a lack of official identity cards, land titles, and access to bilingual basic education (McDowell and Hess 2012).

Another challenge for indigenous and minority groups in many countries is that migrant laborers (often members of ethnic minorities) are more likely to work outdoors, in sectors such as agriculture and construction, where they are vulnerable to heat stress and to unfavorable weather conditions (Lowry et al. 2010). This is seen, for example, in the Gulf States (Verner 2012). In addition, migrant workers are often neglected when it comes to disaster recovery. This is often compounded where migrants lack the legal status to apply for support (Abramovitz 2011).

### *2.5.4.5 Political/Legal Vulnerability*

Social status, discrimination patterns, and access to resources are almost always determined by political processes and the distribution of power (Mascarenhas and Wisner 2012). The most vulnerable groups are often the least vocal, mobilized, and empowered in decision-making processes, and they often suffer disproportionately from weak local institutions. As a result, they are frequently deprioritized for infrastructure investments (such as storm drains) that would reduce their vulnerability to extreme events (Hardoy and Pandiella, 2009) and for services like training and education that could help them build adaptive capacity (Rossing and Rubin 2011). Vulnerable groups are also less likely to be able to influence disaster risk reduction planning (Douglas et al. 2008; Tacoli 2009) and to get adequate relief after disasters (Ruth and Ibarran 2009). After the cyclone that hit Orissa, India, in 1990, for example, more than 80 percent of disabled persons faced food shortages due to a lack of clear information on the location of relief supplies and how to access them (Handicap International 2008).

Weaker institutions in areas primarily populated by marginalized groups increases their vulnerability to the effects of disasters (Kahn 2005)—possibly because building codes and zoning controls are less well enforced where institutions are weak. Marginalized groups are also often powerless to prevent processes of adaptation or development that increase their vulnerability (e.g., capture of water resources by better-off groups and/or large-scale businesses in some parts of the Caribbean and the Andes (Buytaert and De Bièvre 2012; Cashman et al, 2010)); they also lack the political clout to ensure that mitigation strategies (such as REDD+) take their interests into account. Where marginalized groups are involved in adaptation planning, however, measures to reduce the risk of disasters can be much more effective. In St Lucia, for example, participatory planning in a low-income urban community involving both local people and engineers led to the identification of effective ways to stabilize slopes and a reduction in vulnerability to rain-induced landslides (Arnold et al. 2014). Likewise, where disadvantaged groups organize for development purposes, these can enable individuals and communities to implement natural resource management measures that enhance resilience, as India's self-help group experience shows (Arnold et al. 2014).

Political/legal vulnerability also involves a lack of recognition of rights. For example, many poor people's vulnerability is compounded by an insecurity regarding tenure rights to housing and land. This can lead to people being forced to live on marginal land that is highly vulnerable to flooding; it can also limit incentives to invest in hazard-proofing housing where land rights are unclear and people can be evicted at any time (Moser et al. 2010).

Effective public policies can play an important role in reducing vulnerability and boosting adaptive capacity. Social protection measures range from disaster risk preparedness and rescue to cash transfers and insurance to protect assets and livelihoods (Kuriakose et al. 2012). Finally, the extent to which effective adaptation or mitigation policies, climate-sensitive social protections, and disaster risk reduction measures are institutionalized reflects, at least in part, a government's political orientation and institutional capacity as both factors contribute to increasing or reducing the vulnerability of exposed groups to climate change (Cannon 2000; Hewitt 1997).

### 2.5.5 Evidence of the Social Implications of Climate Change

The framework outlined in Figure 2.14 focuses on five main areas of the social dimensions of climate change: food security and nutrition, income/consumption poverty, human health, migration, and social cohesion (i.e. the issues in the central orange box). Table 2.2 below provides a summary assessment of the state of evidence on the social implications of climate change in these areas, drawing both on literature concerning the three regions of focus in this report and the wider literature from other parts of the globe covered in the previous *Turn Down the Heat* reports. Table 2.2 follows IPCC Working Group II judgments on the strength of evidence made in the 5th Assessment Report, with author assessments on issues not covered by the IPCC.[27] A more detailed summary of available evidence of social vulnerability to climate change impacts is provided in Appendix, Summary of Evidence Concerning Social Vulnerability.

As Table 2.2 shows, the strongest evidence of the likely social impacts of climate change relates to impacts on human health: there is clear evidence of the negative effects of increasing temperatures and of the spread of some vector- and water-borne diseases. There is also clear evidence of impacts on some sectors (and livelihoods), such as fisheries and crop production, as well as moderate evidence of negative impacts on many other areas of food security, leading to projections of increased poverty among small-scale producers and low-income urban consumers.

There is also moderate evidence that climate change is likely to lead to increased migration, as people move to try to develop more climate-resilient livelihoods or as a result of disaster-related displacement. While many studies have probed whether climate change is likely to be associated with reduced social cohesion and increased future conflict, there is no overall consensus; the studies generally agree, however, that the risk of increased tensions and violence cannot be ruled out. Two areas that are increasingly flagged in the literature on social vulnerability, but for which there is as yet limited evidence, are the impacts of climate change on mental health and its relation to incidences of domestic violence.

Overall, the literature reviewed suggests that helping vulnerable people build stronger, more climate-resilient lives and livelihoods is critical for reducing social vulnerability to climate change. Development investments that reduce poverty by enabling people to build assets of all types (including stronger physical and financial assets) is a vital component of this; so is much greater investment in disaster risk reduction and response capacity. Focused efforts to combat the drivers of social exclusion and systemic inequalities (such as gender inequalities) that underlie vulnerability will also be necessary. Effective poverty reduction and disaster risk management require investments in governance: to build strong institutions that are capable of planning and implementing policies and programs, and to ensure that the voices of affected or likely-to-be-affected people (including those of women, young people, and other socially excluded groups) are much more strongly taken into account in both disaster preparedness and longer-term planning and management of climate resilience activities.

[27] On issues where there are no assessments in the IPCC Working Group II 5th Assessment Report, this report has used the following criteria for assessing the strength of evidence: a strong evidence base denotes a consensus among studies, and/or eight or more studies with similar findings; a moderate evidence base denotes mixed findings, or 4–7 studies with similar findings; a limited evidence base indicates inconclusive findings or fewer than three studies. These relatively small numbers reflect the limited evidence base on many aspects of social vulnerability.

**Table 2.2:** Evidence Summary—Social Vulnerability to Climate Change.

| POTENTIAL IMPACTS OF INTERACTING CLIMATE CHANGE AND BROADER DEVELOPMENT TRENDS | EVIDENCE BASE AND CONFIDENCE | EXAMPLES OF AFFECTED REGIONS, SECTORS, AND AREAS | EXAMPLES OF AFFECTED SOCIAL GROUPS |
|---|---|---|---|
| **Food Security and Nutrition** | | | |
| Reduction of land available suitable for crops and ecosystems | Moderate Evidence | MENA : Israel, Occupied Palestinian Territory, Lebanon, Syria, Iraq and the Islamic Republic of Iran | Small scale farmers and marginalized groups likely to be displaced by competition for land<br>Indigenous communities and small-scale farmers who lack land entitlements |
| Reduction in crop productivity especially for wheat and maize and negative yields impacts for nuts and fruit trees | Strong Evidence | Tropical and subtropical regions<br>Rain-fed agriculture in LAC<br>Western Balkans<br>Central Asia | Rural food producers<br>Low income urban consumers<br>Groups reliant on glacial melt water |
| Reduction in affordability of food and/or variability of food prices | Moderate Evidence | Low-income and food-importing countries<br>Africa<br>LAC (northeast Brazil, parts of the Andean region)<br>Central Asia<br>MENA | Low-income people in rural and urban areas<br>Children at risk of malnutrition |
| Increased livestock vulnerability and mortality | Moderate Evidence | Arid and semi-arid regions<br>Europe and North America | Agro-pastoralists and pastoralists |
| Disruption to fishery and shellfishery production, including fish migrations | Limited Evidence | Tropical developing countries<br>Decrease in fishery catch potential at the Caribbean coasts, the Amazon estuaries, and the Rio de la Plata<br>Increase in fishery production at higher latitudes | Artisanal fishermen<br>People engaged in fish processing and trading<br>Small coastal communities |
| Declines in coral reefs resulting in declines in fish stocks | Strong Evidence | Caribbean<br>Western Indian Ocean | Small coastal communities relying on coral ecosystems<br>People engaged in fish processing and trading |
| **Poverty Impacts** | | | |
| Increase in poverty headcount rate and risk of chronic poverty in different warming scenarios | Moderate Evidence | Sub-Saharan Africa (Malawi, Mozambique, Tanzania, Zambia), Bangladesh, and Mexico | Urban poor groups and urban wage laborers<br>Residents of informal settlements<br>Dwellers in rural hotspots where hunger is expected to become prevalent |
| Increase in disaster related impoverishment and destruction of assets; risk of chronic poverty compounded by limited access to disaster relief | Limited Evidence | Exposed areas globally (e.g., low-lying coastal areas, flood-prone land, mountain slopes) | Low-income groups<br>Children and adolescents (stunting and missing education)<br>Self-employed urban groups |
| Coping strategies with negative social impacts | Limited Evidence | Exposed areas globally | Low-income groups<br>Children (e.g. child labor, removal from school)<br>Girls/young women (e.g., forced marriage) |
| Strained social cohesion and decline in reciprocity | Limited Evidence | Exposed areas globally | Low-income groups, groups experiencing sudden impoverishment and competition for resources |

Strong Evidence    Moderate Evidence    Limited Evidence

**Table 2.2:** Continued.

| POTENTIAL IMPACTS OF INTERACTING CLIMATE CHANGE AND BROADER DEVELOPMENT TRENDS | EVIDENCE BASE AND CONFIDENCE | EXAMPLES OF AFFECTED REGIONS, SECTORS, AND AREAS | EXAMPLES OF AFFECTED SOCIAL GROUPS |
|---|---|---|---|
| Worsening poverty as a result of mitigation strategies | | Tropical forests globally and farmland in Sub-Saharan Africa used for biofuels | Groups with limited land rights and socially excluded (indigenous groups, women, smallholders without formal tenure) |
| **Migration** | | | |
| Migration as a means for securing livelihoods in the face of slow-onset climatic stress | | Coastal cities and fertile deltas likely to attract more migrants<br>Small islands and coastal plains likely to see out-migration at higher levels of sea rise (e.g., Caribbean and Mediterranean Coast countries)<br>Maghreb countries serving as receiving and transit countries for Sahelian and other Sub-Saharan African migrants<br>Russian Arctic likely to experience flooding, subsidence and emigration, as well as some in-migration to exploit emerging farming and extractive opportunities | People with few or no land holdings are more likely to migrate<br>Men are more likely to migrate but this depends on local social norms and labor market opportunities; women left behind will face additional work burdens |
| Displacement (as a result of extreme events) | | Areas prone and vulnerable to hazards | Elderly and poorest are less likely to leave, and when they leave, they are at greater risk of permanent displacement<br>Displaced women sometimes find it more difficult to generate a livelihood (discriminatory labor markets) |
| **Health** | | | |
| Increase in malaria | | Highland areas<br>MENA and Colombia (LAC) | People who lack immunity<br>Children in poverty affected areas<br>Migrants<br>Low-income groups |
| Increase in dengue fever | | Tropical cities | Low-income groups |
| Increase in water-borne diseases (diarrheal disease and cholera) | | Tropical cities<br>Coastal populations | Children in poverty affected areas<br>Elderly populations<br>Low-income groups |
| Increase in respiratory diseases | | Globally | Older people and children<br>Women at risk from indoor air pollution<br>Low-income groups |
| Increase in food borne infectious diseases | | Globally | Low-income groups<br>Older people<br>Children |

Strong Evidence    Moderate Evidence    Limited Evidence

| POTENTIAL IMPACTS OF INTERACTING CLIMATE CHANGE AND BROADER DEVELOPMENT TRENDS | EVIDENCE BASE AND CONFIDENCE | EXAMPLES OF AFFECTED REGIONS, SECTORS, AND AREAS | EXAMPLES OF AFFECTED SOCIAL GROUPS |
|---|---|---|---|
| Reduction in availability of clean water and sanitation | | Coastal zones with low lying populations (e.g., Caribbean)<br>Cities reliant on highland or on declining ground water sources (e.g., the Andes, parts of Central Asia) | Low-income groups<br>Women and children (increased workloads and higher violence risks)<br>Poor children are especially vulnerable to disease |
| Increase in heat-related illnesses and reduced labor productivity | | Globally<br>Densely populated large cities<br>MENA, the Arabian peninsula | Elderly<br>Manual laborers and those working outdoors (more exposed to heat stress)<br>Overweight people<br>Displaced people living in shelters<br>Low-income groups<br>Residents of urban heat islands |
| Increased mortality rates from extreme weather events and disasters | | Low elevated coastal zones and land prone to flooding and landslides in all three regions | Women and girls at increased risk (if social norms prevent them from acquiring survival skills)<br>Men/ older boys (if expected to risk their lives to rescue others)<br>Children and older people<br>Low income households |
| Increase in mental illnesses | | Globally (areas exposed to extreme events or affected by slow-onset change) | Low-income groups<br>Displaced people |
| Increasing malnutrition | | Sub-Saharan Africa, South Asia, Central America, and MENA | Children (especially infants)<br>Subsistence farmers (in low rainfall areas)<br>Urban poor<br>Women (particularly in South Asia) |
| Potential for increased risk of domestic and sexual violence | | Globally (areas exposed to extreme events or affected by slow-onset change) | Women and children |
| **Conflict and Security** | | | |
| Risk of land and water scarcity (or excess of water) contributing to conflict/tensions | | Countries already affected by conflict (e.g., North Africa and Sub-Saharan Africa)<br>Countries where there are tensions between the mining industry and farmers/indigenous groups (e.g., Peruvian Andes)<br>Low-lying areas | Land holders<br>Farmers/ Subsistence Farmers<br>Farmers vs Herders<br>Indigenous groups |
| Extreme weather events or sudden disasters leading to conflict/social unrest | | More common where governance is weak or visibly inequitable | Low-income people and children |
| Protests related to increased food or fuel prices | | More common where governance is weak or visibly inequitable | Low-income urban groups |
| Increased risk of conflict through climate/ extreme event-induced displacement | | Countries where resources are scarce/or physically vulnerable to climate change with inequalities along ethnic/regional lines | Low-income groups<br>People who lack political recognition |

Strong Evidence | Moderate Evidence | Limited Evidence

# Chapter 3

# Latin America and the Caribbean

The Latin America and the Caribbean region encompasses a huge diversity of landscapes and ecosystems. The region is highly heterogeneous in terms of economic development and social and indigenous history. It is also one of the most urbanized regions in the world. In Latin America and the Caribbean, temperature and precipitation changes, heat extremes, and the melting of glaciers will have adverse effects on agricultural productivity, hydrological regimes, and biodiversity. In Brazil, without additional adaptation, crop yields could decrease by 30–70 percent for soybean and up to 50 percent for wheat at 2°C warming. Ocean acidification, sea level rise, and more intense tropical cyclones will affect coastal livelihoods and food and water security, particularly in the Caribbean. Local food security is also seriously threatened by the projected decrease in fishery catch potential. Reductions and shifts in water availability would be particularly severe for Andean cities. The Amazon rainforest may be at risk of large-scale forest degradation that contributes to increasing atmospheric carbon dioxide concentration and local and regional hydrological changes.

## 3.1 Regional Summary

The Latin America and Caribbean region is highly heterogeneous in terms of economic development and social and indigenous history with a population of 588 million (2013), of which almost 80 percent is urban. The current GDP is estimated at $5.655 trillion (2013) with a per capita GNI of $9,314 in 2013. In 2012, approximately 25 percent of the population was living in poverty and 12 percent in extreme poverty, representing a clear decrease compared to earlier years. Undernourishment in the region, for example, declined from 14.6 percent in 1990 to 8.3 percent in 2012. Despite considerable economic and social development progress in past decades, income inequality in the region remains high.

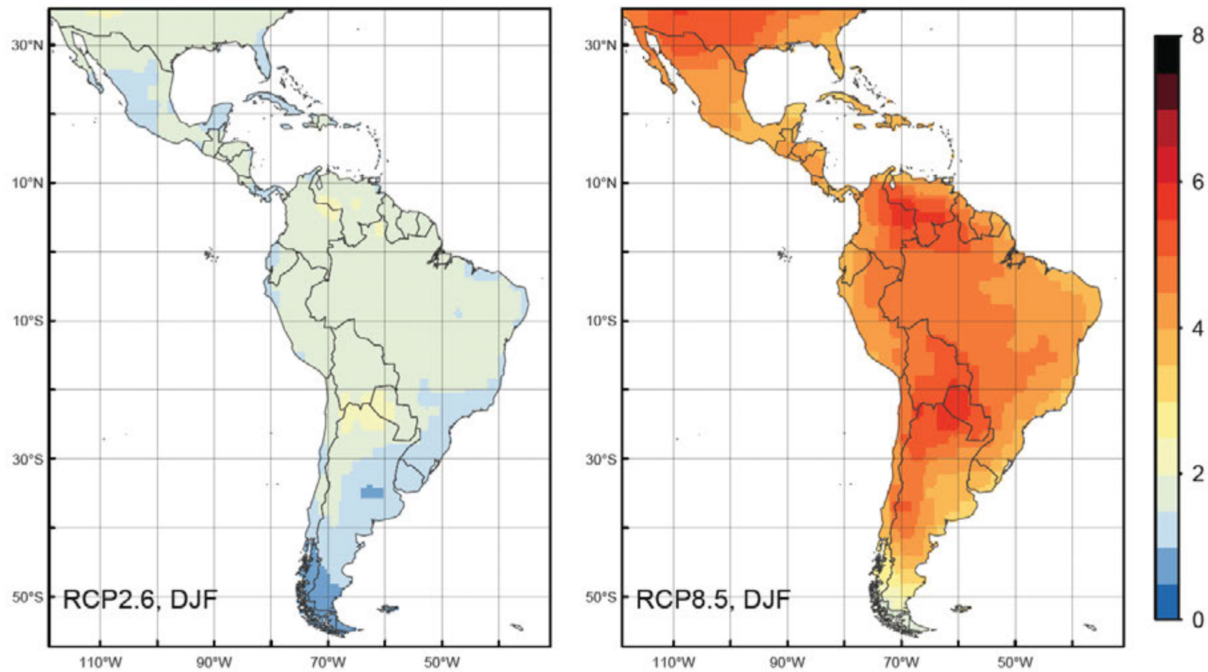
The region is highly susceptible to tropical cyclones and strong El Niño events, as well as to rising sea levels, melting Andean glaciers, rising temperatures and changing rainfall patterns. The rural poor who depend on a natural resource base are particularly vulnerable to climate impacts on subsistence agriculture and ecosystem services; the urban poor living along coasts, in flood plains, and on steep slopes are particularly vulnerable to extreme precipitation events and the health impacts of heat extremes. The intensive grain-producing cropping systems in the southern part of the region are mainly rain-fed and, as a result, susceptible to variable rainfall and temperatures. In the Andean regions, houses built on the often steep terrain are critically exposed to storm surface flows, glacial lake outbursts, and landslides. Coastal residents, particularly in the Caribbean region, face the risks of loss of ecosystem services and livelihoods from degrading marine ecosystems, loss of physical protection from degrading reefs, and coastal flooding, as well as from damages to critical infrastructure (especially in the beach front tourism sector) and threats to freshwater from sea water intrusion due to sea level rise.

### 3.1.1 Regional Patterns of Climate Change

#### *3.1.1.1 Temperatures and Heat Extremes*

By 2100, summer temperatures over the region will increase by approximately 1.5°C under the low-emissions scenario (a 2°C world) and by about 5.5°C under the high-emissions scenario (a 4°C world) compared to the 1951–1980 baseline (Figure 3.1). Along the Atlantic coast of Brazil, Uruguay, and Argentina, the warming is projected to be less than the global average, ranging between 0.5–1.5°C in a 2°C world and 2–4°C in a 4°C world. In the central South American region of Paraguay, in northern

**Figure 3.1:** Multi-model mean temperature anomaly for Latin America and the Caribbean for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the austral summer months (DJF).




Temperature anomalies in degrees Celsius are averaged over the time period 2071–2099 relative to 1951–1980.

Argentina, and in southern Bolivia, warming is likely to be more pronounced, up to 2.5°C in a 2°C world and up to 6°C in a 4°C world by 2071–2099. Similar levels of warming are projected for the equatorial region, including eastern Colombia and southern Venezuela. Projections indicate that in a 4°C world almost all land area (approximately 90 percent) will be affected by *highly unusual*,[28] and more than half of the land area (approximately 70 percent) by *unprecedented*, summer heat extremes.

### *3.1.1.2 Precipitation, Drought, and Aridity*

In general, in a 2°C world, precipitation changes are relatively small (+/–10 percent) and models exhibit substantial disagreement on the direction of change over most land regions. In a 4°C world, the models converge in their projections over most regions, but inter-model uncertainty remains over some areas (such as northern Argentina and Paraguay) (Figure 3.2). Tropical countries on the Pacific coast (Peru, Ecuador, and Colombia) are projected to see an increase in annual mean precipitation of about 30 percent. Similarly, Uruguay on the Atlantic coast (and bordering regions in Brazil and Argentina) will get wetter. Regions which are projected to become drier include Patagonia (southern Argentina and Chile), Mexico, and central Brazil. These patterns indicate that, under climate change, most dry regions will get drier and most wet regions will get wetter. The exception is central Brazil. The annual mean precipitation here is projected to drop by 20 percent in a 4°C world by the end of the century. In general, more intense and frequent extreme precipitation events also become more likely.

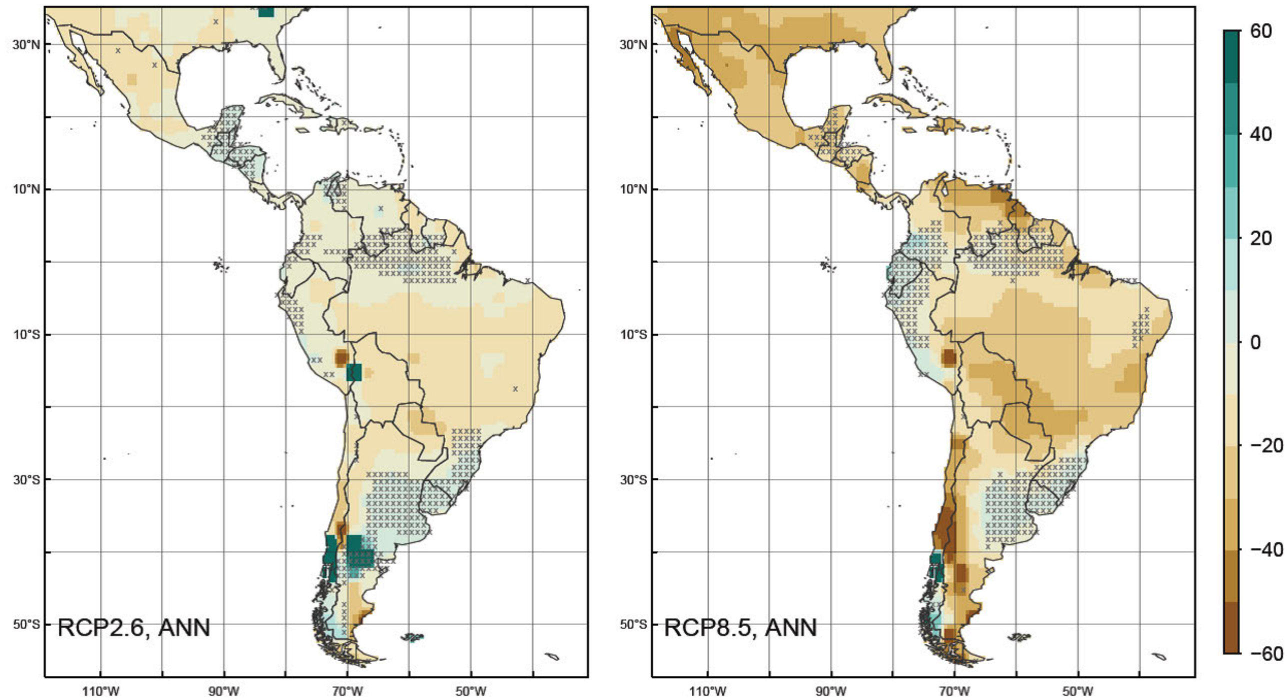
In a 4°C world, the Amazon basin, the full land area of Brazil except the southern coast, southern Chile, the Caribbean, Central America, and northern Mexico, are expected to be under severe to extreme drought conditions relative to the present climate by the end of the 21st century. The total area of land classified as hyper-arid, arid, or semi-arid is projected to grow from about 33 percent in 1951–1980 to 36 percent in a 2°C world, and to 41 percent in a 4°C world.

### *3.1.1.3 Tropical Cyclones*

Observations over the last 20–30 years show positive trends in tropical cyclone frequency and strength over the North Atlantic but not over the eastern North Pacific. While Atlantic tropical cyclones are suppressed by the El Niño phase of ENSO, they are enhanced in the eastern North Pacific. Under further anthropogenic climate change, the frequency of high-intensity tropical cyclones is generally projected to increase over the western North Atlantic by 40 percent for 1.5–2.5°C global warming and by 80 percent in a 4°C world. Global warming of around 3°C is associated with an average 10 percent increase in rainfall intensity averaged over a 200 km radius from a tropical cyclone's center. Although there

[28] In this report, *highly unusual* heat extremes refer to 3-sigma events and unprecedented heat extremes to 5-sigma events (see Appendix).

**Figure 3.2:** Multi-model mean of the percentage change in the aridity index under RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for Latin America and the Caribbean by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that a negative change corresponds to a shift to more arid conditions.[29]

is some evidence from multiple-model studies for a projected increase in frequency of tropical cyclones along the Pacific coast of Central America, overall projections in this region are currently inconclusive. Despite these inconclusive projections, however, any increase in Pacific and Atlantic storms (not necessarily cyclones) making landfall simultaneously would potentially entail more damaging impacts than increasing frequency of any individual Pacific or Atlantic cyclone.

## 3.1.2 Regional Sea-Level Rise

Sea-level rise is projected to be higher at the Atlantic coast than at the Pacific coast. Valparaiso (median estimate: 0.55 m for a 4°C world) is projected to benefit from southeasterly trade wind intensification over the Southern Pacific and associated upwelling of cold water leading to below-average thermosteric (due to ocean temperature rise) sea-level rise. In contrast, the Atlantic coast of Brazil is projected to experience above-average sea-level rise (Recife: median estimate: 0.63 m, low estimate: 0.41 m, high estimate: 1.14 m; Rio de Janeiro: median estimate: 0.62 m, low estimate: 0.46 m, high estimate: 1.11 m). Sea-level rise is exacerbated at low latitudes due to both increased ocean heat uptake and the gravity-induced pattern of ice sheets and glaciers. As an example, Guayaquil on the Pacific Coast of Ecuador is projected to experience 0.62 m (low estimate: 0.46 m, high estimate: 1.04 m) of sea-level rise in a 4°C world. In contrast, Puerto Williams (Chile) at the southern tip of the South American continent is projected to experience only 0.46 m (low estimate: 0.38 m; high estimate: 0.65 m). Port-Au-Prince (Haiti) is projected to experience 0.61 m (low estimate: 0.41 m, high estimate: 1.04 m) of sea-level rise in a 4°C world (Figure 3.11); it serves as a typical example for sea-level rise in other Caribbean islands.

## 3.1.3 Sector-based and Thematic Impacts

### *3.1.3.1 Glaciers and Snowpack Changes*

Glacial recession in South America has been significant. The tropical glaciers in the Central Andes in particular have lost major portions of their volume in the course of the 20th century. A clear trend of glacial retreat is also visible for glaciers in the southern Andes, which have lost about 20 percent of their volume.

[29] Some individual grid cells have noticeably different values than their direct neighbors (e.g., on the border between Peru and Bolivia). This is due to the fact that the Aridity index is defined as a fraction of total annual precipitation divided by potential evapotranspiration (see Appendix). It therefore behaves in a strongly non-linear way, and thus year-to-year fluctuations can be large. Since averages are calculated over a relatively small number of model simulations, this can result in these local jumps.

The recession of the tropical glaciers in the Central Andes will continue as rapidly as it has in recent decades. Even for low or intermediate emissions scenarios inducing a global warming of 2–3°C above pre-industrial levels, two comprehensive studies consistently project a glacial volume loss of 78–97 percent. Both studies predict an almost complete deglaciation (93–100 percent) for a 4°C world. Other studies are slightly less dramatic; irrespective of the temperature evolution in the next decades, however, large parts of the glaciers of the tropical Andes will be gone long before the end of the century. In the Southern Andes, the model spread for the 2–3°C global warming ranges from 22–59 percent glacier volume loss; a comparison for individual scenarios is difficult. In a 4°C world, models project a glacier volume retreat of 44–74 percent by 2100.

Monitoring of snow cover in the high altitudes of Chile and Argentina since 1950 shows no significant trend (possible trends are hard to identify in the records, since the inter-annual variability is large and clearly modulated by ENSO). The lack of reliable projections for snowpack and snow cover changes in the Andes is an important research gap.

#### 3.1.3.2 Water Resources, Water Security, and Floods

Although the magnitude of the change varies, there is a high agreement on decreasing mean annual runoff and discharge in Central America. Water stress may increase, especially in arid areas with high population densities and during the dry season. In the Caribbean, runoff projections are of low confidence due to lack of data. However, freshwater availability may decrease for several reasons, such as sea-level rise leading to an intrusion of sea water into coastal aquifers. Regionally, the risk of flooding and mudslides with high mortality rates is high. Although floods often seem to be associated with land-use change, more severe flooding events may also occur in the context of climate change.

Higher variability of seasonal discharge is projected for the Tropical Andes. Decreased streamflow during the dry season has already been observed, and may decrease further as a result of ongoing glacier retreat. However, streamflow during the wet season may increase. The Andean region could experience a higher flood risk in a 4°C world (e.g. due to accelerated glacier melting). In the Amazon Basin, runoff and discharge projections for most parts of the Amazon basin are diverging. For the western part of the basin a likely increase in streamflow, runoff, flood zone, and inundation time are projected. In southern most South America, a decrease in mean runoff is projected.

Although the Latin America and Caribbean region has an abundance of freshwater resources, many cities depend on local rivers, aquifers, lakes, and glaciers that may be affected by climate change—and freshwater supplies might not be enough to meet demand. For example, Guadalajara (Mexico) and many Andean cities are expected to face increasing water stress and, if the current demand continues, low-income groups who already lack adequate access to water will face more challenges.

#### 3.1.3.3 Climate Change Impacts on Agriculture, Livestock, and Food Security

The results of the climate change impact projections on crop yields differ among studies, but most authors agree that climate change will very likely decrease agricultural yields of important food crops in the Latin America and Caribbean region. An exception is the projected increase in yield of irrigated/flooded rice in some regions. The few available studies on climate change impacts on livestock indicate that beef and dairy cattle production will decline under increasing temperatures, as heat stress is a major influencing factor of cattle productivity. Sheep seem to cope better with warmer and drier conditions than cattle and pigs.

#### 3.1.3.4 Climate Change Impacts on Biodiversity

Climate change-induced negative effects on biodiversity, from range contractions to extinctions, are very likely in a warmer than 2°C world. As the adaptive capacity of affected species and ecosystems is hard to project or quantify, models need to use simplified approaches as implemented in bioclimatic envelope models, species-distribution models, and dynamic global vegetation models.

One clear trend regarding future warming levels is that the more temperature is projected to increase, the more species diversity is affected. Mountainous regions in the tropics (e.g., cloud forests) are projected to become very vulnerable due to the high number of endemic and highly specialized species which might face mountaintop extinction. Most models do not take biotic interactions (e.g., food-web interactions, species competition) or resource limitations into account. Therefore, the realized ecological niche of species within an ecosystem might become much smaller than what is potentially possible according to climatic and other environmental conditions, leading to shifts in ecological zones.

#### 3.1.3.5 Amazon Rainforest Degradation, Dieback, and Tipping Point

Overall, the most recent studies suggest that the Amazon dieback is an unlikely, but possible, future for the Amazon region. Projected future precipitation and the effects of $CO_2$ fertilization on tropical tree growth remain the processes with the highest uncertainty. Climate-driven changes in dry season length and recurrence of extreme drought years, as well as the impact of fires on forest degradation, add to the list of unknowns for which combined effects still remain to be investigated in an integrative study across the Amazon. A critical tipping point has been identified at around 40 percent deforestation, when altered water and energy feedbacks between remaining tropical forest and climate may lead to a decrease in precipitation.

A basin-wide Amazon forest dieback caused by feedbacks between climate and the global carbon cycle is a potential tipping point of high impact if regional temperatures increase by more than 4°C and global mean temperatures increase by more than 3°C toward the end of the 21st century. Recent analyses have, however, downgraded this probability from 21 percent to 0.24 percent for the 4°C regional warming level when coupled carbon-cycle climate models are adjusted to better represent the inter-annual variability of tropical temperatures and related $CO_2$ emissions. This holds true, however, only when the $CO_2$ fertilization effect is realized as implemented in current vegetation models. Moreover, large-scale forest degradation as a result of increasing drought may impair ecosystem services and functions, including the regional hydrological cycle, even without a forest dieback.

### 3.1.3.6 Fisheries and Coral Reefs

Together with ocean acidification and hypoxia, which are very likely to become more pronounced under high-emissions scenarios, the possibility of more extreme El Niño events poses substantial risks to the world's richest fishery grounds. Irrespective of single events, the gradual warming of ocean waters has been observed and is further expected to affect fisheries (particularly at a local scale).

Generally, fish populations are migrating poleward toward colder waters. Projections indicate an increase in catch potential of up to 100 percent in the south of Latin America. Off the coast of Uruguay, the southern tip of Baja California, and southern Brazil the maximum catch potential is projected to decrease by more than 50 percent. Caribbean waters and parts of the Atlantic coast of Central America may see declines in the range of 5–50 percent. Along the coasts of Peru and Chile, fish catches are projected to decrease by up to 30°percent, but there are increases expected toward the south.

Irrespective of the sensitivity threshold chosen, and irrespective of the emissions scenario, by the year 2040, Caribbean coral reefs are expected to experience annual bleaching events. While some species and particular locations appear to be more resilient to such events, it is clear that the marine ecosystems of the Caribbean are facing large-scale changes with far-reaching consequences for associated livelihood activities as well as for the coastal protection provided by healthy coral reefs.

### 3.1.3.7 Health

The Latin America and Caribbean region faces increased risks of morbidity and mortality caused by infectious diseases and extreme weather events. Observed patterns of disease transmission associated with different parts of the ENSO cycle offer clues as to how changes in temperature and precipitation might affect the incidence of a particular disease in a particular location. Projections of how malaria incidence in the region could be affected by climate change over the rest of the century are somewhat inconsistent, with some studies pointing to increased incidence and others to decreased incidence. Such uncertainty also characterizes studies of the relationship between climate change and malaria globally and reflects the complexity of the environmental factors influencing the disease.

### 3.1.3.8 Migration and Security

While migration is not a new phenomenon in the region, it is expected to accelerate under climate change. There are many areas in the Latin America and Caribbean Region prone to extreme events, including droughts, floods, landslides, and tropical cyclones; all of these extreme events can induce migration.

Examples indicate that drought-induced migration is already occurring in some regions. The largest level of climate migration is likely to occur in areas where non-environmental factors (e.g., poor governance, political persecution, population pressures, and poverty) are already present and putting migratory pressures on local populations.

The region is considered to be at low risk of armed conflict. However, in the context of high social and economic inequality and migration flows across countries, disputes regarding access to resources, land, and wealth are persistent. Climate change could increase the risk of conflict in the region through more resource scarcity, more migration, increasing instability, and increasing frequency and intensity of natural disasters.

### 3.1.3.9 Coastal Infrastructure

By 2050, coastal flooding with a sea-level rise of 20 cm could generate approximately $940 million of mean annual losses in the 22 largest coastal cities in the Latin America and Caribbean region, and about $1.2 billion with a sea-level rise of 40 cm. The Caribbean region is particularly vulnerable to climate change due to its low-lying areas and the population's dependence on coastal and marine economic activity. In a scenario leading to a 4°C world and featuring 0.89–1.4 m of sea-level rise, tropical cyclones in the Caribbean alone could generate an extra $22 billion by 2050 (and $46 billion by 2100) in storm and infrastructure damages and tourism losses, compared to a scenario leading to a 2°C world. The potential increase in tropical cyclone intensity may increase port downtime for ships and, therefore, increase shipping costs. Beach tourism is particularly exposed to direct and indirect climate change stressors, including sea-level rise, modified tropical storm patterns, heightened storm surges, and coastal erosion. Coastal tourist resorts are potentially two-to-three times more exposed to climate change-related stressors than inland touristic resorts.

### 3.1.3.10 Energy

The assessment of the current literature on climate change impacts on energy in Latin America and the Caribbean shows that there are only a few studies, most of which make strong assumptions about such key issues as seasonality of water supply for hydropower. These studies are more qualitative than quantitative and important gaps remain. There is also a lack of studies with respect to the impacts of climate change impacts on renewable energies.

In general, the impacts of climate change on energy demand are less well studied than those on energy supply—and, yet, demand and supply interact in a dynamic way. For example, the concomitant increase in energy demand during heat extremes and the decrease in energy supply through reduced river flow and low efficiencies may put existing energy systems under increasing pressure in the future.

### 3.1.4 Overview of Regional Development Narratives

The development narratives build on the climate change impacts analyzed in this report (see Table 3.15: Synthesis table of climate change impacts in LAC under different warming levels) and are presented in more detail in Section 3.5. Climate change impacts have manifold direct and indirect implications for development in the region. These impacts occur on a continuum from rural to urban; not only are there many climate impacts directly affecting rural spaces leading for example to reduced agricultural productivity or altered hydrological regimes, but these impacts also affect urban areas through changing ecosystem services, migration flows, and so forth. Development will likewise be impacted as the challenges of a changing climate mount and interact with socioeconomic factors. In particular, glacial melt and changing river flows, extreme events, and risks to food production systems will put human livelihoods under pressure.

Climate change impacts are and will continue to affect development across the region in several ways. First, changes to the hydrological cycle endanger the stability of freshwater supplies and ecosystem services. An altered hydrological system due to changing runoff, glacial melt, and snowpack changes will affect the ecosystem services that the rural population depends on, freshwater supplies in cities, and such major economic activities as mining and hydropower. Second, climate change places at risk both large-scale agricultural production for export and small-scale agriculture for regional food production. Third, a stronger prevalence of extreme events affects both rural and urban communities, particularly in coastal regions.

At the sub-regional level, the following climate-development interactions are particularly important. In Central America and the Caribbean, extreme events threaten livelihoods and damage infrastructure. In the Andes, changes in water resource availability challenge the rural and urban poor. In the Amazon, the risks of a tipping point, forest degradation, and biodiversity loss threaten local communities. Hydrological changes may affect the wider region. The Southern Cone faces risks to export commodities from loss of production from intensive agriculture. In the Mexican dry subtropical regions and northeastern Brazil, increasing drought stress threatens rural livelihoods and health.

## 3.2 Introduction

This report defines Latin America and the Caribbean (LAC) as the region encompassing the South American continent, Central America,[30] the Caribbean islands, and Mexico. It is constituted by the following countries: Antigua and Barbuda, Argentina, the Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador,


Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, St Kitts and Nevis, St Lucia, St Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, and Venezuela.

The region is very large and has a very diverse range of distributed ecosystems from the Andean mountains that stretch for about 8,850 kilometers, to mountain glaciers, vast rainforests, savannas, grasslands, wetlands, islands, deserts and a coastline that is over 72,000 kilometers long. There are broad differences in development levels both within and among countries (Table 3.1); these factors influence the social vulnerability of the population. In addition, current and projected climate change impacts vary strongly within the region, with some key impacts relating to changing temperatures and precipitation. Changes in extreme events (e.g., heatwaves, droughts, tropical cyclones, and changing ENSO patterns) (see Section 2.3.2, El-Niño/Southern Oscillation) and sea-level rise are also projected to vary across the region. These physical risk factors trigger biophysical impacts on hydrological flows, agricultural productivity, biodiversity in general, and forest dynamics in the Amazon in particular, coral reefs, and fisheries, as well as social impacts on human health, security, energy systems, and coastal infrastructure.

This report analyses these physical, biophysical, and social impacts in an integrated way using data analysis, model projections, and an intensive review of the scientific literature. Wherever possible, the results are regionally stratified.

[30] The World Bank Central America subregion includes the following countries: Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama.

**Table 3.1:** Basic Socioeconomic Indicators of LAC Countries

| INDICATOR | POPULATION | URBAN POPULATION | URBAN POPULATION GROWTH | GDP PER CAPITA | AGRICULTURE, VALUE ADDED[1] | LIFE EXPECTANCY AT BIRTH[2] |
|---|---|---|---|---|---|---|
| UNIT | MILLION | % OF POPULATION | ANNUAL % | CURRENT 1000 US$ | % OF GDP | YEARS |
| YEAR | 2012 | 2012 | 2012 | 2012 | 2011 | 2011 |
| ID | SP.POP.TOTL | SP.URB.TOTL .IN.ZS | SP.URB.GROW | NY.GDP.PCAP.CD | NV.AGR.TOTL.ZS | SP.DYN.LE00.IN |
| **Argentina** | 41.1 | 92.6 | 1.03 | 11.6 | 10.7 | 75.8 |
| **Antigua and Barbuda** | 0.1 | 29.9 | 1.01 | 12.7 | 2.5 | 75.5 |
| **Bahamas, The** | 0.4 | 84.4 | 1.75 | 21.9 | 2.3 | 74.8 |
| **Belize** | 0.3 | 44.6 | 2.01 | – | 13.1 | 73.5 |
| **Bolivia** | 10.5 | 67.2 | 2.27 | 2.6 | 12.5 | 66.6 |
| **Brazil** | 198.7 | 84.9 | 1.19 | 11.3 | 5.5 | 73.3 |
| **Barbados** | 0.3 | 44.9 | 1.65 | 14.9 | 1.5 | 75.0 |
| **Chile** | 17.5 | 89.3 | 1.13 | 15.5 | 3.7 | 79.3 |
| **Colombia** | 47.7 | 75.6 | 1.68 | 7.7 | 6.9 | 73.6 |
| **Costa Rica** | 4.8 | 65.1 | 2.12 | 9.4 | 6.5 | 79.5 |
| **Cuba** | 11.3 | 75.2 | –0.07 | 0.0 | 5.0 | 78.9 |
| **Dominica** | 0.1 | 67.3 | 0.57 | 6.7 | 13.5 | – |
| **Dominican Republic** | 10.3 | 70.2 | 2.07 | 5.7 | 6.0 | 73.0 |
| **Ecuador** | 15.5 | 68.0 | 2.43 | 5.4 | 10.4 | 75.9 |
| **Grenada** | 0.1 | 39.5 | 1.25 | 7.3 | 5.3 | 72.5 |
| **Guatemala** | 15.1 | 50.2 | 3.43 | 3.3 | 11.8 | 71.3 |
| **Guyana** | 0.8 | 28.5 | 0.88 | 3.6 | 21.3 | 65.9 |
| **Honduras** | 7.9 | 52.7 | 3.12 | 2.3 | 15.3 | 73.2 |
| **Haiti** | 10.2 | 54.6 | 3.85 | 0.8 | – | 62.3 |
| **Jamaica** | 2.7 | 52.2 | 0.36 | 5.4 | 6.6 | 73.1 |
| **St. Kitts and Nevis** | 0.1 | 32.1 | 1.41 | 14.3 | 1.8 | – |
| **St. Lucia** | 0.2 | 17.0 | –3.03 | 6.8 | 3.3 | 74.6 |
| **Mexico** | 120.8 | 78.4 | 1.60 | 9.7 | 3.4 | 76.9 |
| **Nicaragua** | 6.0 | 57.9 | 1.98 | 1.8 | 19.7 | 74.1 |
| **Panama** | 3.8 | 75.8 | 2.42 | 9.5 | 4.1 | 77.2 |
| **Peru** | 30.0 | 77.6 | 1.68 | 6.8 | 7.0 | 74.2 |
| **Puerto Rico** | 3.7 | 99.0 | –0.64 | 27.7 | 0.7 | 78.4 |
| **Paraguay** | 6.7 | 62.4 | 2.58 | 3.8 | 21.4 | 72.1 |
| **El Salvador** | 6.3 | 65.2 | 1.40 | 3.8 | 12.5 | 71.9 |
| **Suriname** | 0.5 | 70.1 | 1.47 | 9.4 | 10.0 | 70.6 |
| **Trinidad and Tobago** | 1.3 | 14.0 | 2.26 | 17.4 | 0.5 | 69.7 |
| **Uruguay** | 3.4 | 92.6 | 0.45 | 14.7 | 9.4 | 76.8 |
| **St. Vincent and the Grenadines** | 0.1 | 49.7 | 0.80 | 6.5 | 6.4 | 72.3 |
| **Venezuela, RB** | 30.0 | 93.7 | 1.73 | 12.7 | – | 74.3 |

Note: [1]Agriculture corresponds to ISIC divisions 1–5 and includes forestry, hunting, and fishing, as well as cultivation of crops and livestock production. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources.
[2]Life expectancy at birth indicates the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life. Source: World Bank (2013b).

### 3.2.1 Social, Economic and Demographic Profile of the Latin America and Caribbean Region

The Latin America and Caribbean Region comprises a population of 588 million (in 2013) of which almost 80 percent is urban. The current GDP is estimated at US$ 5.655 trillion (in 2013) with a GNI per capita of US$ 9,314 in 2013. In 2012, approximately 28.2 percent of the population were living in poverty and 11.3 percent in extreme poverty or deprivation (ECLAC 2014). These figures represent a decrease of about 1.4 percent in the poverty rate with respect to 2011 (ECLAC 2014). Although the number of people living in poverty in the region has been going down slowly, in absolute terms, this means that 164 million people were poor—of whom 66 million were extremely poor (ECLAC 2014).

Despite progress in the past decade and a growing middle class now surpassing the number of poor, inequality in the region remains high, and may be stagnating. Thirty eight percent of the population live just above the poverty line on an income of $4–10 per day (Fereira et al. 2013).

Income inequalities in the region affect vulnerability to climate change, as the poor are more likely to be exposed to both climate and economic shocks and limited ability to prepare for or mitigate impacts. Haldén (2007) notes that disparities and divisions could impede growth and undermine adaptation strategies, with the additional risk that substantial inequality might also destabilize societies and increase the likelihood of conflict in the light of climate change and variability (see Section 2.5, Social Vulnerability to Climate Change). These income inequalities are further exacerbated by gender, spatial, and ethnic inequalities. Ethnicity correlates closely with poverty. In seven countries for which data are available, the poverty rate is 1.2–3.4 times higher for indigenous and afrodescendent groups than for the rest of the population (ECLAC and UNFPA 2009). Furthermore, while indigenous peoples in LAC represent 10 percent of the population, their income levels and human development indicators (e.g., education and health status) have consistently fallen behind those of the rest of the population (Hall and Patrinos 2005).

The region's population is expected to rise to 622 million in 2015 and to 700 million by 2030. The distribution of the population is increasingly urban. In 2010, the urban population accounted for 78.8 percent of the total; this number is projected to rise to 83.4 percent by 2030 (ECLAC 2014). The concentration of poverty in urban settlements is a central determinant of vulnerability to climate change. In addition, differences in fertility levels of social groups in Latin America and the Caribbean show that the poor segments of the urban population contribute most to urban growth, exacerbating the contribution of predominantly poor rural-urban migrants. Residents in densely populated low-income settlements (Ravallion et al. 2008) are more likely to be adversely affected by climate extremes.

### 3.2.2 Vulnerabilities to Climate Change in the Latin America and the Caribbean Region

In the LAC region, climate change is expected to accentuate pre-existing socioeconomic vulnerabilities. People living in low-lying coastal areas, slums (Douglas et al. 2008), and certain population groups (such as poor (Ahmed et al. 2009; Hertel et al. 2010) and women-led households (Kumar and Quisumbing 2011)), are particularly exposed to shocks and future climate change risks.

Several socioeconomic and physical factors can contribute to increasing the vulnerability of populations to climate change. For example, poverty hinders households' adaptive capacity (Kelly and Adger 2000). According to Calvo (2013), the following characteristics of the population in the LAC region increase the exposure to climate change impacts and the likelihood of being affected by economic shocks: (1) one third of the population can be classified as poor or extremely poor, so that any shock can push them into further poverty; (2) there are more children in poor and extremely poor households given the higher fertility rates amongst the poor, so that shocks can have particularly adverse consequences for children, given that they are at a stage of life with greater needs and dependency; and (3) poor households have members with fewer years of formal education, which can limit their capacity to adapt to climate change impacts or macroeconomic shocks.

### 3.2.3 Vulnerabilities Faced by Rural Populations

Even though urban and rural areas have both experienced poverty reduction, the gap between the rural and urban experience is still wide. In 2010, the rural poverty rate was twice as high as that of urban areas; when considering extreme poverty, it was four times as high (IFAD 2013). Close to 60 percent of the population in extreme poverty lives in rural areas (RIMISP 2011). Many rural people in the region continue to live on less than $2 per day and have poor access to financial services, markets, training, and other opportunities. The rural poor are thus more likely to feel the impacts of climate change and variability given their dependency on small-hold, rain-fed agriculture and other environmental resources that are particularly susceptible to the effects of climate change (Hoffman and Grigera 2013). Moreover, these populations have limited political influence and are less able to leverage government support to help curb the effects of climate change (Hardoy and Pandiella 2009). The dependence of the rural population on land as a source of food and income, coupled with lack of physical and financial adaptive capacity, means that poor farmers are also at increased risk of harm from slow-onset change (Rossing and Rubin 2011).

### 3.2.4 Urban Settlements and Marginalized Populations

In addition to high levels of urbanization, in many countries in the region a high proportion of the urban population lives in a few very large cities. National economies, employment patterns, and government capacities—many of which are highly centralized—are also very dependent on these large cities. This makes them extremely vulnerable (Hardoy and Pandiella 2009). Based on two global model studies, Ahmed et al. (2009), Hertel et al. (2010), and Skoufias et al. (2011) estimate that urban salaried workers will be the most affected by climate change given the increase in prices of food resulting from reduced agricultural production. Increasing pressure on rural economic activities induced by droughts, heat waves, or floods—also driven by future climate change impacts—could result in a greater rural exodus and add further pressure on human and economic development in cities (Marengo et al. 2012, 2013; Vörösmarty et al. 2002).

Spatial vulnerability within urban centers is a major source of risk. There are particularly hazardous areas within Latin American cities where settlements have been built, including flood plains (Calvo 2013). These settlements already face infrastructural problems that affect water supplies, sanitation, and solid waste management as they were built for less populated cities. This leaves these areas at greater risk of flooding and other disasters (Hardoy and Pandiella 2009) (Box 3.1). In 2004, for example, 14 percent of the population in the LAC region (more than 125 million people) did not have access to improved sanitation, and an even-higher percentage lacked good quality sanitation and drainage. Limited access to sanitation and freshwater sources is also a key source of vulnerability as this increases the risk of the spread of water-borne diseases (McMichael and Lindgren 2011; McMichael et al. 2012).

Houses in informal settlements are built incrementally with deficient materials and no attention to building or zoning regulations. As a result, a significant share of the population is exposed to flooding, contamination of groundwater by salt water, and constraints on the availability and quality of drinking water, as well as to a rising sea level (Magrin et al. 2007). In addition, the impacts of extreme weather events are more severe in areas that have been previously affected and have not yet been able to recover properly, with cumulative effects that are difficult to overcome. Limited disaster preparation and a lack of planning compound the problems (Martí 2006).

A great deal of urban expansion in the region has taken place over floodplains, on mountain slopes, and in other zones ill-suited to settlement, such as areas prone to flooding or affected by seasonal storms, sea surges, and other weather-related risks. Such land is cheap or is state-owned land and relatively easy for low-income groups to occupy. In most cases, the poor have no formal tenure of the land and face not only environmental risks but also the risk of eviction. Left with few options, low-income groups live in overcrowded houses in neighborhoods with high population densities (Hardoy and Pandiella 2009). All these factors contribute to a high level of vulnerability to floods and landslides.

In most LAC cities there are concentrations of low-income households at high risk from extreme weather (Hardoy et al. 2001). For example, an estimated 1.1 million people live in the favelas of Rio de Janeiro that stretch over the slopes of the Tijuca mountain range (Hardoy and Pandiella 2009). Most low-income groups live in housing without air-conditioning or adequate insulation; during heat waves, the very young, the elderly, and people in poor health are particularly at risk (Bartlett 2008; see also Section 3.4.7, Human Health). In northern Mexico, for example, heat waves have been correlated with increases in mortality rates; in Buenos Aires, 10 percent of summer deaths are associated with heat strain; and records show increases in the incidence of diarrhea in Peru (Mata and Nobre 2006).

Although LAC has an abundance of freshwater resources, many cities depend on local rivers, underground water, lakes, and glaciers that may be affected by climate change (see Section 3.4.1, Glacial Retreat and Snowpack Changes and Section 3.4.2, Water Resources, Water Security, and Floods). Considering city growth, environmental deterioration, and possible climate change impacts, the supply of fresh water might not be enough to meet demand. Guadalajara in Mexico (Von Bertrab and Wester 2005) and many Andean cities may face increasing water stress and, if the current

#### Box 3.1: Hurricane Mitch's Impact in Urban Areas

In 1998, Hurricane Mitch cut a swath across Central America, hitting Honduras especially hard. Overall, 30 percent of the central district of Honduras, including the cities of Tegucigalpa, was destroyed. Most of the damage was concentrated around the four rivers that cross the cities; as a result, 78 percent of Tegucigalpa's drinking water supply pipelines were destroyed. Factors that increased the vulnerability of the city included obsolete and inadequate infrastructure, especially regarding water, sanitation, and drainage; a lack of zoning codes; concentration of services and infrastructure in only a few areas; a lack of official prevention and mitigation strategies; and inappropriate management of the river basins. Source: Hardoy and Pandiella (2009).

situation continues, low-income groups who already lack adequate access to water will be even less likely to obtain it. Quito is likely to face water shortages as a result of glacier retreat (Hardoy and Pandiella 2009). In Santiago de Chile, an estimated 40 percent reduction in precipitation would impact water supply in a city that is expecting a 30 percent population growth by 2030 (Heinrichs and Krellenberg 2011). A similar situation exists in Sao Paulo, where the local catchment of Alto Tiete provides just 10 percent of the water supply for 11 million people and where urban areas are expanding over agricultural and natural areas; this is impacting the area's storm-water retention capacity, thereby making the city more prone to flood events (Heinrichs and Krellenberg 2011).

## Box 3.2: The Case of Mexico City

Mexico City provides a good case study for examining the potential future impacts of climate change on urban areas in the region. The main climate-related risk factors in Mexico City stem from increased dry-spell periods and heat waves (see Section 3.3.2, Heat Extremes).

Greater Mexico City, with about 20 million inhabitants, is among the most highly populated cities on the planet. Despite a very high GDP per capita, the city exhibits a very large income inequality, with about 13 percent of the population lacking enough money to meet minimum food needs and approximately 23 percent unable to access education or affordable health care (Ibarrarán 2011).

According to UN-Habitat, Mexico City is already exposed to several environmental challenges: The urban region is rapidly expanding, increasing the demand for space, infrastructure, water, and energy. This taxes already-deficient water supplies and an inadequate sewage system. Waste management is similarly challenging, as collection, transportation, and adequate final disposal are limited compared to the daily volume of waste produced by the 20 million inhabitants of the city.

In addition to these preexisting socioeconomic and environmental vulnerabilities, climate change stressors are projected to increase Mexico City's overall vulnerability. Four principal climate-related stressors are projected to affect Mexico City: (1) the higher frequency of heat waves and hotter days; (2) the decreased instance of cooler days; (3) the increased occurrence of flash floods; and (4) the extension of summer droughts (Ibarrarán 2011). An increase in the frequency of heat waves could have two potential consequences in Mexico City. First, the steadily growing elderly population will be particularly exposed as they are more sensitive to heat extremes than the rest of the population (Gasparrini and Armstrong 2011). Second, in response to heat waves, the population could purchase more air conditioning and cooling systems. This may put power plants under severe stress, particularly as they work less efficiently under higher temperatures. The extension of the summer droughts is projected to increase Mexico City's water stress situation (Novelo and Tapia 2011; Romero Lankao 2010). Furthermore, the increased occurrence and extension of summer droughts may disproportionately impact the rural population, who may then be more inclined to migrate to cities to find less climate-dependent economic activities (Ibarrarán 2011). As a consequence, the population of Mexico's urban areas is expected to grow, putting more pressure on the urban environments and resources.

#### *3.2.4.1 Gender and Age-specific Vulnerabilities*

In the context of a male-dominated, patriarchal society, gender and age are important aspects of vulnerability in the LAC region. Many women and children are particularly vulnerable to the effects of climate change as they have limited access to resources and fewer capabilities and opportunities for participating in decision and policy making (Hardoy and Pandiella 2009). The most vulnerable groups seldom have an influential voice with regard to disaster preparedness or response, and their needs receive little attention.

Economic dependency places women and children in a particularly disadvantaged situation, and climate change could exacerbate the problem. According to ECLAC and UNFPA (2009), poverty is 1.7 times higher among minors under 15 than in adults, and 1.15 times greater among women than men. For example, in Uruguay poverty is 3.1 times higher among children than adults; in Chile, it is 1.8 times greater; and, in Nicaragua, it is 1.3 times greater. Sudden-onset disasters or a worsening of drought conditions have the potential to trigger severe acute malnutrition with greater effects on women and children (see Section 2.5, Social Vulnerability to Climate Change).

There are various ways in which women can be affected by climate change differently than men. One way is through the rise in domestic violence in the context of environmental disasters. Gender-based violence is already a significant problem for women in LAC, where most studies estimate that prevalent physical violence between intimate partners affects between 20–50 percent of women. While there are important differences in the estimates, studies similarly find that 8–26 percent of women and girls report having been sexually abused (Morrison et al. 2004). Moser and Rogers (2005) indicate that rapid socioeconomic changes—such as those that can occur as a result of climate shocks—might have destabilizing effects within families, leading to an increased risk of domestic violence. Although evidence of the effects of climate-induced disasters in the region remains mixed and limited, accounts of gender-based violence have been found in Nicaragua after Hurricane Mitch, in the Dominican Republic after Tropical Storm Noel, and in Guatemala after Tropical Storm Agatha (Bizzarri 2012).

Some groups of indigenous women are also particularly vulnerable given their involvement in specific activities. Within indigenous populations in the Colombian Amazon, for example, impacts on horticulture would affect mainly women as they are traditionally in charge of this activity (Kronik and Verner 2010). However, not all gender differences are necessarily worse for women and children. For example, in the case of indigenous groups, impacts in the availability of fish and game will affect mainly young men (Kronik and Verner 2010).

Changes in migration patterns as a result of climate change are also likely to have important effects on women. While traditionally it is young males who have migrated domestically or abroad, over the past two decades rural indigenous women have also started migrating, generally with the support of their social and family networks. Studies indicate that the experiences of migrant indigenous women tend to be less favorable, however, as they become vulnerable and disadvantaged by discrimination, lack of previous crosscultural experiences, illiteracy, and language barriers. Because of these barriers, their only option for work tends to be low-wage employment in the informal sector (Andersen et al. 2010).

#### 3.2.4.2 Indigenous People

There are about 40 million indigenous people within the LAC region, with the majority located in the cooler high regions of the Andes and in Mesoamerica (Kronik and Verner 2010). The indigenous population is made up of about 400 indigenous groups (Del Popolo and Oyarce 2005), of which about 30 percent are afrodescendant (Rangel 2006). Bolivia is the country with the highest share of indigenous people (66 percent) and Mexico has the highest absolute number (Table 3.2). When compared to non-indigenous groups, the profile of indigenous peoples shows that they have higher levels of poverty and infant and maternal mortality, lower levels of life expectancy, income, and schooling, and less access to water and sanitation; together, this highlights the exclusion of and discrimination against these groups (Del Popolo and Oyarce 2005; World Bank 2014). As a response to urbanization, indigenous populations in LAC are found both in urban and rural areas (Del Popolo and Oyarce 2005). Popolo et al. (2009) found that on average 40 percent of the indigenous population in 11 countries in Latin America were living in urban areas in 2000/2001. Whereas the ratio varies from country to country, recent census information highlights that 21.4 percent of indigenous peoples in Colombia (Paz 2012), 54 percent in Bolivia (Molina Barrios et al. 2005), 55.8 percent in Peru (Ribotta 2011), 64.8 percent in Chile, (Ribotta 2012a), and 82 percent in Argentina (Ribotta 2012b) are currently living in towns and cities.

Understanding the climate change impacts on indigenous populations requires an understanding of the cultural dimension of their livelihood strategies and the social institutions that support them (Kronik and Verner 2010). In rural areas, indigenous groups are particularly vulnerable to climate change because of their reliance on natural resources, traditional knowledge systems, and culture (Kronik and Verner 2010) and due to poor access to infrastructure and technology (Feldt 2011). Indigenous populations with greater territorial autonomy, and with their livelihoods more intertwined with forest and water resources, are therefore more affected by climate change when compared to indigenous populations with restricted territorial autonomy (whose livelihoods are more diversified, and include wage labor, tourism, and other income-generating activities) (Kronik and Verner 2010). Indigenous groups with territorial autonomy are normally located in the Amazon region whereas those without are more likely to be found in the Andes (Kronik and Verner 2010).

Kronik and Verner (2010) studied the impacts of climate change on indigenous populations in the LAC region, in particular on those

**Table 3.2:** Total Population and Indigenous Population Census 2000

| COUNTRY AND CENSUS YEAR | TOTAL POPULATION | INDIGENOUS POPULATION | % INDIGENOUS POPULATION | RECOGNIZED PEOPLES GROUPS |
|---|---|---|---|---|
| **Bolivia (2001)** | 8,090,732 | 5,358,107 | 66.2 | 36 groups (49.5% Quechua, 40% Aymara) |
| **Brazil (2000)** | 169,872,856 | 734,127 | 0.4 | 241 groups |
| **Costa Rica (2000)** | 3,810,179 | 65,548 | 1.7 | |
| **Chile (2002)** | 15,116,435 | 692,192 | 4.6 | 9 groups (83% Mapuche) |
| **Ecuador (2001)** | 12,156,608 | 830,418 | 6.8 | |
| **Guatemala (2002)** | 11,237,196 | 4,433,218 | 39.5 | 21 groups (all Maya) |
| **Honduras (2001)** | 6,076,885 | 440,313 | 7.2 | |
| **Mexico (2000)** | 97,014,867 | 7,618,990 | 7.9 | 62 groups |
| **Panama (2000)** | 2,839,177 | 285,231 | 10.0 | 3 groups (Ngöbe-Buglé, Kuna, and Embera-Wounan) |
| **Paraguay (2002)** | 5,183,074 | 87,568 | 1.7 | |

Please note that data are from 2000 but used here to provide a comprehensive overview of the share of indigenous population. Sources: Del Popolo and Oyarce (2005); Rangel (2006).

living in the Amazon, the Andes, the Caribbean, and in Central America. In the Colombian Amazon, they found the biggest direct impacts related to changes in the seasonal cycle (i.e., floods, and dry and rainy periods): river flooding affects fish and turtle reproduction, thereby impacting the food security of indigenous populations; changes in periods during which important local fruits ripen and the succession of dry and rainy seasons affect the harvests of wild fruits; and changes in the length of the dry season affects agriculture productivity, particularly in alluvial plateaus gardens. Increases in temperature and changes in precipitation affect mainly horticulture, favoring specific crops such as cassava but threatening harvest diversity (Echeverri 2009). Climate change and climate variability is also apparent in the 'decoupling' of ecological markers from seasonal changes (whereby seasons appear to occur significantly late or early), affecting livelihood decision-making in particular for indigenous peoples. This may affect the credibility of elders and traditional leaders, as their authority to predict the natural seasonality is challenged (Kronik and Verner 2010).

In the indigenous Andes, rising temperatures can increase demand for water. At the same time, higher evapotranspiration rates and glacial retreat are expected to reduce the water supply; restricting pasture land availability in the dry season, and potentially provoking conflict over land use (Kronik and Verner 2010). In the Bolivian Altiplano, however, Aymara communities have declared that high-elevation zones have now become productive, as changing climatic conditions have turned the area into arable land (Kronik and Verner 2010).

Indigenous populations in the Andes are not only subjected to biophysical vulnerability. In the rural Andes, social marginalization and social determinants that limit the ability to improve terms of labor, education and access to technical assistance, undermine the adaptive capacity of the indigenous population (McDowell and Hess 2012). In Palca (Bolivia), for example, farmers are not only vulnerable due to the retreat of the Mururata glacier and the resulting impact on water supply but also to historical marginalization due to the lack of official identity cards, land titles, or access to bilingual (Aymara-Spanish) basic education (McDowell and Hess 2012).

In the Caribbean and Central America, an increase in the frequency of some natural disasters (e.g., hurricanes) could limit the access of indigenous populations to key crop, forest, and fish resources (Kronik and Verner 2010); slow onset changes, meanwhile, could decrease the productivity of traditional varieties of maize, generating pressure to switch to more commercial varieties (Kronik and Verner 2010). Given that rural areas are mainly populated by indigenous groups—especially those that are most remote—means that they are the most likely to be affected. This is exacerbated by the strong dependence of indigenous groups on natural resources as well as by their reliance on traditional farming techniques. In contrast to the situation of rural indigenous populations, the vulnerability of indigenous groups living in urban areas is more related to the social conditions they face (e.g., discrimination and social exclusion) than linked to their livelihoods.

### 3.2.4.3 Risk for Populations in Coastal Areas

Coastal communities in the region are particularly exposed to climate change extremes and sea-level rise (Trab Nielsen 2010). The region's 64,000 km coastline is one of the most densely populated in the world (Sale et al. 2008). Coastal states have more than 521 million residents, of whom two-thirds (348 million) live within 200 km of the coastline. More than 8.4 million people in LAC live in the path of hurricanes, and roughly 29 million live in low-elevation coastal zones where they are highly vulnerable to sea-level rise, storm surges, and coastal flooding (McGranahan et al. 2007; UNEP 2007). For example, several countries have a large section of their urban population living in areas where elevation is below five meters above sea level (CIESIN 2011). In Belize, the Bahamas, Antigua and Barbuda, and Suriname, between 15 and 62 percent of the urban population live below five meters above sea level (Table 3.3). This low elevation significantly increases the urban population's exposure to sea-level rise, storm surges, and modified tropical storm patterns.

Furthermore, human activities such as overfishing, marine pollution, and coastal development have eroded the ecosystems in many coastal areas to a level where they no longer provide buffers to climate extremes. Climate change and variability are likely to compound the damage to ecosystems and to human settlements, directly through more intense and frequent storms and sea-level rise and indirectly through the further degradation of the ecosystems (Trab Nielsen 2010).

Coastal communities at greatest risk from climate change and variability are generally those that rely on natural resources for a living, occupy marginal lands, and have limited access to the livelihood assets that are necessary for building resilience to climate change. They include communities that rely on coastal tourism and on fisheries. They also include much of the region's large population of urban slum dwellers (Trab Nielsen 2010).

More than 50 percent of the Caribbean population lives along the coastline, and around 70 percent live in coastal cities (Mimura et al. 2007; UNEP 2008). Many economic activities (e.g., tourism) are also concentrated in coastal areas (UNEP 2008). Pressures arise on the islands over limited land resources as people are dependent on these natural resources for economic development and their livelihoods. The GDP of the region is generated mainly from two sectors—tourism and agriculture. Both are highly vulnerable to climate-induced hazards, including flooding, sea-level rise, storms, and coastal erosion (Karmalkar et al. 2013). Small islands are especially vulnerable to extreme events (UNEP 2008).

The east coast of Mexico and Central America, and the Caribbean, are strongly affected by wind storms and cyclones

**Table 3.3:** Percentage of Latin American and Caribbean Population Living in Urban Areas and Below Five Meters of Elevation.

| COUNTRIES | URBAN POPULATION IN PERCENTAGE OF TOTAL POPULATION (IN 2012) | PERCENTAGE OF POPULATION LIVING IN INFORMAL SETTLEMENTS (2005) | PERCENTAGE OF LAND AREA BELOW 5 METERS OF ELEVATION | PERCENTAGE OF URBAN POPULATION LIVING BELOW 5 METERS OF ELEVATION (2010) |
|---|---|---|---|---|
| **Caribbean Countries** | | | | |
| Antigua and Barbuda | 29.87 | 47.9 | 10.30 | 15.50 |
| Bahamas, The | 84.45 | – | 1.61 | 23.55 |
| Barbados | 44.91 | – | 0.92 | 0.92 |
| Belize | 44.59 | 47.3 | 0.56 | 17.36 |
| Cuba | 75.17 | – | 0.38 | 2.66 |
| Dominica | 67.30 | – | 1.39 | 3.05 |
| Dominican Republic | 70.21 | 17.6 | 0.20 | 0.90 |
| Grenada | 39.49 | 59.0 | 1.77 | 1.92 |
| Haiti | 54.64 | 70.1 | 0.20 | 2.44 |
| Jamaica | 52.16 | 60.5 | 2.05 | 3.08 |
| St. Kitts and Nevis | 32.11 | – | 9.25 | 9.46 |
| St. Lucia | 16.97 | 11.9 | 0.76 | 0.84 |
| St. Vincent and the Grenadines | 49.70 | – | 0.00 | 0.00 |
| Trinidad and Tobago | 13.98 | 24.7 | 1.68 | 2.85 |
| **Latin American Countries** | | | | |
| Argentina | 92.64 | 26.2 | 0.07 | 3.29 |
| Bolivia | 67.22 | 50.4 | 0.00 | 0.00 |
| Brazil | 84.87 | 28.9 | 0.06 | 3.04 |
| Chile | 89.35 | 9.0 | 0.02 | 0.65 |
| Colombia | 75.57 | 17.9 | 0.09 | 1.35 |
| Costa Rica | 65.10 | 10.9 | 0.08 | 0.26 |
| Ecuador | 67.98 | 21.5 | 0.29 | 4.68 |
| El Salvador | 65.25 | 28.9 | 0.10 | 0.11 |
| Guatemala | 50.24 | 42.9 | 0.02 | 0.04 |
| Guyana | 28.49 | 33.7 | 0.22 | 11.81 |
| Honduras | 52.73 | 34.9 | 0.05 | 0.49 |
| Nicaragua | 57.86 | 45.5 | 0.03 | 0.31 |
| Panama | 75.78 | 23.0 | 0.13 | 1.90 |
| Paraguay | 62.44 | 17.6 | 0.00 | 0.00 |
| Peru | 77.58 | 36.1 | 0.02 | 0.81 |
| Suriname | 70.12 | 38.9 | 0.27 | 62.04 |
| Uruguay | 92.64 | – | 0.14 | 3.65 |
| Venezuela, RB | 93.70 | 32.0 | 0.16 | 2.63 |
| **Mexico** | **78.39** | **14.4** | **0.15** | **1.30** |

Source: Data from CIESIN (2011); UN-HABITAT (2013); and World Bank (2013b).

(Maynard-Ford et al. 2008). Coastal areas are prone to storm surge floods and sea-level rise (Woodruff et al. 2013). Floods and hurricanes present both a high risk of death (Dilley et al. 2005) and a threat to regional development and economic stability in Central America and the Caribbean (Mimura et al. 2007).

## 3.3 Regional Patterns of Climate Change

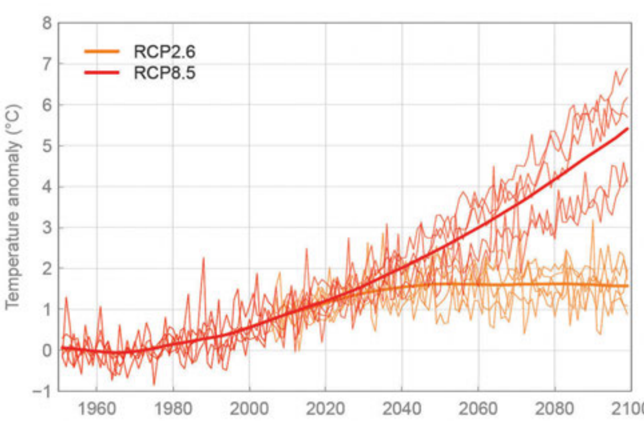
### 3.3.1 Projected Temperature Changes

Figure 3.3 shows projected austral summer (December, January, February—or DJF) temperatures for the LAC land area (see Appendix). By 2100, summer temperatures over the LAC land area will increase by ~1.5°C under the low-emissions scenario (a 2°C world) and by ~5.5°C under the high-emissions scenario (a 4°C world) compared to the 1951–1980 baseline. This is about 0.5°C less than the projected global mean land warming which is typical for the Southern Hemisphere (see Figure 2.5 in World Bank 2013). in a 2°C world, warming of 1.5°C (multi-model mean) is reached by mid-century. Summer temperatures will continue to increase beyond mid-century under the high-emissions scenario, causing the multi-model mean warming for the 2071–2099 period to be about 4.5°C (Figure 3.3. and Figure 3.4).

The regional maps (Figure 3.5) show rather uniform patterns of summer warming, with regions in the interior of the continent generally projected to see a somewhat stronger temperature increase. Along the Atlantic coast of Brazil, Uruguay, and Argentina, the warming remains limited, with about 0.5–1.5°C in a 2°C world and 2–4°C in a 4°C world. The central South American region of Paraguay, northern Argentina, and southern Bolivia will see more pronounced warming, up to 2.5°C in a 2°C world and up to 6°C in a 4°C world by 2071–2099. Similar levels of warming are projected for eastern Colombia and southern Venezuela.

The normalized warming (that is, the warming expressed in terms of the local year-to-year natural variability—see Appendix) is plotted in the lower panels of Figure 3.4. The normalized warming indicates how unusual the projected warming is compared to the natural fluctuations a particular region has experienced in the past, here the period 1951–1980 (Coumou and Robinson 2013; Hansen et al. 2012; Mora and Frazier et al. 2013). The tropics will see the strongest increase in normalized monthly summer temperatures since historic year-to-year fluctuations are relatively small. In the eastern part of the equatorial region between 15°S and 15°N, monthly temperatures will shift by 3–4 standard deviations in a 2°C world and by 6–7 standard deviations in a 4°C world. A shift of 3–4 standard deviations implies that an average monthly temperature in the future will be as warm as the most extreme monthly temperatures experienced today (i.e., events in the tail of the current distribution). A shift twice as large (i.e., 6–7 standard deviations) implies that extremely cold summer months by the end of the 21st century will be warmer than the warmest months today. Thus, in a 4°C world, monthly summer temperatures in tropical South America will move to a new climatic regime by the end of the century. Subtropical regions in the south (northern Argentina) and the north (Mexico) are expected to see a much less pronounced shift. Nevertheless, a shift by at least 1-sigma (in a 2°C world) or 2-sigma (in a 4°C world) is projected to occur here over the 21st century.

**Figure 3.3:** Temperature projections for the Latin American and Caribbean land area compared to the 1951–1980 baseline for the 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.



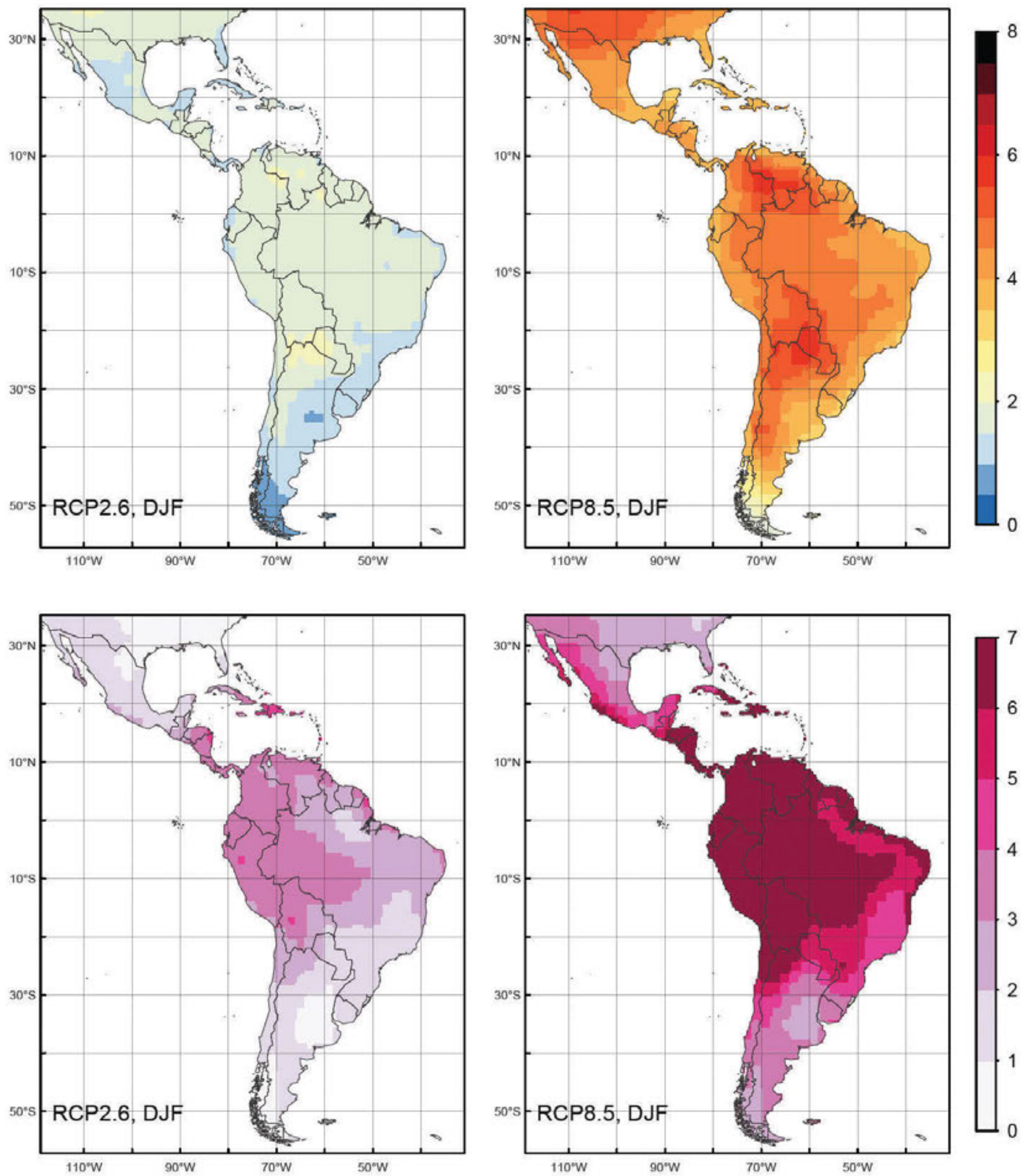

The multi-model mean has been smoothed to give the climatological trend.

### 3.3.2 Heat Extremes

Figure 3.5 and Figure 3.6 show a strong increase in the frequency of austral summer months (DJF) warmer than 3-sigma and 5-sigma (see Appendix) over LAC by the end of the century (2071–2099). The tropics, which are characterized by relatively small natural variability, will see the largest increase in such threshold-exceeding extremes. Especially along the tropical coasts, including Peru, Ecuador, and Colombia, summer month heat extremes will become much more frequent, consistent with the large shift in the normalized temperature distribution here (see Figure 3.5). The 5-sigma events, which are absent under present-day climate conditions, will emerge in these countries even in a 2°C world, and are projected to occur in roughly 20 percent of summer months. At the same time, 3-sigma events, which are extremely rare today, will become the new norm (i.e., this threshold will be exceeded in roughly half of the summer months during 2071–2099). In a 4°C world, almost all summer months will be warmer than 3-sigma and, in fact, most will be warmer than 5-sigma as well (70 percent). Thus, under this scenario, the climate in tropical South America will have shifted to a new hot regime.

Compared to the tropics, the subtropical regions in the north (Mexico) and south (Uruguay, Argentina, and southern Chile)

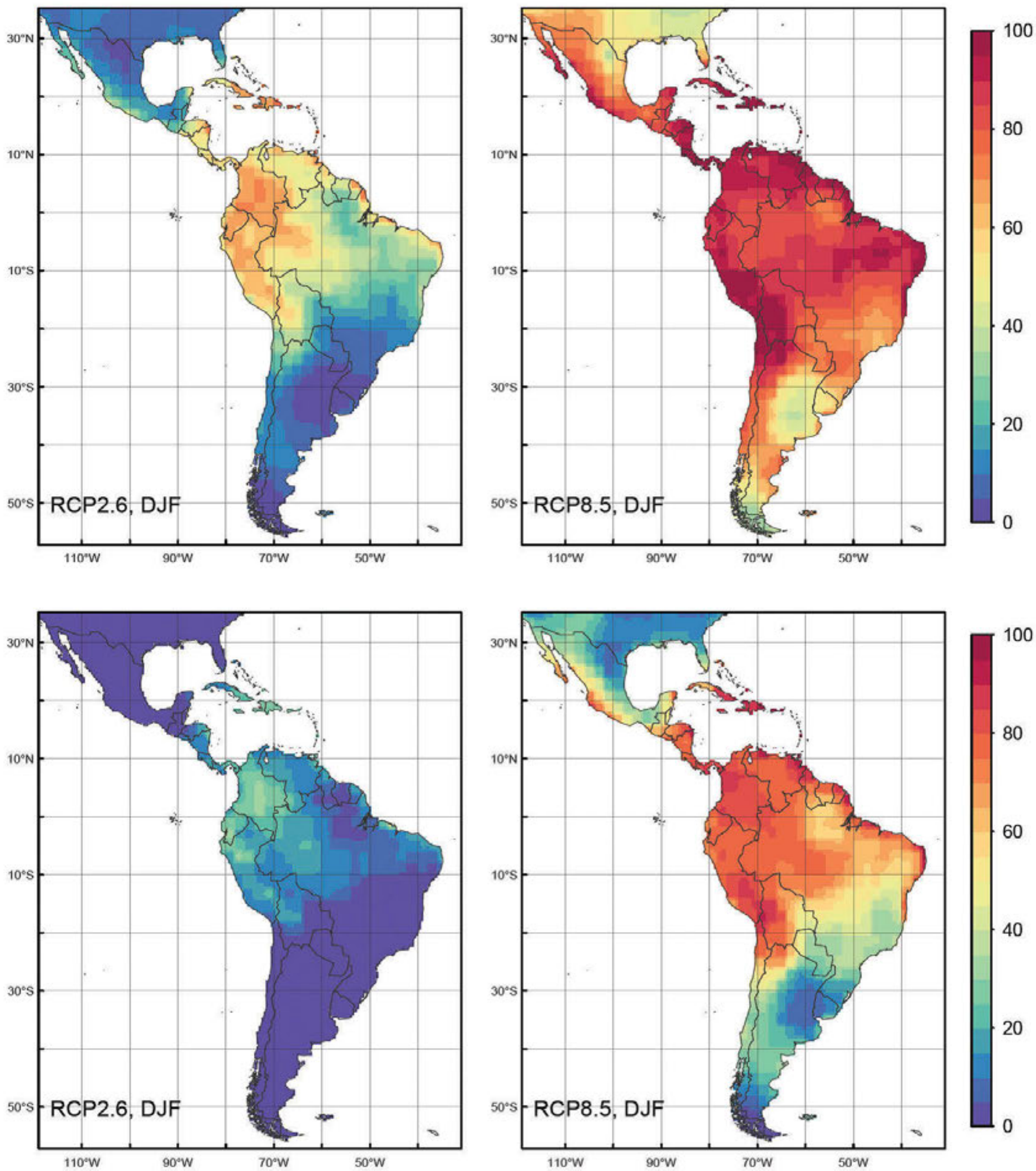
**Figure 3.4:** Multi-model mean temperature anomaly for Latin America and the Caribbean for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the austral summer months (DJF). Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–2099 relative to 1951–1980, and normalized by the local standard deviation (bottom row).




are projected to see a more moderate increase in the frequency of threshold exceeding extremes. In fact, in a 2°C world, 5-sigma events will remain absent and 3-sigma events will still be rare (less than 10 percent of summer months). In a 4°C world, however, a substantial increase in frequency is projected. In most subtropical regions, at least half of all summer months are expected to be warmer than 3-sigma by 2071–2099 (i.e., this will have become the new norm). Furthermore, 5-sigma events will also emerge and occur typically in about 20 percent of summer months over subtropical regions.

The strong increase in frequency of summer months warmer than 3- and 5-sigma in the tropics, as reported here, is quantitatively

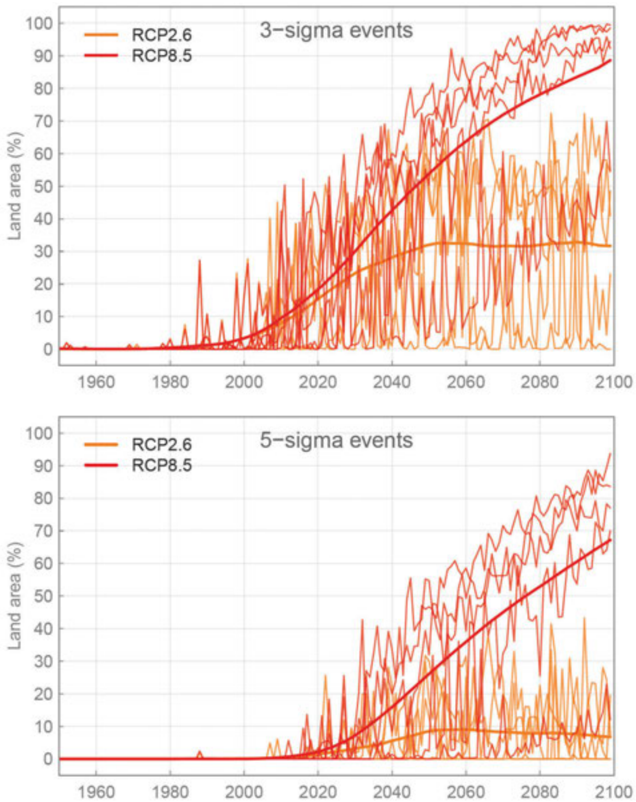
**Figure 3.5:** Multi-model mean of the percentage of austral summer months (DJF) in the time period 2071–2099 with temperatures greater than 3-sigma (top row) and 5-sigma (bottom row) for scenario RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) over Latin America and the Caribbean.




consistent with published results from analyses using the full CMIP5 dataset of climate projections (Coumou and Robinson 2013; Sillmann et al. 2013a; b). In addition, minimum night-time and maximum day-time temperatures in the summer are projected to increase by 1–2°C in a 2°C world and by 5–6°C in a 4°C world (Sillmann et al. 2013b), in good agreement with the projected seasonal mean temperatures in Figure 3.3.

The duration of warm spells is projected to increase most in the tropics—already by 60–90 days in a 2°C world and by 250–300 days in a 4°C world. In the tropics, temperatures experienced during the 10 percent warmest summer nights of the 1961–1990 period will occur most nights (50–70 percent) in a 2°C world and almost all nights (90–100 percent) in a 4°C world by the end of the century (Sillmann et al. 2013b).

**Figure 3.6:** Multi-model mean and individual models of the percentage of Latin American and Caribbean land area warmer than 3-sigma (top) and 5-sigma (bottom) during austral summer months (DJF) for scenarios RCP2.6 (2°C world) and RCP8.5 (4°C world).




Changes in heat extremes in subtropical regions are less dramatic but nevertheless pronounced. In the Southern Hemisphere subtropics, the length of warm spells increases by roughly 0–15 days (2°C world) or 30–90 days (4°C world). In the Northern Hemisphere subtropics (Mexico) these values roughly double, but they are still less than the increase in the tropics (Sillmann et al. 2013b). Nighttime temperatures experienced during the 10 percent warmest austral summer nights in 1961–1990 will occur in roughly 30 percent of nights (2°C world) and 65 percent of nights (4°C world).

### 3.3.3 Regional Precipitation Projections

Projected changes in annual and seasonal precipitation (see Appendix) are plotted in Figure 3.7 for the LAC region for 2071–2099 relative to 1951–1980. Note that projections are given as percentage changes compared to the 1951–1980 climatology and thus, especially over dry regions, large relative changes do not necessarily reflect large absolute changes. In general, in a 2°C world these changes are relatively small (+/–10 percent) and models exhibit substantial disagreement on the direction of change over most land regions. With a more pronounced climatic signal (i.e., a 4°C world, RCP8.5), the models converge in their projections over most regions, but inter-model uncertainty remains over some areas (hatched shading in the maps). Nevertheless, a well-defined pattern of change in annual precipitation can be extracted for defined sub regions. For example, tropical countries on the Pacific coast (Peru, Ecuador, and Colombia) are projected to see an increase in annual mean precipitation of about 30 percent. This enhanced rainfall occurs year-round and can be detected in both the austral winter and summer seasons. Similarly, Uruguay on the Atlantic coast (and bordering regions in Brazil and Argentina) are projected to get wetter. Again, this increase in annual rainfall is year-round, though it is most pronounced during the summer (DJF). Regions which are projected to become drier include Patagonia (southern Argentina and Chile), Mexico, and central Brazil. These patterns indicate that, under climate change, most dry regions may get drier and most wet regions may get wetter in the future (but see Greve et al. 2014 for a discussion of this concept for past climate). The exception is central Brazil (i.e. the region from 0–20°S and 50–65°W), which contains the southeastern part of the Amazon rainforest. The annual mean precipitation here is projected to drop by 20 percent in a 4°C world by the end of the century. This drop in annual rainfall is entirely due to a strong and robust decrease in winter (JJA) precipitation (–50 percent), with essentially no change in summer (DJF) precipitation. In fact, this reduction in winter precipitation appears already in a 2°C world.

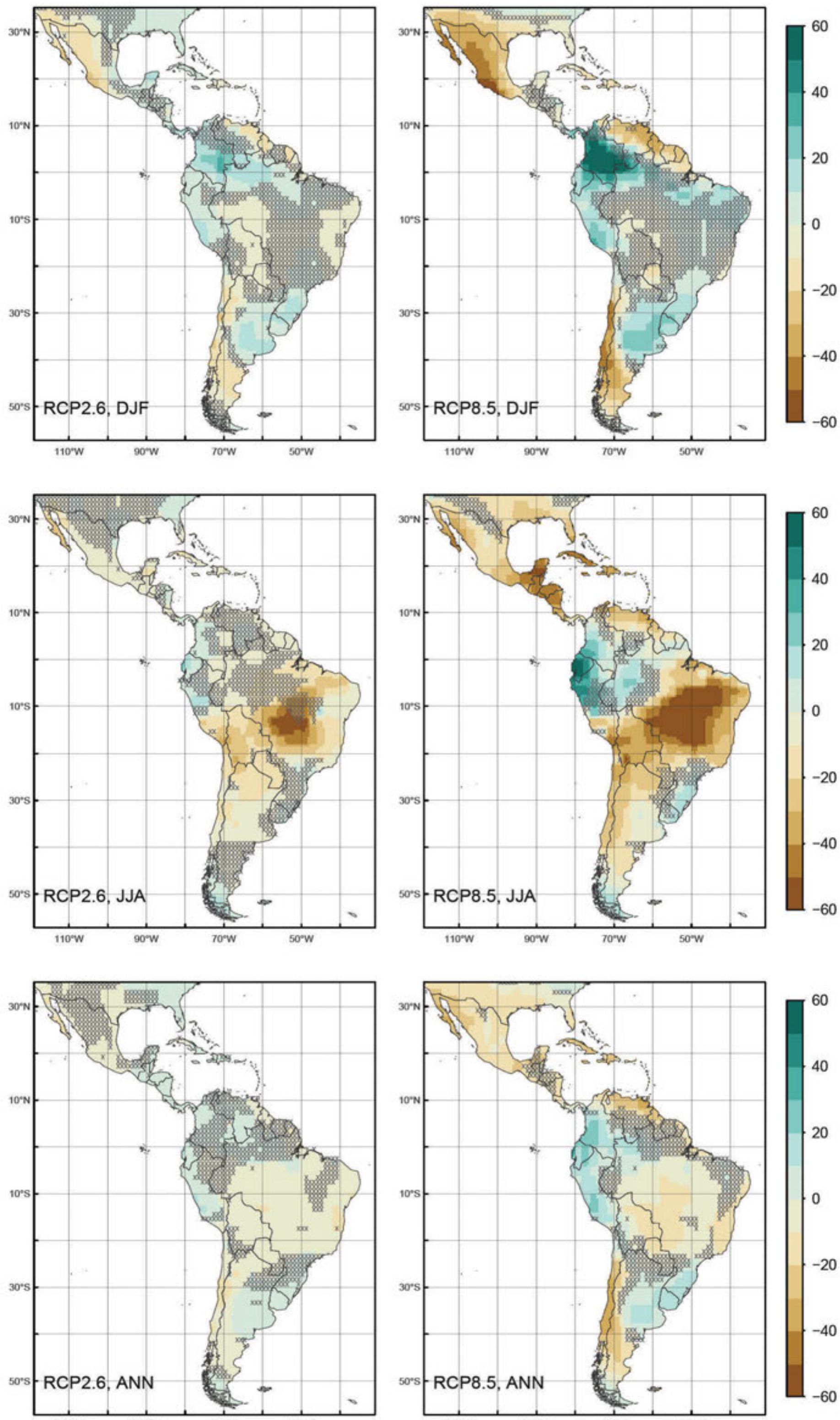
These projected changes in annual and seasonal temperatures generally agree well with those provided by the IPCC AR5 based on the full set of CMIP5 climate models (Collins et al. 2013). However, there is one important difference in that the full set of CMIP5 models shows significant JJA Amazon drying over northern Brazil only. Over central Brazil, the multi-model mean of the full set of CMIP5 models projects drying, as also seen in Figure 3.7, but the magnitude of change is small. Instead, significant drying over the full Amazon region primarily occurs during austral spring (September-October-November).

### 3.3.4 Extreme Precipitation and Droughts

Analysis of the observational record since the 1950s indicates a robust increase in overall precipitation and in intensity of extreme precipitation events for South America, particularly over southern South America and the Amazon region (Skansi et al. 2013). Long-term trends in meteorological droughts are not statistically robust over 1950–2010. Over the recent decade, however, two severe droughts (2005 and 2010) have affected the Amazon, likely connected to an anomalous warm tropical North Atlantic (Marengo et al. 2011; Zeng et al. 2008).

Dai (2012) finds a statistical significant increase in drought conditions for Central America and the Caribbean for the 1950–2010

**Figure 3.7:** Multi-model mean of the percentage change in austral summer (DJF, top), winter (JJA, middle) and annual (bottom) precipitation for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for Latin America and the Caribbean by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change.

period, although the significance of this trend depends on the reference period and the formulation of the underlying drought index (Trenberth et al. 2014). Fu et al. (2013) report a significant increase in the length of the dry season over southern Amazonia since 1979.

Using an ensemble of CMIP5 models, Kharin et al. (2013) investigated extreme precipitation events based on annual maximum daily precipitation with 20-year return values. In a 4°C world, these events are found to intensify by about 25 percent over LAC with a large uncertainty range.[31] In addition, the return time of a 20-year extreme precipitation event from the 1985–2005 period would reduce to about 6 years by the end of the 21st century (2081–2100) in a 4°C world (Kharin et al. 2013).

These increases are not, however, homogeneous over the full continent. This is consistent with the variable seasonal precipitation projections in Figure 3.7. While little-to-not statistically significant, an increase in frequency is projected for the Caribbean, Meso-America, Southern Argentina, and Chile, and hotspots with extreme precipitation increases of more than 30 percent are projected in the Serra do Espinhaco in Brazil, the Pampas region in Argentina, and the Pacific coastline of Ecuador, Peru, and Colombia (Kharin et al. 2013). The latter may be related to an increase in frequency of future extreme El Niño events (Cai et al. 2014; Power et al. 2013). These regions are also found to show the strongest rise in compound maximum 5-day precipitation (which is most relevant for flooding events) by the end of the 21st century in a 4°C world (Sillmann et al. 2013b). Increases in extreme precipitation in southern Brazil and northern Argentina are in line with results from regional climate models (Marengo et al. 2009) and might be dominated by intensification of the South American monsoon system (Jones and Carvalho 2013). Projections of extreme precipitation for Meso-America and the Caribbean discussed above do not comprehensively account for the risk of extreme precipitation related to tropical cyclones (that are discussed in Section 3.3.6, Tropical Cyclones/Hurricanes). In a 2°world, changes in heavy precipitation would be greatly reduced and barely significant over most parts of the continent.

While an increase in extreme precipitation represents a potential threat for some regions, increase in duration and intensity of droughts might represent the bigger threat over all of Latin America and the Caribbean. An increase and intensification in meteorological droughts is projected for large parts of South and Central America in a 4°C world (Sillmann et al. 2013b), although large model uncertainties remain in particular for Central America (Orlowsky and Seneviratne 2013). A more comprehensive analysis of future droughts accounting for the effects of runoff and evaporation as well as local soil and vegetation properties was undertaken by Dai (2012). He found that the Amazon basin, the full land area of Brazil except the southern coast, southern Chile, and Central America, and in particular northern Mexico, is expected to be under severe to extreme drought conditions relative to the present climate by the end of the 21st century under the RCP4.5. These results are confirmed by a multi-model impact analysis under a 4°C scenario that also reveals a strong increase in drought risk in the Caribbean, although uncertainties remain substantial (Prudhomme et al. 2013).

The increase in future drought risk in Central America and the Caribbean is generally related to an extension and intensification of the so-called midsummer drought period (Rauscher et al. 2008). While an overall reduction in precipitation during the dry season is robustly projected by regional and global models alike (Campbell et al. 2011; Karmalkar et al. 2013; Taylor et al. 2013), it is not clear if this will lead to an increase in meteorological drought conditions (e.g., an increase in the number of consecutive dry days) (Hall et al. 2012). This illustrates the added value of a comprehensive impact model analysis, as undertaken by Prudhomme et al. (2013), that accounts for the full change in the regional water cycle in investigating future drought risk.

Changes over the Amazon basin and eastern Brazil are found to be particularly pronounced during the dry season (from July to September), which amplifies the risk of large-scale forest degradation; this contrasts with Central America, Venezuela and southern Chile, where the drought risk is projected to increase during the austral summer (Prudhomme et al. 2013). Drought risks are found to be strongly scenario-dependent and to be much less pronounced in a 2°C world, in particular for Meso-America and the Caribbean; a substantial risk remains for South America under this scenario (Prudhomme et al. 2013).

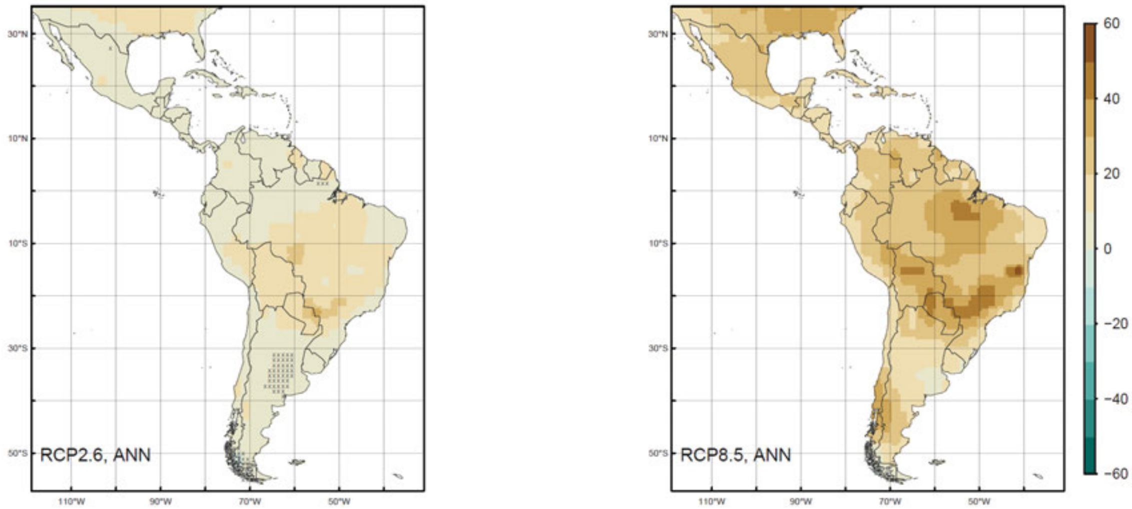
In the Amazon region, climate change is not the only anthropogenic interference expected over the decades to come; deforestation will be at least equally important. The link between large-scale deforestation and reduced precipitation is well established (e.g., Davidson et al. 2012; Medvigy et al. 2011; Runyan 2012), and Bagley et al. (2014) used a regional climate model to demonstrate that deforestation might have amplified the severe droughts over the last decade. However, none of the projections given above accounts for the possible adverse effects of deforestation and forest degradation on the climate of the Amazon region, which, in the presence of possible self-amplifying feedbacks between reduced forest cover and extreme droughts, represent a substantial risk of large-scale Amazon dieback (see Section 3.4.5, Amazon Rainforest Dieback and Tipping Point).

### 3.3.5 Aridity

Apart from a reduction in precipitation, warming can also cause a region to shift toward more arid conditions as enhanced surface temperatures trigger more evapotranspiration—thereby drying the soil. This long-term balance between water supply and demand is captured by the aridity index (AI), which is shown in Figure 3.9 for the Latin American region. The AI is defined as the total annual precipitation divided by the annual potential evapotranspiration

[31] The lower and upper limits of the central 50 percent inter-model range are 14 and 42 percent respectively.

**Figure 3.8:** Multi-model mean of the percentage change in the annual-mean of monthly potential evapotranspiration for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for Latin America and the Caribbean by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertainty regions with two or more out of five models disagreeing on the direction of change.

(see Appendix); it fundamentally determines whether ecosystems and agricultural systems are able to thrive in a certain area. A decrease in the value of the AI thus indicates that water becomes more scarce (i.e., more arid conditions), with areas classified as hyper-arid, arid, semi-arid, and sub-humid as specified in Table 3.4. Potential evapotranspiration is a measure of the amount of water a representative crop type would need over a year to grow, (i.e. a standardized measure of water demand; see Appendix). Under most circumstances, changes in potential evaporation are governed by changes in temperature.

Changes in annual-mean potential evapotranspiration (Figure 3.8) broadly follow those of absolute warming (Figure 3.4), with regions in the continental interior generally experiencing the strongest increase. Thus, though potential evapotranspiration depends on several meteorological variables, it seems primarily driven by future temperature changes. The signal is weak in a 2°C world, with relative changes in potential evapotranspiration smaller than 20 percent everywhere except for some isolated regions in the continental interior. In a 4°C world, changes become much more pronounced, with countries like Paraguay and Bolivia projected to see an increase in potential evapotranspiration of up to 50 percent. Consistent with this result, these regions are also projected to see the strongest absolute warming (Figure 3.4).

Over almost all of the LAC land area, the multi-model mean projects more arid conditions under future climate change. Still, over extended areas, notably near the equator, at the Pacific tropical coast (Peru), and at the sub-tropical Atlantic coast (southern Brazil, Uruguay, and northern Argentina), the AI changes little and models disagree on the direction of change. Thus, there is substantial model uncertainty in these regions and no robust statements can be made about whether conditions will become more or less arid. A prime reason for this is that both annual precipitation and potential evapotranspiration in these regions have upward trends, and it is the relative magnitude of these trends which determines whether a region becomes more or less arid. In other words, it is unclear whether or not warming-driven drying outpaces the increase in annual precipitation projected for these regions.

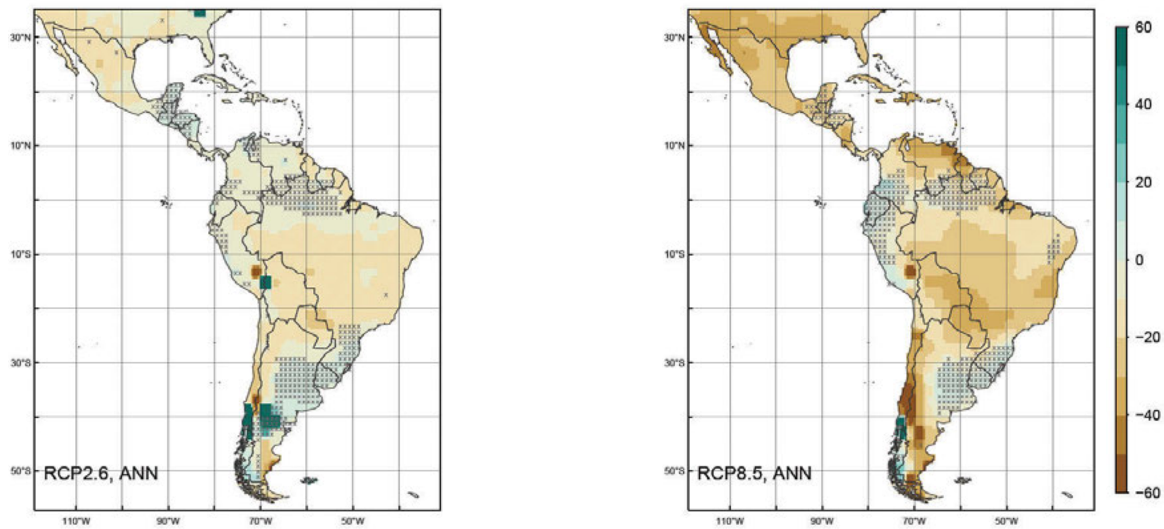
Outside these uncertain regions, the LAC land area is projected to become more arid other than for an isolated region in the southern tip of Chile. Again three major drying regions can be identified: (1) Northern Hemisphere subtropics (Mexico); (2) the interior of the South American continent (southern Amazonia, Bolivia, and Paraguay); and (3) central Chile and Patagonia. Over the first two regions, the AI is projected to decrease by up to 20 percent in a 2°C world and up to 40 percent in a 4°C world. For the third region, the decrease in AI is especially pronounced in a 4°C world, dropping up to 60 percent (note that this region is already arid today).

The shift in AI in Figure 3.9 causes some regions to be classified in a different aridity class (see Table 3.4). The total area of land classified as either hyper-arid, arid, or semi-arid is projected to grow from about 33 percent in 1951–1980 to 36 percent in a 2°C world (i.e., an increase of nearly 10 percent) and to 41 percent in a 4°C world (i.e., an increase of nearly 25 percent).

### 3.3.6 Tropical Cyclones/Hurricanes

In Central America and the Caribbean, tropical cyclones occur regularly and have severe impacts, especially when making landfall;

**Figure 3.9:** Multi-model mean of the percentage change in the aridity index under RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for Latin America and the Caribbean by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that a negative change corresponds to a shift to more arid conditions.[32]

**Table 3.4:** Multi-model mean of the percentage of land area in Latin America and the Caribbean which is classified as hyper-arid, arid, semi-arid and sub-humid for 1951–1980 and 2071–2099 for both the low (2°C world, RCP2.6) and high (4°C world, RCP8.5) emissions scenarios.

| | 1951–1980 | 2071–2099 (RCP2.6) | 2071–2099 (RCP8.5) |
|---|---|---|---|
| Hyper-Arid | 8.6 | 10.1 | 12.8 |
| Arid | 10.3 | 11.2 | 12.7 |
| Semi-Arid | 14.3 | 14.8 | 15.9 |
| Sub-Humid | 5.5 | 5.8 | 6.0 |

the impacts on marine ecosystems, transport, and infrastructure can also be severe. Strobl (2012), for instance, derived an average 0.83 percent drop in economic output after tropical cyclones strikes in this region, with big variations between countries.

The energy of tropical cyclones is derived from the ocean surface and lower atmosphere. Warming, along with increased greenhouse gas concentrations and/or aerosol concentrations, increases the amount of heat that is absorbed by the atmosphere and can increase the potential for tropical cyclones to form. Changes in the frequency and intensity of tropical storms are modulated, however, by other factors, including vertical wind shear and humidity. Of particular importance is the vertical wind shear (i.e., the difference between wind speeds near the surface and higher up in the troposphere). High wind shear disrupts the process of tropical cyclone formation and intensification, so that increases in wind shear counter increases in sea surface temperature—impacting tropical cyclone formation and intensity. El Niño events (see Section 2.3.2, El-Niño/Southern Oscillation) tend to enhance wind shear over the Gulf of Mexico and the Caribbean Sea and thus suppress Atlantic tropical cyclones (Aiyyer and Thorncroft 2011; Arndt et al. 2010; Kim et al. 2011). On the other hand, El Niño events have been shown to increase tropical cyclone activity in the eastern North Pacific (Kim et al. 2011; Martinez-Sanchez and Cavazos 2014). Observational evidence, however, suggests atmospheric patterns tend to steer tropical cyclones away from the Mexican coast during El Niño years (and toward the coast in La Niña years), so that the net effect on the Pacific coastlines of the Americas remains unclear. In both regions, changes in the El-Niño/Southern-Oscillation (ENSO) due to climate change and the associated uncertainties affect tropical cyclone projections. In addition to such dynamic changes, thermodynamic processes alone can also work to suppress tropical cyclone formation and intensification (Mallard et al. 2013).

[32] Some individual grid cells have noticeably different values than their direct neighbors (e.g., on the border between Peru and Bolivia). This is due to the fact that the Aridity index is defined as a fraction of total annual precipitation divided by potential evapotranspiration (see Appendix). It therefore behaves in a strongly non-linear fashion, and thus year-to-year fluctuations can be large. Since averages are calculated over a relatively small number of model simulations, this can result in these local jumps.

These factors make projecting changes in tropical cyclone frequency and intensity difficult. The recent IPCC WGI AR5 report found in relation to observed changes that "there is low confidence in attribution of changes in tropical cyclone activity to human influence owing to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity, and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings" (Bindoff et al. 2013).

Observational records show little or no historical global trend in tropical cyclone frequency or intensity, in particular in light of uncertainties resulting from the potential undercounting of tropical cyclones in early parts of the record predating satellite observations (before about 1970). The North Atlantic, however, is an exception. Tropical cyclone frequency has increased in the North Atlantic sharply over the past 20–30 years, but uncertainty is large over longer time-periods (Bindoff et al. 2013). Emanuel (2008) noted an increase in the Power Dissipation Index (a combination of frequency and intensity) of North Atlantic tropical cyclones over a 1949–2004 observational period. Using a new record of observations, Kossin et al. (2013) showed a strong and statistically significant increase in lifetime maximum intensity of tropical cyclones over the North Atlantic of 8 $m.s^{-1}$ per decade, over the period 1979–2010, particularly for mid- to high-intensity storms. This can be compared to the median lifetime maximum intensity of around 50 $m.s^{-1}$ of tropical cyclones across the region in this historical time series. Such observed changes were shown to be linked to both anthropogenic climate change and internal climate variability (Camargo et al. 2012; Villarini and Vecchi 2013; Wang and Wu 2013). Differential warming of the tropical Atlantic, with historically observed warming higher than average for the tropics, tends to enhance tropical cyclone intensification in this region (Knutson et al. 2013). No significant trends have been observed over the Eastern North Pacific (Kossin et al. 2013). In general however, tropical cyclones haven been observed to migrate polewards (Kossin et al. 2014).

In the long term, model simulations from a range of models lead to the expectation that tropical cyclone frequency will not be affected much by continued global warming but that mean intensity, as well as the frequency of the most intense tropical cyclones, are projected to increase (Knutson et al. 2010; Tory et al. 2013). IPCC AR5 WGI found that:

> "Projections for the 21st century indicate that it is likely that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with a likely increase in both global mean tropical cyclone maximum wind speed and rain rates . . . The influence of future climate change on tropical cyclones is likely to vary by region, but there is low confidence in region-specific projections. The frequency of the most intense storms will more likely than not increase substantially in some basins." (Stocker et al. 2013)

Short-term variability in tropical cyclones is large and GCM resolution too low to resolve high-intensity tropical cyclone structures. Projections therefore rely on proxies of tropical cyclone characteristics, or a cascade of low- to high-resolution models. Using CMIP5 models (50 percent uncertainty range across 17 GCMs), Villarini and Vecchi (2013) projected that the Power Dissipation Index would increase by 100–150 percent in a 2°C world over the North Atlantic. A considerably larger increase and a much wider range of about 125–275 percent were projected for a 4°C world.

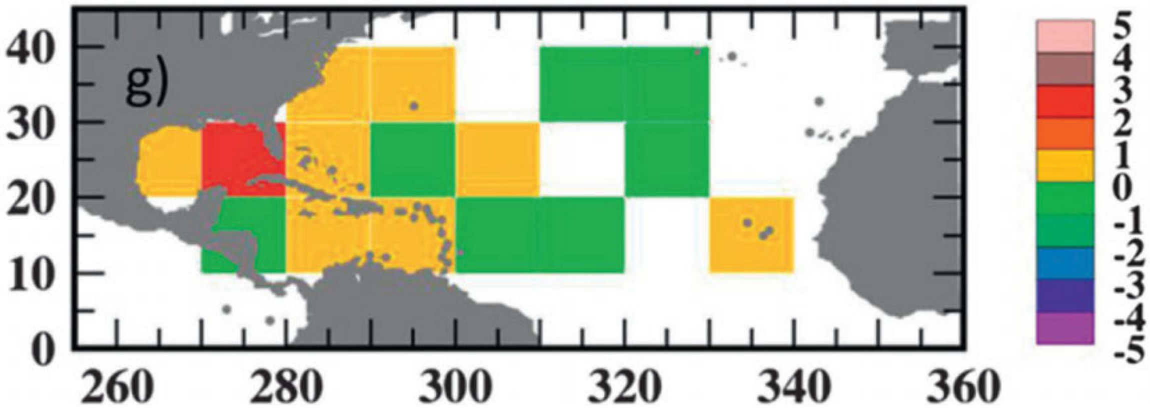
Bender et al. (2010) used a variety of models to initialize a very high-resolution operational hurricane-prediction model, noting an increase of 80 percent in the frequency of the strongest category 4 and 5 Atlantic tropical cyclones in a 4°C world (compared to the present.) Knutson et al. (2013) also found an 80 percent increase in the strongest category tropical cyclones for the same scenario and class of models and around a 40 percent increase for a lower emissions scenario and for the most recent generation of global models included in IPCC AR5 (2013b) at roughly 1.5–2.5°C warming (early and late 21st century RCP4.5). The largest increase (see Figure 3.10) occurred in the Western Atlantic, north of 20°N (i.e., to the north of Haiti), a pattern confirmed by Emanuel (2013). Using a very different statistical downscaling method, Grinsted et al. (2013) projected a twofold to sevenfold increase in the frequency of "Katrina magnitude events" regarding storm surge (not wind speed) for a 1°C rise in global temperature. For context: in terms of wind speeds, the 2005 Gulf of Mexico tropical cyclone Katrina was a class 5 tropical cyclone.

The eastern North Pacific is less well represented in the scientific literature. Based on variations of one high-resolution model, Murakami et al. (2012, 2011) projected no significant trends for this region under future climate change. By contrast, Emanuel (2013), using an ensemble of 6 different CMIP5 models, projected an increase in frequency of tropical cyclones along the Pacific coast of Central America (particularly large near the coast of southeast Mexico); the author notes, however, that the method does not capture well the currently observed storm frequency in this region.

With projected increased intensity and frequency of the most intense storms, and increased atmospheric moisture content, Knutson et al. (2013) estimated an increase of 10 percent in the rainfall intensity averaged over a 200 km radius from the tropical cyclone center for the Atlantic, and an increase of 20–30 percent for the tropical cyclone's inner core, by the end of the 21st century for roughly 2.5–3.5°C global warming. This confirms the earlier results of Knutson et al. (2010) reported in IPCC AR5 WGI (2013b). This effect would greatly increase the risk of freshwater flooding from tropical cyclones making landfall.

The projections above focus on changes in frequency of tropical cyclones and wind and rainfall intensity. Colbert et al. (2013) projected a shift in tropical cyclone migration tracks in the tropical North Atlantic, with more frequent ocean recurving tropical cyclones and fewer cyclones moving straight westward toward land.

**Figure 3.10:** Change in average rate of occurrence of Category 4 and 5 tropical cyclones per hurricane season (August–October) at about 2.5°C warming globally above pre-industrial levels by the end of the 21st century compared to the present-day.




Source: Knutson et al. (2013). © American Meteorological Society. Used with permission.

Together with changes in genesis area, but assuming constant tropical cyclone frequency, this lead to a projected increase in tropical cyclones per season in the central Atlantic and a decrease in the Gulf of Mexico and the Caribbean. Murakami and Wang (2010), however, found no change in trajectories. Current literature does not provide evidence for a (change in) risk of synchronized landfall of different tropical cyclones (e.g., in Central America from both the Pacific and the Atlantic). While individual tropical cyclones may not be strong, their compound impact may be more severe. Moreover, any increase in trend of Pacific and Atlantic storms (not necessarily cyclones) making landfall simultaneously would potentially entail more damaging impacts than increasing frequency of any individual Pacific or Atlantic cyclone alone.

In summary, observations show historical positive trends in tropical cyclone frequency and strength over the North Atlantic but not over the eastern North Pacific. While Atlantic tropical cyclones are suppressed by the El Niño phase of ENSO, they are enhanced in the eastern North Pacific. Under further anthropogenic climate change, the frequency of high-intensity tropical cyclones is generally projected to increase over the western North Atlantic by 40 percent for 1.5–2.5°C global warming and by 80 percent in a 4°C world. Global warming around 3°C is associated with an average 10 percent increase in rainfall intensity averaged over a 200 km radius from the tropical cyclone center. Although there is some evidence from multiple-model studies for a projected increase in frequency of tropical cyclones along the Pacific coast of Central America, overall projections in this region are currently inconclusive.

### 3.3.7 Regional Sea-level Rise

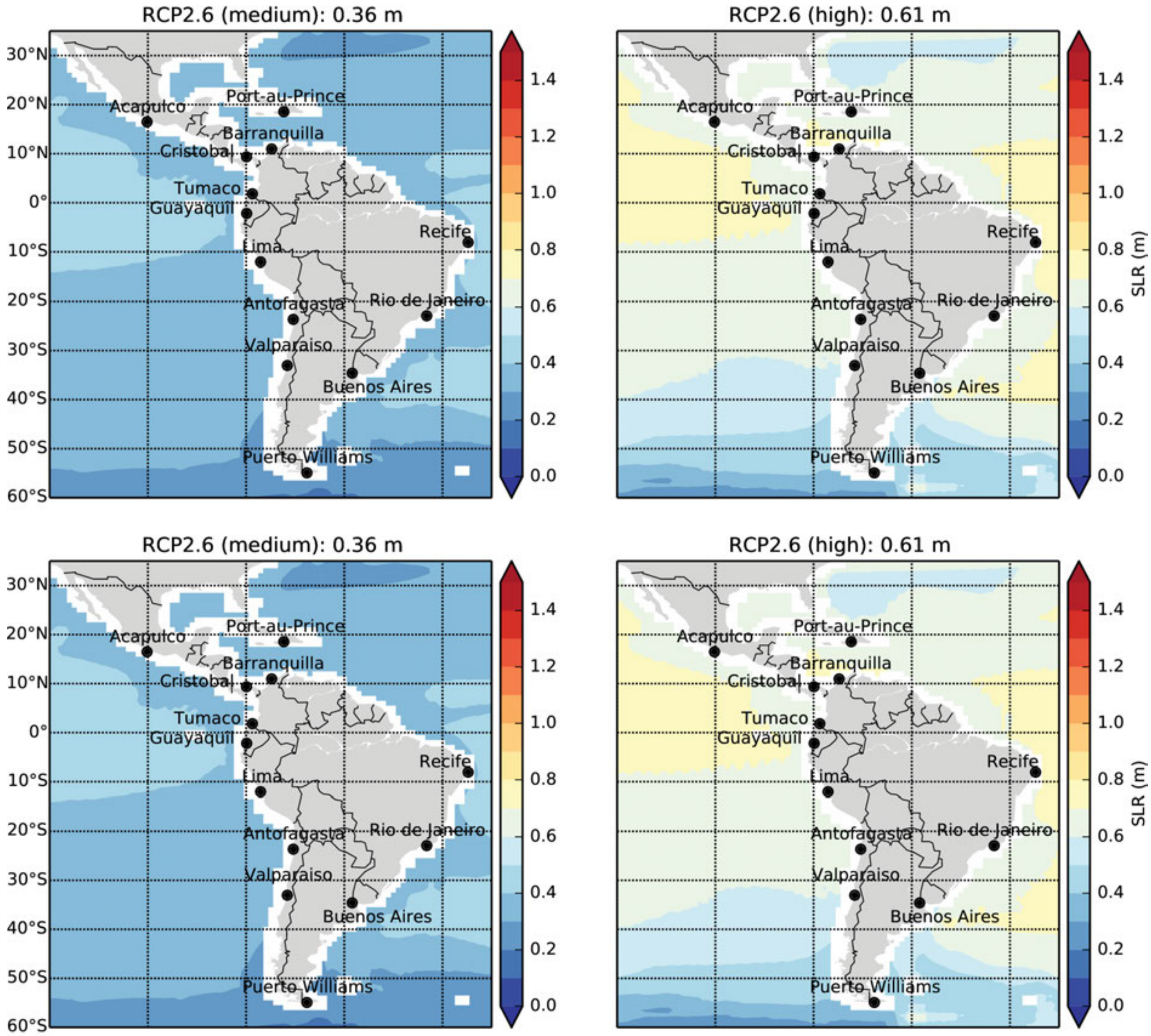
Regional sea-level rise will vary in a large and geographically diverse region such as Latin America and the Caribbean, and will depend on the climate-driven factors of local heat uptake of the ocean, ocean current changes, and the far-reaching influence of changing gravity from the ice sheets. In LAC, regional sea-level rise largely reflects the rise in global mean sea level. Still, consistent regional features exist across both the 1.5°C and 4°C world scenarios in both the median and high estimate (Figure 3.11, Table 3.5). These features are more pronounced for stronger overall sea-level rise.

**Table 3.5:** Sea-level rise between 1986–2005 and 2081–2100 for the RCP2.6 (1.5°C world) and RCP8.5 (4°C world) in selected locations of the LAC region (in meters).

| | RCP2.6 (1.5°C WORLD) | RCP8.5 (4°C WORLD) |
|---|---|---|
| Acapulco | 0.38 (0.23, 0.61) | 0.6 (0.42, 1.01) |
| Antofagasta | 0.37 (0.22, 0.58) | 0.58 (0.42, 0.98) |
| Barranquilla | 0.39 (0.22, 0.65) | 0.65 (0.43, 1.12) |
| Buenos Aires | 0.34 (0.24, 0.52) | 0.56 (0.45, 0.97) |
| Cristobal | 0.39 (0.22, 0.65) | 0.66 (0.44, 1.07) |
| Guayaquil | 0.39 (0.25, 0.62) | 0.62 (0.46, 1.04) |
| Lima | 0.38 (0.24, 0.61) | 0.6 (0.45, 1.02) |
| Port-au-Prince | 0.38 (0.21, 0.61) | 0.61 (0.41, 1.04) |
| Puerto Williams | 0.27 (0.19, 0.37) | 0.46 (0.38, 0.65) |
| Recife | 0.39 (0.23, 0.65) | 0.63 (0.41, 1.14) |
| Rio de Janeiro | 0.37 (0.24, 0.61) | 0.62 (0.46, 1.11) |
| Tumaco | 0.38 (0.24, 0.6) | 0.61 (0.44, 1.01) |
| Valparaiso | 0.35 (0.21, 0.54) | 0.55 (0.41, 0.91) |

Numbers in parentheses indicate low and high bounds (see Section 6.2, Sea-Level Rise Projections for an explanation of the 1.5° world).

**Figure 3.11:** Patterns of regional sea-level rise.

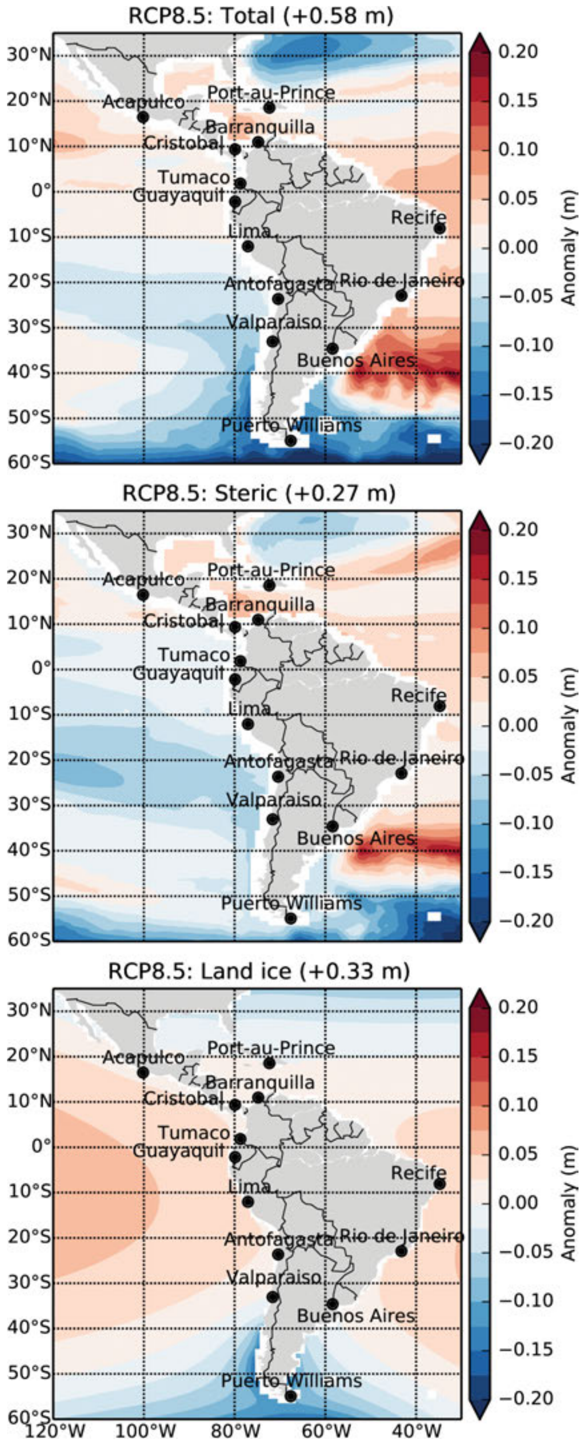



Median (left column) and high (right column) estimates of projected regional sea-level rise for the RCP2.6 scenario (1.5°C world, top row) and the RCP8.5 scenario (4°C world, bottom row) for the period 2081–2100 relative to the reference period 1986–2005. Associated global mean rise is indicated in the panel titles. Representative cities are denoted by black dots and discussed in the text with numbers provided in Table 3.5.

Sea-level rise is projected to be higher at the Atlantic coast than at the Pacific coast. Valparaiso is projected to benefit from this effect (median estimate: 0.55 m for a 4°C world), where southeasterly trade wind intensification over the Southern Pacific and associated upwelling of cold water (Merrifield and Maltrud 2011; Timmermann et al. 2010) lead to below-average thermosteric sea-level rise (Figure 3.13). In contrast, Recife on the Atlantic coast of Brazil is projected to experience above-average sea-level rise (median estimate: 0.63 m for a 4°C world). A similar rise is projected for the Rio de Janeiro region (Figure 3.11) (median estimate: 0.62 m for a 4°C world), where a large number of people are at risk (Nicoldi and Mueller Petermann 2010).

Sea-level rise is enhanced at low latitudes due to both increased ocean heat uptake in the region (Figure 3.12; middle) and the gravity-induced pattern of ice sheets and glaciers (Figure 3.12 bottom). As an example, Guayaquil on the Pacific Coast of Ecuador is projected to experience a sea-level rise of 0.62 m (median estimate; low estimate: 0.46 m; high estimate: 1.04 m) of sea-level rise in a 4°C world (Figure 3.13). Guayaquil is among the most vulnerable coastal cities in terms of relative GDP losses (Hallegatte et al.

**Figure 3.12:** Regional anomaly pattern and its contributions in the median RCP8.5 scenario (4°C world).




Total sea-level rise (top), steric-dynamic (middle), and land-ice (bottom) contributions to sea-level rise, shown as anomalies with respect to the global mean sea-level rise. Global mean contributions to be added on top of the spatial anomalies are indicated in the panel titles.

2013). In contrast, Puerto Williams (Chile) at the southern tip of the South American continent is projected to experience only 0.46 m (median estimate for a a 4°C world) (low estimate: 0.38 m; high estimate: 0.65 m). The upper bound differs between the two locations since it is largely determined by the risk of high ice-sheet-driven sea-level rise.

Port-Au-Prince (Haiti) is projected to experience 0.61 m (low estimate: 0.41 m, high estimate: 1.04 m) of sea-level rise in a 4°C world (Figure 3.13); it serves as a typical example for sea-level rise in other Caribbean islands. The sea-level rise at the continental Caribbean Coast exceeds the projection for the Caribbean islands (Barranquilla, median estimate: 0.65; low estimate: 0.43; and high estimate: 1.12 in a 4°C world). The difference may be linked to a weakening of the Caribbean Current that is connected to the Atlantic meridional overturning circulation[33] (Pardaens et al. 2011). The high upper bounds are due to the strong influence of the Antarctic ice sheet.

The ocean is predicted to warm, with high rates in the Southern Ocean off Buenos Aires (Kuhlbrodt and Gregory 2012). The coastal waters are, however, dominated by the cold Malvinas Current, a branch of the Antarctic Circumpolar Current (ACC). Since minor warming is projected for the ACC and the Malvinas Current, the strong warming signal in the Southern Ocean does not lead to additional sea-level rise at the Rio de la Plata estuary—which is projected to rise slower than the global mean (Buenos Aires, median estimate: 0.56 m; low estimate: 0.42 m; and high estimate: 1.03 m in a 4°C world). Sea-level rise in the region will be influenced by the future strength of the Brazil and Malvinas Currents and the position of their confluence zone (Lumpkin and Garzoli 2011).

## 3.4 Regional Impacts

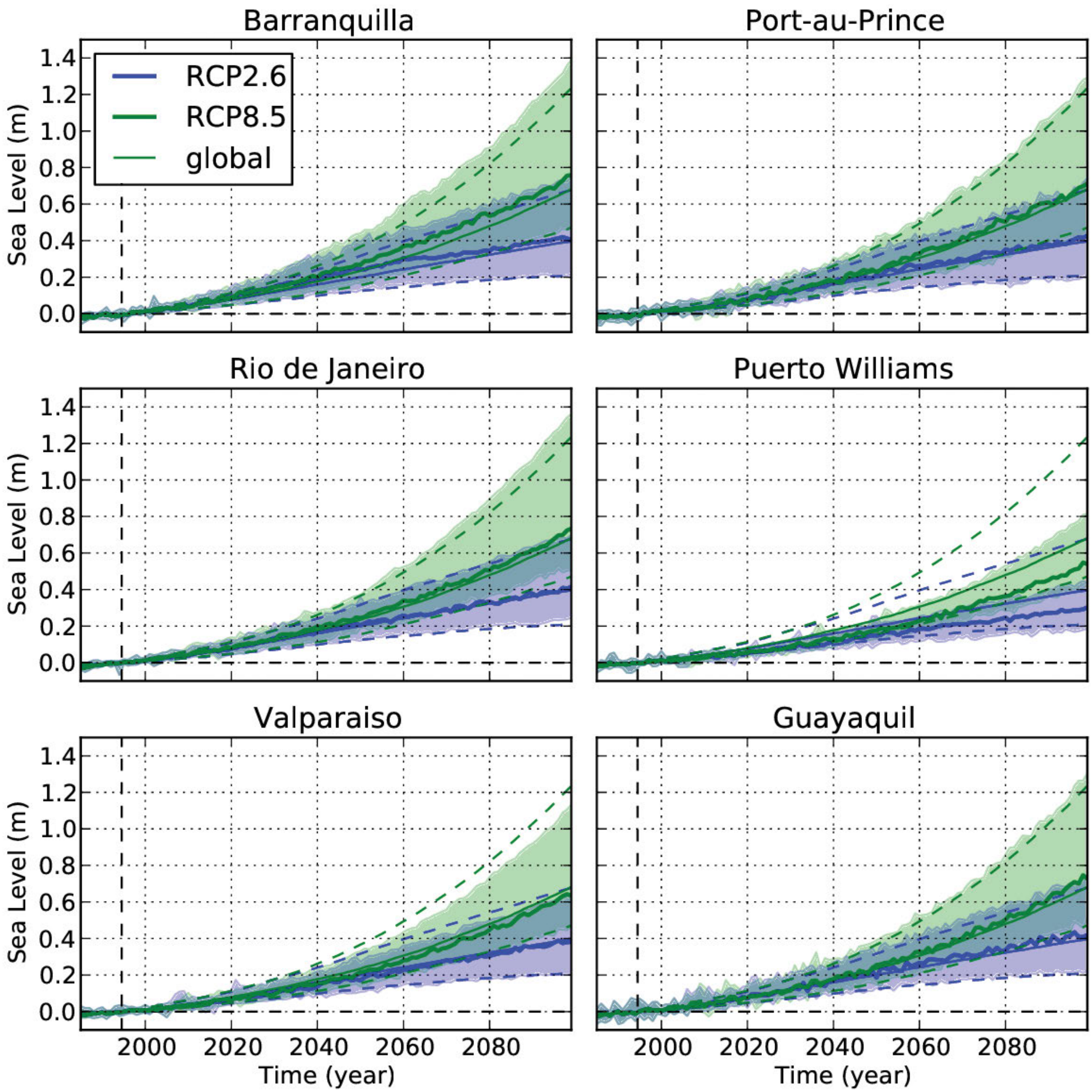
### 3.4.1 Glacial Retreat and Snowpack Changes

#### *3.4.1.1 Topography of Glaciers in the Andes*

The Andes are the longest continental mountain range in the world, stretching about 7,000 km along the coast of South America. There are major ice masses in the Patagonian Andes and on Terra del Fuego in the Southern Andes. A much smaller amount of ice (about 217 Gt), covering an area of about 4,900 $km^2$, is stored in the Central Andes; this region hosts more than 99 percent of the world's glaciers that are located in tropical latitudes (Tropical Andes). These glaciers exist at high altitudes between 4,000 and 6,500 m above sea level and are of crucial importance for the livelihood of the local populations as they act as critical buffers against highly seasonal precipitation and provide water during the dry season for

[33] This ocean current system transports a substantial amount of heat energy from the tropics and Southern Hemisphere toward the North Atlantic, where the heat is then transferred to the atmosphere. Changes in this ocean circulation could have a profound impact on many aspects of the global climate system.

**Figure 3.13:** Sea level projections for selected cities.




Time series for sea-level rise for the two scenarios, RCP2.6 (1.5°C world, blue) and RCP8.5 (4°C world, green). Median estimates are given as full thick lines and the lower and upper bound given as shading. Full thin lines are global median sea-level rise with dashed lines as lower and upper bound. Vertical and horizontal black lines indicate the reference period and reference (zero) level.

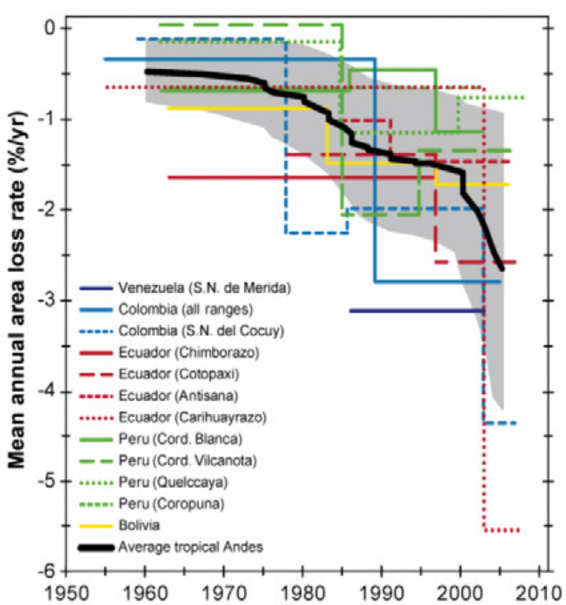
domestic, agricultural, and industrial use. In addition, the water and energy supplies (see Section 3.4.11) of the capital cities of Lima (Peru), La Paz (Bolivia), and Quito (Ecuador) depend on the glacial melt water (see Section 3.4.2, Water Resources, Water Security, and Floods). Andean snowpack is also a crucial natural water resource, particularly in the semi-arid regions of Southern South America (Masiokas et al. 2012, 2013).

### *3.4.1.2 Current Situation and Observed Changes*

#### Characteristics of Tropical Glaciers

Tropical glaciers are particularly threatened by climate change due to their high altitude, the high level of radiation, and the tropical climate dynamics. Observations have shown that the variability of the surface temperature of the Pacific Ocean is the governing factor, explaining the dramatic glacier recession of the 20th century, although the precipitation trend has not been significant during that period. The impact of the ENSO phenomenon (see Section 2.3.2, El-Niño/Southern Oscillation) on the inter-annual mass balance is consequently high in the tropical glacier zone, with low temperatures, high precipitation, high wind speeds, high albedo, and a nearly balanced or positive mass balance during La Niña events and a strongly negative mass balance during El Niño events (Chevallier et al. 2011).

**Figure 3.14:** Compilation of mean annual area loss rates for different time periods for glaciated areas between Venezuela and Bolivia.




The grey box around the average represents the uncertainty corresponding to ±1 standard deviation. Source: Rabatel et al. (2013), Figure 4.

#### Observed Glacier Recession

As a general trend, the Andean glaciers are shrinking. This is caused by increased melt rates, decreased accumulation, changes in the ice dynamics, and/or a combination of all these factors. For the period 1980–2011, Giesen and Oerlemans (2013) calculated, for the tropical glaciers, a relative volume change of 7.3 percent (39 Gt) with respect to a total glaciated area of 4,940 $km^2$ (99 percent of which is located in the Central Andes). Over a much longer historical period (1901–2009) and for a larger region (accounting for 82 percent of all tropical glaciers), Marzeion et al. (2012) estimated an area reduction of glaciers of about 79 ± 2 percent (15,900 ± 500 $km^2$), which corresponds to a volumetric ice loss of 90 percent (1,740 Gt). The Southern Andes contain a much larger ice mass of 11,430 Gt (1980) extending over a glaciated area of 33,700 $km^2$. This huge ice mass decreased in volume by 6.1 percent (695 Gt) between 1980–2011 (Giesen and Oerlemans 2013). Over the 20th century (1901–2009), Marzeion et al. (2012) infer a reduction of about 32 percent in area (15,500 ± 200 $km^2$), which can be associated with a volume loss of 22 ± 5 percent (1,340 ± 290 Gt).

These global projections, however, rely on coarse resolution models that cannot adequately simulate glacier dynamics in the steep topography of the narrow mountain chain of the Andes. In particular, the strong recession rate of the comparably small tropical glaciers is likely overestimated by the global-scale methodology. Regional models, in contrast, can provide more comprehensive analyses with resolutions of up to a few hundred meters.

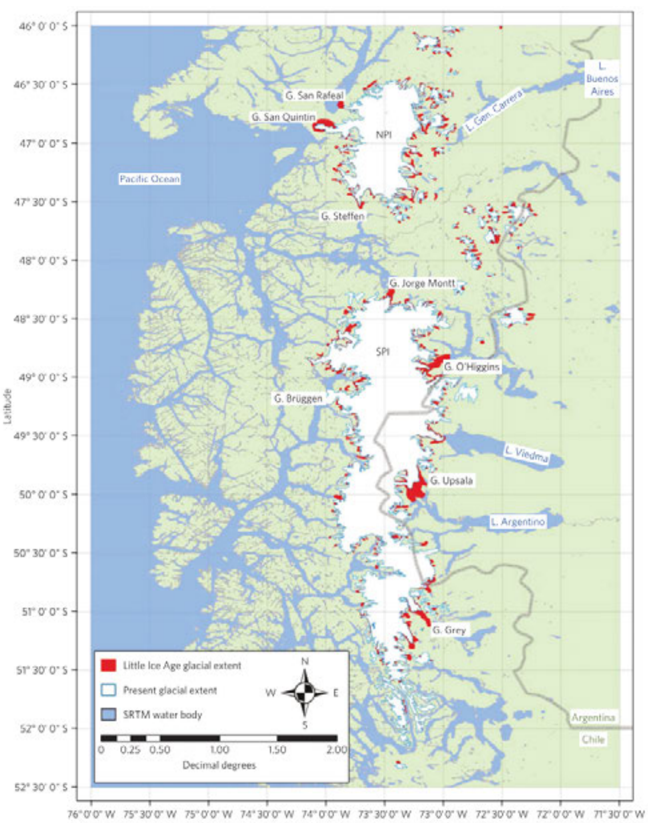
Rabatel et al. (2013) reviewed the various studies on the current state of Tropical Andes' glaciers, considering a variety of different measurement techniques (e.g., monitoring of the mass balance, aerial photography, and remote sensing). Generally, a clear change in glacier evolution can be seen after the late 1970s, accelerating in the mid-1990s and again in the early 2000s (Figure 3.14). This is different from the glaciers located at mid or high latitudes, where accelerated melting started in the 1990s. The glaciers in the tropical Andes appear to have had more negative mass balances than glaciers monitored worldwide.

In the Peruvian Andes, glacial areas have been well documented and multiple reports found on average a retreat of 20–35 percent between the 1960s and the 2000s; most of that retreat occurred after 1985 (Vergara et al. 2011). A similar pattern of glacial recession is found in the Bolivian Andes. A rapid decline has also been reported for the Ecuadorian Andes, where glaciers on Chimborazo shrunk by 57 percent during the period 1962–1997, while glaciers on the Cotopaxi and Antisana volcanoes shrunk in area during the period 1979–2007 by 37 percent and 33 percent respectively. For the Andes of Colombia, a moderate glacier area loss of 11 percent has been documented in the period of the 1950s to the 1990s, with a fourfold acceleration in retreat during the period of the 1990s to 2000s. In Venezuela, glacial retreat has been even more dramatic, with a loss of about 87 percent between 1953–2003.

Although the conditions in the Southern Andes are very different (e.g., in terms of climate or sun angle) the trend in glacier retreat is obvious here as well (Figure 3.15). Lopez et al. (2010) investigated changes in glacier length in 72 glaciers in the Chilean Southern Andes (Northern and Southern Patagonian Ice Field and Cordillera Darwin Ice Field) between 1945–2005, based on aerial photographs and satellite images (ASTER, Landsat). They concluded that the observed general trend in glacial retreat is likely controlled by atmospheric warming. In the Northern Patagonian Ice Field, glaciers retreated in length by 4–36 percent, in the Southern Patagonian Ice Field by 0–27 percent, and further south in the Cordillera Darwin Ice Field by 3–38 percent. However, glacial length fluctuations provide only limited insight into the imbalance of glaciers, and the large heterogeneity of glacial retreat is very much influenced by such local conditions as exposition, basin geometry, glacier dynamics, and response times.

A different way of measuring glacier mass loss rates is by space gravimetry (GRACE)—by measuring the changing gravity field from satellites in regions with large continuous ice extent (a method available since 2003). For the large ice caps of Northern and Southern Patagonia, Ivins et al. (2011) inferred ice loss rates of 26 ± 6 Gt per year between 2003–2009, which explains a total loss of about 154 ± 36 Gt over six years. Jacob et al. (2012) reached similar estimates using the same technique, with mass balance rates for the period 2003–2011 of 23 ± 9 Gt per year in the Patagonian glaciers and of 6 ± 12 Gt per year in the rest of South America (including the tropical glaciers). However, the spatial resolution of about 300 km is extremely coarse and difficulties arise in distinguishing signals from hydrological storage and glacial isostatic adjustment (Gardner et al. 2013).

**Figure 3.15:** Ice loss from outlet glaciers on the Patagonian Ice Field in southern South America since the Little Ice Age.




Source: Glasser et al. (2011), Figure 1.

## Snowpack and Snow Cover Changes

In the tropical glacier region, due to the high solar radiance, with the sun close to the zenith, albedo appears to be a major determinant in attenuating the melting process. Consequently, the frequency and intensity of snowfall plays a major role in determining the net radiation over the entire year, modulated by wet and dry seasons (Rabatel et al. 2013). In the subtropical Andes of Chile and western Argentina, where snowpack has been monitored for more than 50 years (1951–2004), there is no significant trend over this period (Masiokas et al. 2006, 2012). However, the data display a marked inter-annual variability ranging from 6–257 percent around the 1966–2004 mean, with a clear influence from the warm phases of ENSO (El Niño).

Studies about snowpack in the Southern Andes are rare. It can generally be stated that changes in snowpack extent magnify changes in the seasonality of the water availability by a reduction of the flows in dry season and an increase in flows in wet seasons (Vicuña et al. 2013).

### *3.4.1.3 Projections of Glacial Change*

As the IPCC confirms with high confidence, glaciers worldwide are out of balance with current climatic conditions. Furthermore, it is very likely that anthropogenic forcing played a statistically significant role in the acceleration of the global glacier loss in the last decades of the 20th century (Bindoff et al. 2013).

Various model projections for different future emissions scenarios indicate that glaciers will continue to shrink in the future, even without further temperature increases. Confidence in these models is supported by their ability to reproduce past observed glacier changes using corresponding climate observations as forcing. Model validation is challenging, however, due to the scarcity of independent observations (currently available for only a small fraction of well-observed glaciers).

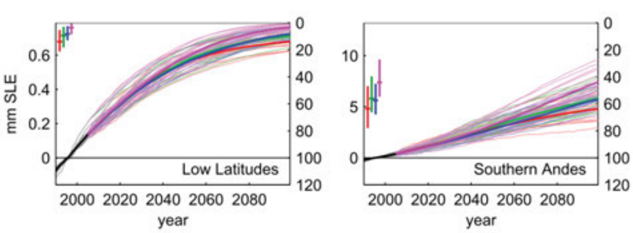
In a 2°C world, Marzeion et al. (2012) expect a reduction in ice volume of tropical glaciers by 78–94 percent based on the period 1986–2005. This signal is less drastic in the Southern Andes, with an expected 21–52 percent volume reduction of the 4,700 Gt ice mass by 2100 for the same warming level. Marzeion et al. (2012) project the amount of tropical glaciers to be lost in a 3°C world at 82–97 percent, very similar to the 2°C world scenario. For the much larger glaciers in the Southern Andes, the same study expects a loss of 33–59 percent in a 3°C world. For the 21st century, with a warming of 3°C above pre-industrial levels by 2100, Giesen and Oerlemans (2013) estimate a volumetric loss of 66 percent in the tropical glaciers (325 Gt) and of 27 percent in the Southern Andes (2,930 Gt). Marzeion et al. (2012) estimate an almost complete deglaciation (91–100 percent) of the remaining 280 Gt tropical glaciers in a 4°C world (Figure 3.16.) This signal is less drastic in the Southern Andes, where a 44–72 percent deglaciation is estimated. An almost complete deglaciation for the 195 Gt tropical glaciers (93–100 percent) in a 4°C world is also projected by Radić et al. (2013). However, for the Southern Andes, the response is much slower, and Radić et al. (2013) expect 50 percent glacial losses (3,080 Gt). All these models use a scaling methodology which may overestimate the recession of the small remnant tropical glaciers. Regarding the Patagonian ice fields in the Southern Andes, Schaefer et al. (2013) estimate a glacial volume loss for the Northern Patagonian Ice Field of 590 ± 50 Gt with 4°C global warming with respect to pre-industrial levels. Their projections of the future surface mass balance of the Northern Patagonian Ice Field predict a strong increase in ablation (refers to all processes that remove snow, ice, or water from a glacier or snowfield) from 2050 onward and a decrease in accumulation from 2080, both due to increasing temperatures.

The accelerated melting will lead to increasing runoff; when the glacier reservoirs disappear, runoff will tend to decrease, particularly in the dry season (see Section 3.4.2, Water Resources, Water Security, and Floods). Following the trend in the tropical Andes (Poveda and Pineda 2010), this peak is expected within the next 50 years (Chevallier et al. 2011) if it has not already occurred (Baraer et al. 2012).

#### 3.4.1.4 Glacial Hazards

Glacier hazards are a serious risk to populations in mountain regions worldwide, where a general trend of glacial retreat has supported the formation of glacial lakes that were precariously dammed behind the moraines of the last maximum extent of the Little Ice Age in the mid-1800s. Carey et al. (2012) performed an interdisciplinary case study on a glacial lake outburst flood (GLOF), which happened in Peru's Cordillera Blanca mountain range in 2010. Based on their analysis, they provide advice for effective glacier hazard management. Hazard management is of high concern, as projected warming will continue to promote glacial lake formation (see Box 3.4: Glacial Lake Outbursts).

**Figure 3.16:** Cumulative regional surface mass balance relative to the 1986–2005 mean from the model forced with CMIP5 projections up to the year 2100. SLE = Sea-level equivalent




Source: Modified after Marzeion et al. (2012), Figure 21.

#### 3.4.1.5 Synthesis

This section indicates that glacial recession in South America has been significant. The tropical glaciers in the Central Andes in particular have lost major portions of their volume in the course of the 20th century. Regional studies show that the retreat has accelerated, with the strongest recession rates after 1985. A clear trend of glacial retreat is also visible for glaciers in the southern Andes, which have lost about 20 percent of their volume. Regional studies highlight that the individual recession rate is very much influenced by local conditions, which cause a large heterogeneity of rates. Space gravimetry (GRACE) confirms that the declining trend in glacier volume has continued in the last decade. Monitoring of snow cover in the high altitudes of Chile and Argentina since 1950 shows no significant trend (i.e., possible trends are hard to identify in the records, since the inter-annual variability is large, and clearly modulated by ENSO).

The recession of the tropical glaciers in the Central Andes will continue as rapidly as it has in recent decades. Even for low or intermediate emissions scenarios inducing a global warming of 2–3°C above pre-industrial levels, two comprehensive studies consistently project a glacial volume loss of 78–97 percent (Marzeion et al. 2012; Radić et al. 2013). Both studies predict an almost complete deglaciation (93–100 percent) for a 4°C world. In contrast, Giesen and Oerlemans (2013) project a loss of only 66 percent of the glacial volume of the year 2000 in the Central Andes with a global warming of about 3°C by 2100. Thus, irrespective of the temperature evolution in the next decades, large parts of the glaciers of the tropical Andes will be gone before the end of the century. In the Southern Andes, the model spread for the 2–3°C global warming ranges from 22–59 percent; a comparison for individual scenarios is difficult. In a 4°C world, three models project a glacier volume retreat of 44–74 percent by 2100. An important research gap is the lack of reliable projections for snowpack and snow cover changes in the Andes.

### 3.4.2 Water Resources, Water Security, and Floods

LAC has abundant overall water resources, but their distribution is temporally and regionally unequal (Magrin et al. 2007). ENSO-related rainfall anomalies play a major role in many areas and determine much of the inter-annual discharge variability (Baraer

## Box 3.3: Water Security in the Mexico City Metropolitan Area

The Mexico City Metropolitan Area (MCMA) faces frequent climate-related hazards. These include extremes of water and heat, with floods on the one side and heat waves and droughts on the other. The most common extreme events from 1980–2006 were floods resulting from heavy precipitation events (Romero Lankao 2010). Up to 42 percent of the population in MCMA was estimated to be vulnerable to climate change and natural hazards. Forty percent of those live in so-called "high-risk areas" which are characterized by very steep slopes of over 15 degrees where landslides can occur after heavy precipitation events (Baker 2012). Exponential population growth in MCMA during the 20th century also contributed to the high vulnerability to flooding and water shortages (Brun 2007).

Currently water is provided from the Mexico City basin aquifer, with one-third transferred from external water basins (Romero Lankao 2010). Overextraction of groundwater in combination with locally unfavorable soil conditions (heavily saturated clay) have caused parts of the city to subside and thus suffer more frequent flooding (Baker 2012; Romero Lankao 2010). Another problem for long-term water security is related to groundwater contamination of the Mexico City basin aquifer, most probably due to surface wastewater (Brun 2007)

The projection of temperature increases, more frequent and prolonged dry spells, and a (probable) precipitation decrease will harm water security and increase water dependencies in the growing MCMA. The water security of the water-providing external areas will also be affected (Magrin et al. 2007; Romero Lankao 2010; Sosa-Rodriguez 2013).

et al. 2012; Cortés et al. 2011; Krol and Bronstert 2007; Mata et al. 2001; Poveda 2004; Ronchail et al. 2005; Shi et al. 2013; Vicuña et al. 2010; Vuille et al. 2008). Large parts of the region are characterized by inter-annual/seasonal rainfall variability through the oscillation of the Intertropical Convergence Zone (Garreaud et al. 2009). Due to the unreliable rainfall, groundwater resources and water from glacier and snowmelt play a crucial role in supplying local water (Chevallier et al. 2011; Hirata and Conicelli 2012; Vuille et al. 2008).

LAC suffers from widespread floods and landslides (Maynard-Ford et al. 2008) which result from different origins (Dilley et al. 2005). Heavy precipitation events in the context of ENSO or tropical cyclones can lead to disastrous floods, especially in regions with steep terrains such as in the Andes and Central America (IPCC 2012; Mata et al. 2001; Mimura et al. 2007; Poveda et al. 2001). Coastal areas in the Caribbean and Central America suffer from flooding as a result of storm surges and tropical cyclones (Dilley et al. 2005; Woodruff et al. 2013). In the Andes, glacial lake outbursts present a permanent hazard for Andean cities (Chevallier et al. 2011).

In many parts of the region there is no clear trend in future discharges due to the uncertainties in rainfall projections in different GCMs (see also Section 3.3.3, Regional Precipitation Projections) and the diverging results of different impact models (Bravo et al. 2013; Davie et al. 2013; Döll and Schmied 2012; Hidalgo et al. 2013; Imbach et al. 2012; Krol and Bronstert 2007; Malhi et al. 2009; Rowell 2011; Schewe et al. 2013).

#### *3.4.2.1 Central America and Mexico*

Milly et al. (2005) modeled a decrease in river runoff for Central America of up to 10 percent for the 20th century. Hidalgo et al. (2013) projected mean annual runoff to decrease by 10–30 percent by the end of the 21st century with a median of 3°C regional warming. The same tendencies were shown in Imbach et al. (2012), who found decreases in annual runoff in 61–71 percent of the area (notably in central Yucatan Peninsula, the mountains of Nicaragua, Honduras, and Guatemala) in a 2°C warmer world, depending on the subregion and the emissions scenario. Increases were projected only for just one percent of the area, mainly along the southern edge. Evapotranspiration was projected to increase more than 20 percent in more humid areas (e.g., Costa Rica, Panama) whereas northern areas were projected to experience no change. Fabrega et al. (2013) found precipitation increases by 5 percent or more for most regions of Panama—but with no statistically significant changes in total runoff in a 3°C world. Maurer et al. (2009) modeled the inflow of two reservoirs in the Rio Lempa basin. They found decreases of 13 percent in total annual reservoir inflow in a 2°C world and of 24 percent in a 4°C world, implying potential reductions in hydropower capacities. Low flow years might occur more frequently, especially under a higher warming (Maurer et al. 2009).

Global studies mostly confirm this picture. Milly et al. (2005) projected a decrease in river runoff in Central America of 5–20 percent for the middle of the 21st century with 3°C global warming. Nakaegawa et al. (2013) also found that the total annual runoff decreases for Mexico and Central America from 2075–2099 with 3°C warming. For the Rio Grande, annual discharge decreases by more than 20 percent. In a 3°C world, Mesoamerica also experiences a strong decrease in discharge in the study of Schewe et al. (2013).

Portmann et al. (2013) reported a mean decrease across several GCMs of more than 10 percent in groundwater recharge in a 4°C world for Central America. The projected changes were much less pronounced when assuming lower global mean temperature increases of 2–3°C.

#### *3.4.2.2 Caribbean*

The assessment of water resources in the Caribbean relies more on assumptions and extrapolations from climatological data than on long-term hydrometric measurements, especially for the smaller islands (Cashman 2013; FAO 2003). Water provisioning is especially difficult on islands which rely mainly on a single source of water (such as groundwater in Barbados, Bahamas, Antigua and

Barbuda, and Jamaica, or surface water in Trinidad and Tobago, Grenada, St. Vincent and the Grenadines, St. Lucia, Dominica, and elsewhere) (Cashman 2013; Gencer 2013).

The lack of long-term measured stream flows in the Caribbean renders the evaluation of hydrological models in the region difficult, and future projections of runoff have only low confidence (Hidalgo et al. 2013). A combination of lower precipitation, high abstraction rates, and sea-level rise may lead to intrusion of saline sea water into coastal groundwater aquifers (Cashman et al. 2010; Cashman 2013). Another hydrological hazard regarding climate change is more severe flooding events related to tropical cyclones (Cashman et al. 2010).

#### 3.4.2.3 Northern South America (Colombia)

Restrepo et al. (2014) found significant discharge increases for the Mulatos, Magdalena (at Calamar), Canal del Dique, and Fundación rivers, especially from 2000 to 2010. Regional studies of climate-related hydrologic impacts are limited, as access to and quantity of observational climate data is limited (Hoyos et al. 2013). Reanalysis or simulated/reconstructed datasets have been used, but Hoyos et al. (2013) reported substantial differences between climatological datasets and observed values. Nakaegawa and Vergara (2010) found a trend of decreasing mean annual river discharge due to increased evapotranspiration in the Magdalena Basin in a 3°C world. Monthly mean river discharge decreased significantly in April, October, and November at Puerto Berrio. It is important, however, to note that mean precipitation was overestimated by about 35 percent for the GCMs used.

#### 3.4.2.4 Andes

In mountainous regions, winter precipitation accumulated as snow and ice, similar to groundwater reserves, helps to buffer water shortages resulting from little or seasonal rainfall (Masiokas et al. 2006; Viviroli et al. 2011; Vuille et al. 2008). Downstream regions with low summer precipitation in particular benefit from this temporal water storage (Masiokas et al. 2013; Viviroli et al. 2011). Glacier retreat thus endangers water security in these areas (Vuille et al. 2008). Current accelerated melting rates, however, imply a short-term local surge in water—and higher river flow peaks can cause landslides and floods. Massive flood events have been associated with glacial lake outburst (Chevallier et al. 2011) (see Box 3.4).

#### 3.4.2.5 Tropical Andes

Baraer et al. (2012) analyzed historical streamflow records for the Cordillera Blanca over the period 1990–2009; they showed that discharge was decreasing annually and during the dry season. The trends were attributed to glacier retreat. Meltwater contributes 10–20 percent to the total annual discharge of the Río Santa (Cordillera Blanca), but may rise to over 40 percent during the dry season (Baraer et al. 2012). In the period from 1990–2009, the overall glaciered area was decreasing by 0.81 percent annually; this is around 30 percent higher than what was measured during the 1930–2009 period (Baraer et al. 2012).

### Box 3.4: Glacial Lake Outbursts

Glacial lake outburst floods (GLOFs) originate from various causes. First, increasing glacier melting raises the water levels of lakes, eventually resulting in an overflow of water or the breaking of dams. Second, ice instability may cause an avalanche of seracs into a lake, leading to suddenly higher water levels and the breaking of dams. Ice instability might increase with increasing temperatures. Third, glacier retreat may trigger major rock slides. It is important to note that the Andes belong to a region of high seismic activity, which can contribute to GLOFs. (Chevallier et al. 2011; Kaser et al. 2003).

Kinouchi et al. (2013) simulated the glacier melt and runoff in a headwater catchment of the Cordillera Real in Bolivia. They applied different 1–1.5°C temperature increase scenarios by 2050 and found only small changes in annual runoff. The seasonal variation was, however, modified significantly. Under their projections, streamflow during the dry and early wet season was reduced (e.g., because of snowmelt decrease, and during the wet season it increased, especially in January and February). Baraer et al. (2012) projected that once the glaciers have melted, the average dry season discharge may decrease more than 60 percent in Parón and Llanganuco and up to 70 percent at La Balsa—with serious implications for water supplies during the dry season. Juen et al. (2007) found little changes in total annual discharge by 2050 and 2080 in the Llanganuco catchment, but they did find a bigger amplitude of discharge seasonality (with a risk of very low flows during the dry season). They concluded that a smaller glacier size causes decreasing glacier melting, but that this decrease is supplemented by an increase in direct runoff from non-glaciered areas. Wet season discharge was projected to increase from 10–26 percent and dry season discharge to decrease from 11–23 percent for warming >1.5°C in 2050 and >2°C in 2080 depending on the emissions scenario and timeframe (see Figure 3.17). For the northern half of the Andes, a very likely increase in flood frequency in a 4°C world was projected (Hirabayashi et al. 2013).

#### 3.4.2.6 Central Andes

The Andes in Central Chile and central western Argentina are characterized by a direct relationship between the amount of snow accumulated in winter and river discharge released during spring-summer (Masiokas et al. 2006), and around 85 percent of the observed river flow variance over 60 years in the area can be explained by snowpack records (Masiokas et al. 2010, 2013).

The inter-annual variability of snowpack extent is enormous, varying from zero percent to over 400 percent of the long-term mean (Masiokas et al. 2006, 2010, 2013). Freshwater availability is thus strongly dependent on mountain snowpack. In very dry

## Box 3.5: Water Security in Quito, La Paz, Bogotá, and Lima

Precipitation patterns are different throughout the tropical Andes. The Pacific slopes in Colombia receive on average more than 8000 mm per year of rainfall, whereas large parts of the highlands of Bolivia and the Peruvian coast get less than 100 mm per year. Water security is a pressing issue because the capital cities experienced population growth rates of 11.9 percent in Quito and 20.6 percent in La Paz for the period 2000–2010.

Bogotá and Quito are situated on steep mountain terrain at 2650 m and 2850 m above sea level respectively. High population densities provoke local water stresses, and both cities require inter-basin water transfers from the wet Amazonian slopes to meet their water demand. Sixty-two percent of Quito's water is currently provided by the Amazonian basin. Lima, meanwhile, is the second-largest desert city in the world and its water is supplied almost solely by the western slope of the Andes. Competition exists with other water users, including the agricultural sector (Buytaert and De Bièvre 2012).

## Box 3.6: Water from the Cordillera Blanca

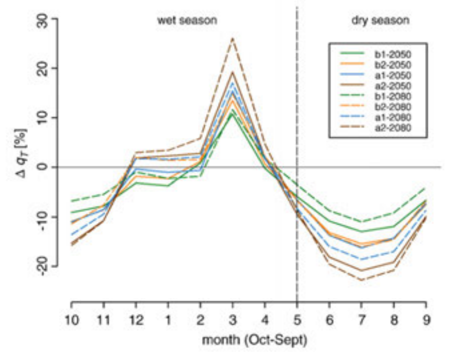
The arid coastal area of Peru is home to approximately half of the country's population. Water is provided mainly by rivers coming down from the western slopes of the Cordillera of the Andes. Contributors to runoff during the rainy season are rainfall, groundwater, and glacier melt. In contrast, during the dry season rivers are fed by groundwater and glacier melting at higher than 5000 m (Chevallier et al. 2011).

The water from the Cordillera Blanca supports human activities at different altitudes. Irrigated agriculture is practiced between 2000–4000 m and at the foot of the Andes. Below 2000 m, electricity is generated (Chevallier et al. 2011; Kaser et al. 2003). To maintain the full capacity of electricity production, a discharge of 60 $m^3$ per second is required. As the minimum flow of the Río Santa usually falls below that level, water management is needed to guarantee the minimum discharge.

The population of the Andes area is increasing. Due to this population trend, and to the possibility of expanding cultivation into higher areas of the Andes under increasing temperatures, water demand is expected to increase. This might lead to conflicts with hydroelectric power generation (Juen et al. 2007; Mark et al. 2005).

years, with no or little solid precipitation in the upper watershed, glacier melting gains in importance, although there is little information about the contribution of ice masses to river flow (Masiokas et al. 2013).

**Figure 3.17:** Changes in seasonal total runoff in 4 IPCC climate-change scenarios with respect to the 1961–1990 mean monthly runoff.




Source: Juen et al. (2007).

Cortés et al. (2011) found that, for the period 1961–2006, river regimes in the dry north were driven by snowmelt whereas those further south were more rainfall-dominated. The southern river systems (to the south of 35°) have displayed consistently earlier timing in peak annual flow rates. Vicuña et al. (2013) found indications of a shift in the last 30 years to an earlier annual snowmelt season of around 15 days for the Mataguito basin.

More high-flow discharges were also observed during the last 10 years. They occurred mostly during autumn months when high rainfall and high minimum temperatures decreased the fraction of precipitation falling as snow and cause a faster rainfall-runoff response (Vicuña et al. 2013). Annual low-flow levels during spring and summer decreased significantly in the Mataguito basin (Vicuña et al. 2013) and for some stations in the Limay River Basin (Seoane and López 2007). This trend in river flow variability might endanger electrical power generation in the region, as the Limay River basin contains many hydropower stations which yield around 26 percent of Argentina's total electrical power generation (Seoane and López 2007).

Projections of the mean number of snowy days decrease by about 9 percent in a 2°C world, and 26 percent in a 4°C world, in the Mataguito basin (Demaria et al. 2013). In addition, the center timing of mass of annual flow was projected to occur earlier, by 12 days in a $>1.5$°C world and by 16 days in a $>3$°C world. In the Limarí basin, reductions in annual streamflow are probably intensified by increased evapotranspiration because a 19 percent rainfall decrease resulted in a 21 percent streamflow decrease in a 4°C world (Vicuña et al. 2010). Vicuña et al. (2010) also found increasing winter flows (28.8–108.4 percent), decreasing summer flows (–16.5 to –57.8 percent), and earlier center timing of mass of annual flows for different sub-basins of the Limarí basin in a $>3$°C world. For northeastern Chile, Arnell and Gosling (2013)

## Box 3.7: Water Security in the Central Andes

In the Andes, between latitudes 30 and 37° lie two major cities, Santiago de Chile (Chile) and Mendoza (Argentina). Human activities in these cities are almost completely dependent on meltwater, especially in the drier Argentinean foothills which receive only around 200 mm of annual precipitation (Masiokas et al. 2013).

Snowmelt is very important for water supply, hydroelectric generation, and viniculture in large parts of Chile (Demaria et al. 2013). The central valley of Chile contains the majority of the country's reservoir storage and supplies water to several large towns. Water demand results as well from agriculture, as 75 percent of the irrigated area in Chile is located here (Demaria et al. 2013). The Central Valley suffers from high inter-annual rainfall variability, with conditions being wetter during El Niño years and drier during El Niña years (Cortés et al. 2011). In years with above-average rainfall, farmers irrigate annual crops (e.g., orchards, vineyards) with surface water, whereas in below-average rainfall years they are forced to use groundwater. The use of groundwater has recently reached unsustainable levels, and the Chilean water authorities have therefore restricted water extraction. Decreasing annual rainfall as a result of climate change would put even more pressure on agriculture and water resources (Arumí et al. 2013).

## Box 3.8: Water Security and Glacial Melt in La Paz and El Alto, Bolivia

La Paz and El Alto receive 80 percent of their water from the Tuni Condoriri range. The contribution of glacier ice melt could be from 30–40 percent (World Bank 2008) up to 60 percent (Painter 2007). Since water demand has risen in recent years, the water management of both cities is very much challenged (Jeschke et al. 2012; Shi et al. 2013). Almost the entire energy supply of La Paz is supplied by hydroelectric power which comes mainly from two glacier ranges—in the Zongo valley and Charquiri (Painter 2007). The glaciers of the Cordillera Real encompass 55 percent of the Bolivian glaciers. Between 1963–2006 they lost more than 40 percent of their volume (Soruco et al. 2009) and they are further declining (Liu et al. 2013). It has been postulated that water demand might soon surpass water supply in El Alto (Shi et al. 2013). Future water and energy supply will be increasingly critical due to rising demand, in combination with decreasing tropical glacier volumes (Rabatel et al. 2013; Vuille et al. 2008).

simulated a decreasing mean annual runoff for warming higher than 1°C over 21 GCMs. Projections by Döll (2009) also showed a reduced groundwater recharge for the central Andes region by the 2050s with 2°C warming.

### *3.4.2.7 Amazon Basin*

Espinoza Villar et al. (2009) found significant decreasing mean and minimum annual runoffs from 1990–2005 for southern Andean rivers (Peru, Bolivia) and increasing mean and maximum annual runoffs for northern Andean Rivers (Ecuador) draining into the Amazon. For the southern Amazon, Li et al. (2008) found more dry events during 1970–1999. Espinoza Villar et al. (2009) reported decreasing mean annual discharge and monthly minimum discharge from 1974–2004 for Tapajós in the southeastern Amazon, the Peruvian Amazon Rivers, and the upstream Madeira.

Guimberteau et al. (2013) analyzed the impacts of climate change on extreme streamflow over several Amazonian sub-basins by the middle of this century for a 2°C global warming scenario. They found that low flows would become more pronounced. The trend is significant at the Madeira and Xingu rivers, with JJA precipitation decreases of 9 percent and 22 percent respectively. At Porto Velho, the decrease in median low flows is about 30 percent; at Altamira, it is about 50 percent. In addition, Tosiyuki Nakaegawa et al. (2013) found total annual runoff decreases in the southern half of the Amazon River in a 3°C world. Average annual runoff varied from –72 percent to +6 percent in a 3°C world for the Bolivian part of the Amazon (Alto Beni), assuming no land use change (Fry et al. 2012). Nevertheless the projected groundwater recharge was consistently negative (–96 percent to –27 percent) because potential evapotranspiration increases.

Malhi et al.(2009) found an increase in dry-season intensity in eastern Amazonia in a 3° world and seasonal increased water stress because of climate change and deforestation. Langerwisch et al. (2013) found shifts in flood patterns in a 3° world. The duration of flooding at the end of the 21st century was projected to be 0.5–1 months shorter than for 1961–1990. The probability of three successive extreme wet years decreased by up to 30 percent (Langerwisch et al. 2013).

Median high flows in the western part of the Amazon basin increase by 5–25 percent by the middle of this century for a warming of 2°C; this trend is not, however, significant (Guimberteau et al. 2013). In a 2°C world, the increase in high flow was projected to be lower than in a warmer than 3°C world; low flows increase 10–30 percent under a 4° warming scenario (Guimberteau et al. 2013). The flood zone is consistently projected to increase with a 2–3 month longer inundation time in a 3°C world over several GCMs (Langerwisch et al. 2013). The average runoff and the maximum runoff increased in two subcatchments of the Paute basin for a 2°C global warming scenario from 2045–65 (Mora and Campozano et al. 2013). Exbrayat et al. (2014) also found increases in annual runoff for a catchment in the Ecuadorian Andes by 2100; they also showed a high variability of runoff projections depending on the choice of GCM, emissions scenario, and hydrological model. Similarly, Buytaert et al. (2009) showed that, due to the wide range of GCM projections, the projected average monthly discharges diverge considerably in the Paute River system in Ecuador under a 1°C increase by 2030.

For the northernmost Amazon and the river mouth region, river flow and runoff coefficients decrease with a global warming of 2°C in 2045–2065 (Guimberteau et al. 2013). In the same study, median low flows decrease by 20 percent for the Japura and Negro river and 55 percent at the Río Branco.

At the main stem of the Amazon River the runoff coefficient is projected to slightly decrease at Óbidos (the last station of the Amazon before the mouth) with a warming of 2°C by 2050 (Guimberteau et al. 2013). Median low flow is projected to decrease by 10 percent, but this trend is uncertain. In a 4°C world, Guimberteau et al. (2013) projected that low flows and high flows would each increase by five percent at Óbidos. Döll and Schmied (2012), however, projected the mean river discharge of the downstream part of the Amazon to increase for under a 2°C warming by 2050 in one GCM but decrease in another GCM.

#### 3.4.2.8 Northeast Brazil

Krol and Bronstert (2007) found that a decrease in precipitation by the end of the 21st century would significantly decrease the runoff of the Jaguaribe River and the stored volume in the Ceará reservoir. In contrast, an increase of precipitation by 50 percent did not significantly increase river runoff because of an accompanying increase in water demand. Döll and Schmied (2012) projected the seasonality of river discharge in northeastern Brazil to remain stable but also that mean river discharge would decrease by the middle of the 21st century under a 2°C global warming scenario.

Due to uncertainty in the GCM projections, there is no clear signal about the relative change of annual discharge for northeastern South America under 2°C warming (Schewe et al. 2013). Portmann et al. (2013) projected both strong decreases and increases in mean groundwater discharge for northeastern Brazil in a 4°C world depending on the GCM. Assuming different warming scenarios with varying levels of decreasing rainfall, Montenegro and Ragab (2010) projected strong decreases in groundwater recharge of up to 77 percent and streamflows of up to 72 percent for a subcatchment of the Sao Francisco River Basin.

#### 3.4.2.9 Río de la Plata

The Río de la Plata region experienced a 10–30 percent increase in river runoff during the 20th century (García and Vargas 1998; Jaime and Menéndez 2002; Menéndez and Berbery 2005; Milly et al. 2005). There is no consensus, however, among river runoff projections for the Río de la Plata and its tributaries because the projected direction of rainfall trend varies among GCMs. Milly et al. (2005) modeled an increase in mean relative runoff for the Rio de la Plata region of 20–50 percent for the middle of the 21st century and using a 3°C warming scenario. River flow projections in the upper Paraguay River basin varied from ±10 percent by 2030 for a 1.5° warming scenario and by ±20 percent by 2070 for a 2°C warming scenario (Bravo et al. 2013). For a 3°C world, Nakaegawa et al. (2013) projected increasing discharge from January–May at Corrientes on the Paraná River—but not at Posadas which lies further upstream. Nóbrega et al. (2011) found that for the Río Grande, a tributary of the Paraná, for every 1°C temperature rise annual flow increased by 8–9 percent in relation to 1961–1990. Assuming 2°C warming, mean river flow ranged from –20 percent to +18 percent.

Camilloni et al. (2013) projected an increase in frequency and duration of river flooding in a >3°C world in the Uruguay and Paraná basins. Hirabayashi et al. (2013) showed a decrease in the 20th century 100-year return period for floods for the Parana in a 4°C world, but there was little consistency across the 11 GCMs used.

Besides river floods, storm surge floods present a major hazard for Buenos Aires. Barros et al. (2005; 2008) found a greater inland reach of recurrent storm surge floods by 2070 under a 3°C global warming scenario. Assuming no changes in population distribution, permanent coastal flooding due to sea-level rise will play a minor role and will affect rather sparsely populated areas at the coast of Buenos Aires and its surroundings. In contrast, Pousa et al. (2013) projected that sea-level rise could aggravate the impact of storm surge floods in Buenos Aires.

#### 3.4.2.10 Southernmost South America

Milly et al. (2005) simulated a decrease in mean relative runoff of up to 10 percent, which is in agreement with observed 20th century trends for southernmost South America. They projected a decrease in mean relative runoff of 10–30 percent for southernmost South America for the middle of the 21st century with 3°C global warming. Schewe et al. (2013) found similar results for a >2°C world.

#### 3.4.2.11 Synthesis

ENSO-related rainfall anomalies play a major role in many areas in LAC and determine much of the inter-annual discharge variability. In **Central America**, there is a high agreement on decreasing mean annual runoff and discharge, although the magnitude of the change varies (Arnell and Gosling 2013; Hidalgo et al. 2013; Imbach et al. 2012; Maurer et al. 2009; Milly et al. 2005; Nakaegawa et al. 2013; Schewe et al. 2013). The trend seems to be more pronounced for the northern than for the southern part of Central America (Hidalgo et al. 2013; Imbach et al. 2012). Therefore, water stress may increase, especially in arid areas with high population densities and during the dry season.

**The Caribbean** lacks long-term measured stream flow data. Runoff projections are therefore of low confidence (Cashman 2013; FAO 2003; Hidalgo et al. 2013). However, freshwater availability may decrease for several reasons. Sea-level rise (Mimura et al. 2007) may lead to an intrusion of sea water into coastal aquifers (Cashman et al. 2010; Cashman 2013) and summer precipitation is projected to decrease (Mimura et al. 2007). Regionally the risk of flooding and mudslides with high mortality rates is high (Cashman 2013; Edwards 2011; Williams 2010). Although floods often seem to be associated with land-use change, more severe flooding events may also occur in the context of climate change (Cashman et al. 2010; IPCC 2012).

**In Northern South America (Colombia),** there are only a limited number of regional hydrological impact studies available for northern South America, and rainfall projections are uncertain. Conclusions about projected hydrological impacts are therefore of low confidence.

**In the Andes,** higher discharge seasonality is projected for the Tropical Andes. Streamflows during the dry season may decrease because of ongoing glacier retreat (Baraer et al. 2012; Juen et al. 2007; Kinouchi et al. 2013). Lower dry season discharge has already been observed during the past two decades (Baraer et al. 2012). However, streamflow during the wet season may increase (Juen et al. 2007; Kinouchi et al. 2013). The region has a high flood risk (e.g., due to accelerated glacier melting; see Box 3.4: Glacial Lake Outbursts) (Carey 2005; Hirabayashi et al. 2013). For the Central Andes, more streamflow was observed and projected to occur at earlier dates locally (Cortés et al. 2011; Vicuña et al. 2013; Demaria et al. 2013). Lower dry season discharges may cause significant water supply problems in urban areas.

**Amazon Basin:** Runoff and discharge projections for most parts of the Amazon basin are diverging, especially for the southern and eastern areas. The main reasons for this are the high variability of rainfall projections using different GCMs and uncertainties introduced by hydrological impact models. However, for the western part of the basin a likely increase in streamflow, runoff, flood zone, and inundation time was projected (Guimberteau et al. 2013; Langerwisch et al. 2013; Mora and Campozano et al. 2013).

**Northeast Brazil:** The direction of discharge and groundwater recharge trends vary due to diverging rainfall projections under different GCMs (Döll and Schmied 2012; Krol and Bronstert 2007; Portmann et al. 2013; Schewe et al. 2013).

**Río de la Plata:** There are no consistent river runoff projections for the basin because the directions of rainfall projections vary among the GCMs (Bravo et al. 2013; Milly et al. 2005; Nakaegawa et al. 2013; Nóbrega et al. 2011).

**Southernmost South America:** A decrease of mean runoff was projected with a high confidence (Milly et al. 2005; Schewe et al. 2013).

## 3.4.3 Climate Change Impacts on Agriculture

### *3.4.3.1 Temperature Sensitivity Crop Thresholds*

Agriculture is one of the most climate dependent human activities, and the development and growth of plants is affected to a very large extent by temperature. Every plant has a range between a maximum and minimum temperature in which the plant can exist and an optimum temperature at which growth is at its optimal rate (Hatfield et al. 2011). Crops often require different temperatures in their numerous development stages and are very sensitive to temperatures above the optimum, especially during the pollination phase (Hatfield et al. 2011). Generally, warmer temperatures act to decrease the development phase of perennial crops, resulting in earlier crop flowering and reduced seed sets (Craufurd and Wheeler 2009). When temperatures increase above the maximum, plant growth and yields can be drastically reduced (Ackerman and Stanton 2013; Berg et al. 2013; Luo 2011).

The optimum seasonal average temperature for maximum grain yield is 15°C for wheat, 18°C for maize, 22°C for soybeans, and 23°C for rice (Hatfield et al. 2011; Lobell and Gourdji 2012). Hatfield et al. (2011) also identified average temperatures leading to a total crop failure: 34°C for wheat, 35°C for maize, 39°C for soybeans, and 35°C for rice. Short intervals of a few days above the optimum average temperature can lead to strong yield decreases (Ackerman and Stanton 2013). Teixeira et al. (2013) project an increasing occurrence of heat stress for maize, rice, and soybeans in Latin America. Lobell and Gourdji (2012) estimate global yield declines of 3–8 percent per °C of temperature increase based on a literature review. It is, however, important to note that there are numerous knowledge gaps concerning plant reactions to temperatures above their optimum averages (Craufurd and Wheeler 2009; Porter et al. 2014). Moreover, plants are somewhat capable of adapting to changing climatic conditions—and it is unclear if climate change will alter growing conditions too fast for crops to adapt on their own (Ackerman and Stanton 2013).

### *3.4.3.2 Plant Diseases*

How pests and diseases will spread under future climate conditions, and how severe the effects will be on yields and production quantities, is unclear. Already today crop diseases are responsible for losses of 10 percent or more of global food production (Chakraborty and Newton 2011; Ghini et al. 2011; Luck et al. 2011).

Climate change is expected to alter the geographic distribution of insects and diseases in much of the world (Porter et al. 2014). The knowledge on climate change and plant diseases, however, is still very limited (Ghini et al. 2011; Luck et al. 2011). The impacts differ greatly between crops and pathogens as do the interactions among hosts, pathogens, microorganisms, and the climate (Ghini et al. 2011; Bebber et al. 2014). The existing knowledge base is inadequate to make generalizations about the behavior of crop diseases under a changing climate (Luck et al. 2011). Factors that are most likely to influence the development of plant diseases are increasing atmospheric $CO_2$, increasing winter temperatures, and increasing humidity (Luck et al. 2011).

One recent example of the impact of plant diseases on agriculture in the LAC region is the outbreak of coffee leaf rust (*Hemileia vastratix*), considered the most destructive coffee disease, in Central America during the 2012–13 growing season. Around 50 percent of the roughly one million ha under coffee production in the region were affected by the disease, reducing the production quantity by an estimated 17 percent in comparison to the previous year (Ghini et al. 2011; ICO 2013). The outbreak devastated small holder

## Box 3.9: Surface Ozone Concentrations

Surface ozone concentrations have negative impacts on agricultural yields. The impact on crop yields strongly depends on the seasonal and regional distribution of surface ozone, as it is not distributed evenly in the atmosphere (Teixeira et al. 2011). Declines in yield levels currently range from 7–125 percent for wheat, from 6–16 percent for soybeans, from 3–4 percent for rice, and from 3–5 percent for maize; wheat and soybeans are especially sensitive to surface ozone (Van Dingenen et al. 2009; Teixeira et al. 2011). Jaggard et al. (2010) noted that the impact of ozone on crop yields has been neglected in many climate impact projections and found that the benefits of the $CO_2$ fertilization effect (see Box 2.4) could be offset by the negative effect of increased ozone concentrations on C3 plants (and even lead to a yield reduction of five percent in C4 plants). By 2030, increasing surface ozone could lead to yield declines in Latin America by up to 7.8 percent for wheat, 2.9 percent for maize, and 7.5 percent for soybeans depending on the emissions levels of ozone precursors (Avnery et al. 2011).

coffee growers and possibly contributed to rising coffee prices globally (NYT 2014). Coffee leaf rust, together with soybean rust (*Phakopsora pachyrhizi*), are expected to move further south and affect South American countries with global temperatures increasing by approximately 3.5°C by 2080 compared to pre-industrial levels (Alves et al. 2011).

### 3.4.3.3 Projected Changes in Crop Yields

Climate change impacts on crop yields vary depending on crop type and location. Fernandes et al. (2012) projected changes in crop yields in 2050 (compared to 1989–2010) under global warming scenarios of between 1.7°C and 2.3°C. Table 3.6 and Figure 3.18 present some of their key results. It is important to note that, when considering adaptation measures, yield declines are less pronounced but still negative for wheat, soybeans, and maize.

Yield projections for rice show a different picture. With the exception of Brazil, Mexico, and the Caribbean, where temperatures are already high, rice yields could increase by up to 12 percent by 2020 and by 17 percent by 2050 as average conditions for rice photosynthesis would improve with increasing temperatures (Fernandes et al. 2012).

Nelson, Rosegrant and Koo et al. (2010) project yield changes for different crops in LAC with a 1.8–2.5°C global temperature increase by 2050. Their key results, shown in Table 3.6, show that yields generally decline without $CO_2$ fertilization; this is most pronounced for irrigated maize, soybeans, and wheat. $CO_2$ fertilization increases yields for rice, soybean, and maize by over 10 percent besides irrigated maize (Nelson, Rosegrant, Koo et al. 2010).

In Chile, even when including the $CO_2$ fertilization effect, yields could be reduced by 2050 by 5–10 percent for maize and 10–20 percent for wheat in comparison to 1971–2000 levels with 2.7°C global warming if no adaptation measures are implemented (Meza and Silva 2009). In Argentina, yields for wheat, maize, and soybeans are projected to decline by 16, 24, and 25 percent respectively by 2080 under a 3.5°C global warming scenario without $CO_2$ fertilization (ECLAC 2010). Yield declines are less pronounced with only 2.7°C global warming, with declines of 11 percent for wheat, 15 percent for maize, and 14 percent for soybeans; including $CO_2$ fertilization increases yields slightly (ECLAC 2010). In southern Brazil, bean and maize productivity would decline by 15–30 percent in comparison to 1971–2000 levels under a global mean warming of 2°C by 2050 and by 30–45 percent with 4°C warming by 2080 without $CO_2$ fertilization but with technological progress (Costa et al. 2009). Including $CO_2$ fertilization for beans leads to productivity increases of up to 15 percent (Costa et al. 2009). Because maize is a C4 crop, including $CO_2$ fertilization has only a limited impact and productivity keeps decreasing (Costa et al. 2009). Rain-fed sugarcane yields could increase by 15–59 percent with global warming of 1.5–2.3°C by 2050, including $CO_2$ fertilization and technological improvement (Marin et al. 2012). In the Brazilian Amazon, soybean yields decline by 44 percent with 4°C mean global warming by 2050 and by 1.8 percent with a 2°C temperature increase (Lapola et al. 2011). On average and over all analyzed crop types, yields are projected to decline by 31 percent when temperatures increase by 4°C without $CO_2$ fertilization and increase by 14 percent when temperatures increase by 2°C with $CO_2$ fertilization (Lapola et al. 2011).

In Ecuador, ECLAC (2010) projects yield declines of 53 percent for maize, 9 percent for beans, 41 percent for bananas, 36 percent for sugarcane, 23 percent for coffee, and 21 percent for cocoa; ECLAC also projects yield increases of up to 37 percent for rice for the year 2080 with 3.5°C warming. Colombian agriculture, meanwhile, is projected to be severely impacted by climate change. Up to 80 percent of agricultural crops currently cultivated in Colombia in 60 percent of the cultivation areas of the country would be negatively affected by 2–2.5°C global temperature increases by 2050 if no adaptation measures are introduced (Ramirez-Villegas et al. 2012). Perennial crops (notably such high-value crops as tropical fruit, cocoa, bananas, and coffee) could be particularly affected by climate change (Ramirez-Villegas et al. 2012). Coffee farming might have to migrate to higher altitudes or other cultivation regions to maintain present yields, a problem also relevant in other parts of Latin America (Camargo 2010; Laderach et al. 2011; Zullo et al. 2011).

In Panama, yield changes for maize range from −0.8 to +2.4 percent for global warming of 1.7–1.9°C in 2055, and from +1.5 to +4.5 percent for global warming of 2.2–3.3°C in 2085 including $CO_2$ fertilization (Ruane et al. 2013). Accelerated crop development helps to complete the grain-filling phase before the

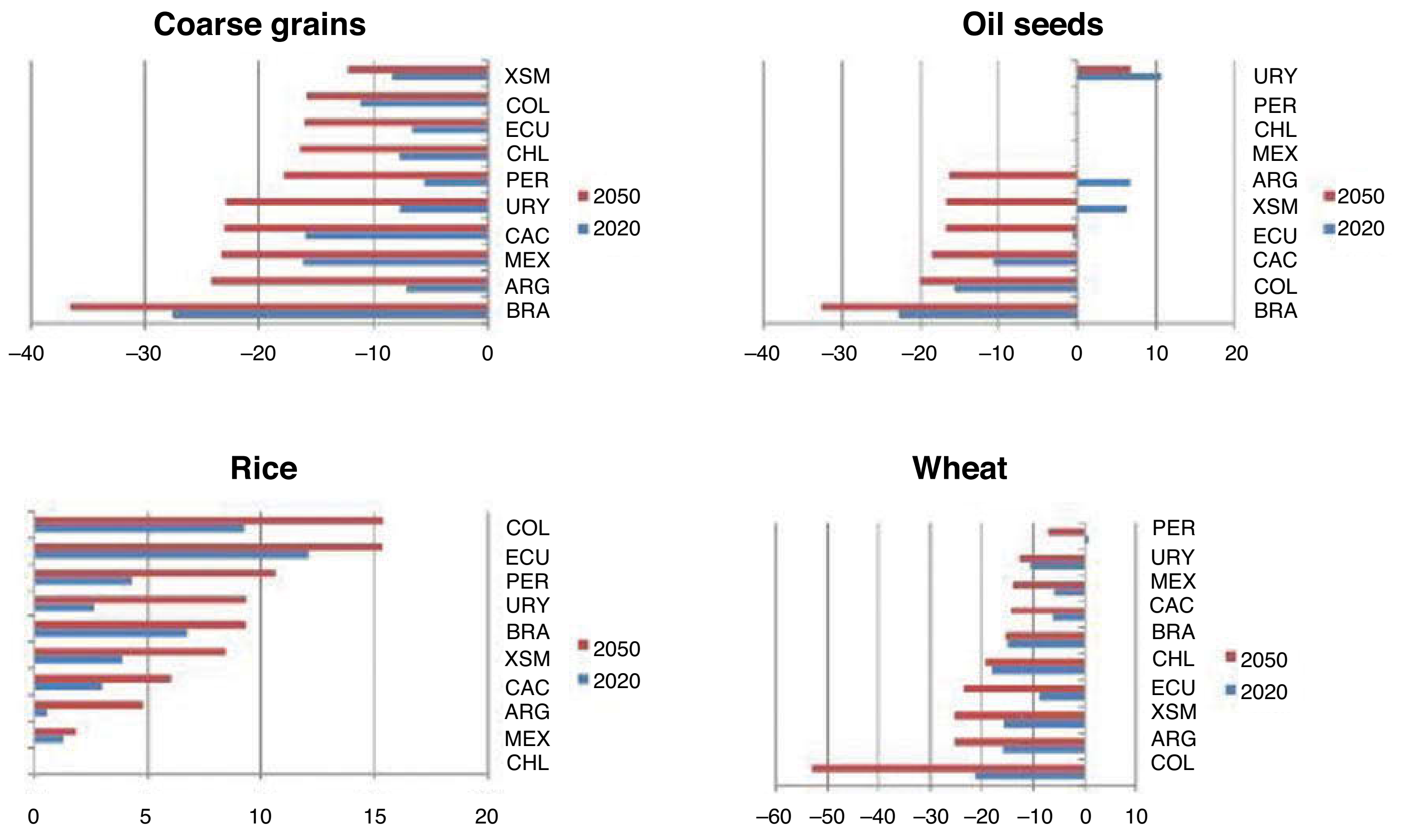
**Table 3.6:** Projected Changes in Yields and Productivity Induced by Climate Change.

| SOURCE | SCENARIO | TIME HORIZON | REGION | CROP | YIELD OR PRODUCTIVITY EFFECT |
|---|---|---|---|---|---|
| **Fernandes et al. (2012)** | A1B / B1 | 2050 | Brazil | Soybeans | –30 to –70 % |
| | | | Brazil, Ecuador, | Maize | up to –60 % |
| | | | Brazil | Wheat | –13 to –50 % |
| | | | LAC | Rice | up to +17 % |
| **Meza and Silva (2009)** | A1F1 | 2050 | Chile | Maize | –5 to –10 % |
| | | | | Wheat | –10 to –20 % |
| **Costa et al. (2009)** | A2 | 2050 | Brazil | Beans | –15 to –30 % |
| | | | | Maize | –15 to –30 % |
| **Ruane et al. (2013)** | A2 / B1 | 2050 | Panama | Maize | –0.8 to +2.4 % |
| | A2 /B1 | 2080 | Panama | Maize | +1.5 to +4.5 % |
| **Lapola et al. (2011)** | A2 | 2050 | Brazilian Amazon | Soybeans | –1.8 to –44 % |
| **Marin et al. (2013)** | A2 / B2 | 2050 | Southern Brazil | Sugarcane | +15 to +59 % |
| **ECLAC (2010)** | A2 | 2080 | Ecuador | Maize | –53 % |
| | | | | Beans | –9 % |
| | | | | Bananas | –41 % |
| | | | | Sugarcane | –36 % |
| | | | | Coffee | –23 % |
| | | | | Cocoa | –21 % |
| | | | | Rice | +37 % |
| | A2 / B2 | | Argentina | Wheat | –11 to –16 % |
| | | | | Maize | –15 to –24 % |
| | | | | Soybeans | –14 to –25 % |
| **Nelson et al. (2010)** | A2 | 2050 | LAC | Maize | –3.0 to +2.2 % |
| | | | | Rice | –6.4 to +12.7 % |
| | | | | Soybeans | –2.5 to +19.5 % |
| | | | | Wheat | –5.6 to +12.2 % |

beginning of dry periods with high levels of water stress (Ruane et al. 2013). In Mexico, wheat yields decline with global temperatures rising between 1.6–2.1°C by 2050 across several crop models and GCMs (Rosenzweig et al. 2013b). Yield declines are more pronounced with stronger warming, but they remain relatively small because $CO_2$ fertilization reduces the negative yield effect in the crop models (Rosenzweig et al. 2013b).

A meta-analysis of the impacts of climate change on crop yields for the LAC region (see Section 6.3, Meta-analysis of Crop Yield Changes with Climate Change,) reveals no significant influence of temperature increase over crop yields across all available studies. A significant positive relationship between crop yield change and temperature is revealed, however, when $CO_2$ fertilization is considered (see Table 3.7 and Figure 3.19), although the beneficial effects of $CO_2$ fertilization are highly uncertain (Ainsworth et al. 2008)(see Box 2.4) The interpretation of these results therefore requires some caution, as model assumptions made regarding $CO_2$ fertilization may not hold in an actual crop production environment. If the effects of $CO_2$ fertilization are not considered, the relationship remains significant but becomes negative, with increasing temperature leading to considerable yield declines (see Figure 3.19).

**Figure 3.18:** Aggregate impacts on crop yields in the LAC region with adaptation, computed by the AZS-BioMA platform under 2020 and 2050 NCAR GCM for A1B scenario.



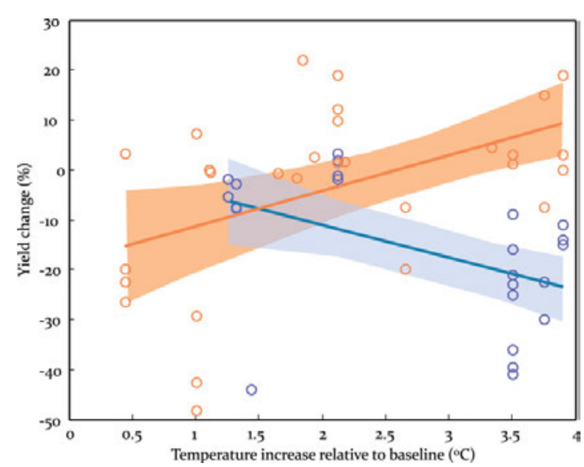

Source: Fernandes et al. (2012), Figure 4.1.

**Table 3.7:** Summary of Crop Yield Responses to Climate Change, Adaptation Measures, and $CO_2$ Fertilization.

| | SLOPE | R2 | T-STAT | P-VALUE |
|---|---|---|---|---|
| **Full dataset** | 0.0023 | 0 | 0.1255 | 0.9 |
| **Crop yield change with effect of $CO_2$ fertilization** | 0.07 | 0.266 | 2.81 | 0.009** |
| **Studies not considering the effects of adaptation measures or $CO_2$ fertilization** | –0.065 | 0.24 | –2.65 | 0.0145* |

Results of a general linear model applied to all studies with reported values for changes in yield and changes in temperature, to studies considering the effect of $CO_2$ fertilization, and to studies not considering the effects of adaptation measures nor those of $CO_2$ fertilization. Significance levels: *P<0.05, **P<0.01, ***P<0.001.

**Figure 3.19:** Meta-analysis of crop yield reductions.




Best-fit line for LAC studies not considering the effects of adaptation measures or those of $CO_2$ fertilization (blue line) and for studies considering the effects of $CO_2$ fertilization (but no adaptation, orange) and their 95 percent confidence intervals of regressions consistent with the data based on 500 bootstrap samples (patches).

To conclude, the possible effects of climate change on crop yields in the region are very diverse. Yield impacts differ among regions and crops and also among different GCMs, emissions scenarios, and crop models (see Table 3.6) (Berg et al. 2013). Most of the effects of rising temperatures are expected to be negative, even if lessened $CO_2$ fertilization (which introduces large uncertainties into the impact projections). For some crops, however, increasing temperatures might have positive effects, such as increasing yields for rice and sugarcane.

#### 3.4.3.4 Climate Change Impacts on Livestock

The livestock sector in the LAC region is of high economic importance, especially in major livestock producing and exporting countries Brazil and Argentina (ECLAC et al. 2012), and the impacts of climate change on livestock systems in developing countries are diverse (Thornton et al. 2009). Climate change can severely impact the quantity and quality of feed, as rising temperatures, increasing atmospheric $CO_2$ concentrations, and changes in precipitation patterns influence the availability of nutrients, the productivity of grasslands, and the composition of pastures. Furthermore, heat stress directly affects livestock productivity. Cattle, in particular, are susceptible to high temperatures. Heat stress is known to reduce food intake and milk production and also to affect reproduction, growth, and cattle mortality rates (Porter et al. 2014). Higher temperatures are also closely linked to growing water demand for livestock, increasing the competition and demand for water in water-scarce regions. More scientific research is needed, meanwhile, on the effects of climate change on livestock diseases and livestock biodiversity.

#### 3.4.3.5 Projected Impacts on Livestock

With a 2.7°C warming by 2060, livestock species choice (i.e., the adoption of new livestock) is projected to decline across Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay, and Venezuela by 3.2 percent for beef cattle; by 2.3 percent for dairy cattle; by 0.9 percent for chicken; and by 0.5 percent for pigs. Meanwhile, the adoption of sheep species is projected to increase by an average of 7 percent across the region, and by more in Colombia (11.3 percent), Chile (14.45 percent), and Ecuador (19.27 percent) (Seo et al. 2010).

With a lower warming of 1.3–2.3°C by 2060, the pattern of declining livestock species choice for beef cattle, dairy cattle, chicken, and pigs, and the increasing choice of sheep, remains the same but is less pronounced (Seo et al. 2010). According to Seo et al. (2010), the choice of sheep increases with increasing temperatures and decreasing precipitation because sheep are better adapted to these conditions than other livestock species. In Paraguay, beef cattle production is projected to increase by 4.4 percent by 2020, but then decline by 7.4 percent by 2050 and 27.1 percent by 2080 in a scenario leading to 3.5°C regional warming (ECLAC 2010). Beef cattle production is projected to decline by 1.5 percent by 2020, by 16.2 percent by2050, and by 22.1 percent by 2080 with 2.9°C regional warming (ECLAC 2010).

#### 3.4.3.6 Climate Change Impacts on Food Security

Nelson, Rosegrant and Koo et al. (2010) project that international crop prices will increase significantly even when ignoring climate change—mainly driven by population growth, income growth, and demand for biofuels. The price of wheat is projected to increase by 39 percent, rice by 62 percent, maize by 63 percent, and soybeans by 72 percent. Including climate change with global mean temperature increasing by 2.5 °C by 2050, and without $CO_2$ fertilization, would accelerate price increases by an additional 94–111 percent for wheat, 32–37 percent for rice, 52–55 percent for maize, and 11–14 percent for soybeans. Including $CO_2$ fertilization would lead to less severe price increases by 2050 (Nelson, Rosegrant, Koo et al. 2010). These results are confirmed by the IPCC AR5 report: Increasing food prices as a consequence of changing climatic conditions are to be expected by 2050 without taking the $CO_2$ fertilization effect into account; including elevated $CO_2$ will temper price increases (Porter et al. 2014).

Climate change poses great risks to the economic development of Latin America and the Caribbean; it not only threatens economic growth but also poverty reduction and food security (ECLAC 2010). Without climate change, calorie availability would be expected to increase by 3.7 percent, up to 2,985 calories per capita in 2050 in LAC (Nelson, Rosegrant, Koo et al. 2010). However, with climate change and without $CO_2$ fertilization, per capita calorie availability in 2050 is expected to drop below the value for the year 2000 (2,879 calories per capita) (Nelson, Rosegrant, Koo et al. 2010). These projections show that climate change threatens food security, especially for people with low incomes, as access to food is highly dependent on income (FAO 2013). The cascading impacts of warming that reduce productivity in other sectors apart from agriculture can further reduce economic output and negatively affect incomes (Porter et al. 2014). Results from a Brazilian study (Assad et al. 2013) on climate change impacts on agriculture to 2030 project that Brazil could face a reduction of approximately 11 million hectares of high quality agricultural land as a result of climate change with the South Region (current grain belt) being the worst impacted losing ~5 million ha of 'low climate risk' crop land. The increase in climate risk in the south could be partially offset by transferring grain production to the central region currently occupied by low productivity pastures (sub regional reallocation). Intensification of livestock and pasture systems will also offset projected losses due to climate change. In general, however, the production declines can be expected to impact prices, domestic demand, and net exports of most crops/livestock products. Simulations from this study across all the climate change scenarios suggest that rising staple and export crop and beef prices could double the agricultural contribution to Brazil's economy.

## Box 3.10: Critical Ecosystem Services of High Andean Mountain Ecosystems

A highly critical ecosystem service provided by the LAC region is that of carbon storage. For example the ecosystems of the Andean mountains, including tropical montane cloud forests, the high-altitude wetlands, and the páramos ecosystem, store large amounts of carbon. Despite the fact that they cover a mere 3 percent of global land area they store about 30 percent of the global carbon stock of terrestrial ecosystems (Peña et al. 2011). Further, numerous large cities (such as Quito, Bogota or La Paz) extract part of their water supply from páramos areas.

#### *3.4.3.7 Synthesis*

The results of the climate change impact projections on crop yields differ among studies, but most authors agree that climate change will very likely decrease agricultural yields of important food crops in LAC (see Table 3.6) (ECLAC 2010; Fernandes et al. 2012; Nelson, Rosegrant, Koo et al. 2010). An exception is the possible yield development of rice in some regions (ECLAC 2010; Fernandes et al. 2012; Nelson, Rosegrant, Koo et al. 2010). Although studies on climate change impacts on livestock are scarce (Thornton et al. 2009), the few studies that are available indicate that beef and dairy cattle production will decline under increasing temperatures, as heat stress is a major influencing factor of cattle productivity (Seo et al. 2010; Thornton et al. 2009). Sheep production could become more important in the future, as sheep are better adapted to warmer and drier conditions than cattle and pigs (Seo et al. 2010).

### 3.4.4 Climate Change Impacts on Biodiversity

#### *3.4.4.1 Current Status and Current Threats to Biodiversity*

Biodiversity, the diversity of genes, populations, species, communities, ecosystems, and biomes, is the foundation for all ecosystem processes (MEA 2005). Climate change is a major threat to biodiversity, as species have evolved to live within specific temperature ranges that may be surpassed faster than species are able to adapt.

South America is a biodiversity hotspot, particularly due to the large extent of tropical rainforests (MEA 2005; Myers et al. 2000) and the continent's long geographical isolation until approximately 3 million years ago—which together have nurtured a high number of endemic species. Habitat destruction and fragmentation by land-use change as well as the commercial exploitation of species groups are currently larger threats to biodiversity than climate change (e.g., Hof et al. 2011). Land-use change is expected to have a greater impact on plants than climate change by 2050, after which climate change becomes increasingly important for species loss (MEA 2005; Vuuren et al. 2006).

#### *3.4.4.2 Impacts of Future Climate Change on Biodiversity*

Forecasts of future changes in biodiversity are generally alarming (e.g., Bellard et al. 2012; Foden et al. 2013). Using a global meta-analysis, MacLean and Wilson (2011) found a mean extinction probability of 10 percent by 2100 across taxa, regions, and warming levels. Warren et al. (2013) found that, globally, 57 percent of plants and 34 percent of animals will lose greater than 50 percent of their habitat in a 4°C world.

A comparative review of different model predictions across taxa and regions revealed a large variability in the predicted ranges of biodiversity loss, especially at the local level (Bellard et al. 2012). One reason for this variability is that there is still high uncertainty about the capacity of species to buffer the effects of climate change (Moritz and Agudo 2013). Nonetheless, Scholes et al. (2014) state that there is "high confidence that climate change will contribute to increased extinction risk for terrestrial and freshwater species over the coming century."

#### *3.4.4.3 Projections of Potential Future Shifts in Ecosystems and Ecoregions*

The G200 ecoregions (Olson and Dinerstein 2002) located in Latin America and the Caribbean may experience severe climate change in the future (Beaumont et al. 2010). Li et al. (2013) found strong local climatic changes in the ecoregions Coastal Venezuela Montane Forests, Amazon River and Flooded Forests, and Atlantic Dry Forests for 2–4°C global warming. Further, 38.4 percent of the surface of the biodiversity hotspot of Tumbes-Choco-Magdalena and 11.5 percent of the Mesoamerican biodiversity hotspot will be experiencing no-analogue climates in a warmer than 2°C world (Garcia-Lopez et al. 2013).

Heyder et al. (2011) find a range of small to severe ecosystem changes for the whole South American continent in their projections for a 2°C and warmer world. In a 4°C world, results of one dynamic vegetation model show severe ecosystem changes for more than 33 percent of the area in 21 out of 26 distinct biogeographic regions in South America (Gerten et al. 2013). Warszawski et al. (2013), meanwhile, projected such severe ecosystem changes in a 3°C world in South America (notably in Amazon, Guyana moist forests, and Brazilian Cerrado) when applying an ensemble of seven dynamic vegetation models. Imbach et al. (2012) projected that such severe ecosystem changes at global mean warming levels greater than 3°C would lead to a considerable decrease in tree cover, indicated by a change in leaf area index of more than 20 percent across 77–89 percent of the area. Bellard et al. (2014) projected that out of 723 Caribbean islands, 63 and 356 of them will be entirely submerged under one and six meters of sea-level rise, respectively. They also found that 165 of the islands will be at least half-submerged (i.e., having lost more than 50 percent of their area) under one meter of sea-level rise, and 533 under six meters of sea-level rise. While a six meter sea-level rise is not realistically expected to happen within this century, a one meter sea-level rise is within the range of sea-level rise projected under a global mean warming of 4°C at the end of this century (see Section 3.3.7, Regional Sea-level Rise).

#### 3.4.4.4 Projections of Habitat Changes, Species Range and Distribution Shifts, and Extinction Risks for Species and Species Groups

##### Microorganisms

Little is known about the consequences of future climate change on microbial biodiversity due to the complex microbial feedback loops within the climate system (Singh et al. 2010). The ratio between heterotrophic soil bacteria and fungi will likely be affected (Rinnan et al. 2007). Generally, temperature increase stimulates microbial growth and accelerates decomposition, which leads to an increase in heterotrophic respiration (Davidson and Janssens 2006).

##### Invertebrates

Insects act as pollinators to ensure plant fertilization, but they may also emerge as pests. Climate change affects temperature-driven reproductive cycles of many insect populations. In a 4°C world, Deutsch et al. (2008) projected a range contraction of 20 percent for tropical insects, because tropical insects will face near-lethal temperatures much faster than those in temperate climates. Estay et al. (2009) projected an increase in insect population densities of grain pests in Chile of 10–14 percent in a 3°C world and 12–22 percent in a 4°C world.

##### Amphibians and Reptiles

Due to the difficulties in entangling the relative contributions of climate versus land use change, Scholes et al. (2014) stated that "due to *low agreement* among studies, there is only *medium confidence* in detection of extinctions and attribution of Central American amphibian extinctions to climate change." Amphibians are particularly vulnerable because, due to their permeable skin, they depend on constant water availability at least during some periods of their life cycle. Loyola et al. (2013) found that most of the 444 amphibian species in the Atlantic Forest Biodiversity hotspot in Brazil could increase their range, while 160 species would face range contractions with 1.9°C global warming in 2050. A more recent projection for 2050 includes different dispersal scenarios for the amphibians in this region and projects a majority of the 430 amphibian species would face range contractions accompanied by an overall species loss with 1.9°C global warming (Lemes et al. 2014). Already in a 2°C world, 85–95 percent of species face net loss in range size, and 13–15 percent of species would lose 100 percent of their current range depending on the modeled dispersal limitation (Lawler et al. 2009). In a 4°C world, most ecoregions are projected to experience at least 30 percent species turnover, and many in western South America and Central America to experience at least 50 percent species turnover, so that future communities would bear little resemblance to the currently established ones (Lawler et al. 2009). In a greater than 3°C world, the entire LAC region would experience high bioclimatic unsuitability for amphibians in general (many grid cells between 50–80 percent loss). In the Northern Andes, 166 frog species (73 percent of local frog fauna) and, in Central America, 211 species (66 percent of local salamander fauna), would lose their local climatic suitability between 2070–2099 (Hof et al. 2011).

Based on historical data, Sinervo et al. (2010) assume that if the rate of change in maximum air temperature at 99 Mexican weather stations continues unabated by 2080, 56 percent of the viviparous lizard species would go extinct by 2050 and 66 percent by 2080; of the oviparous species, 46 percent would go extinct by 2050 and 61 percent by 2080. By 2080, the predicted loss of suitable areas for the royal ground snake (*Liophis reginae*) is 30 percent (Mesquita et al. 2013).

Sea-level rise will affect the reproductive behavior of sea turtles, which return to the same nesting sites every breeding season and therefore rely on relatively constant shorelines for laying their eggs. Fish et al. (2005) predict a 14/31/50 percent habitat loss of nesting sites for endangered sea turtles by 2050 under 0.2/0.5/0.9 m sea-level rise respectively on Bonaire Island. Narrow and shallow beaches are predicted to be most vulnerable, but turtles seem to prefer steep slopes which might to some extent alleviate climate change impacts at their preferred nesting sites.

##### Birds

Birds are most diverse in the tropics where they typically have smaller home ranges than migratory birds in temperate zones (Jetz et al. 2007). This renders tropical bird diversity especially vulnerable to extinctions caused by climate change and accompanying habitat destruction. Anciaes et al. (2006) projected that 50 percent of 49 neotropical manakin (passerine bird) species will have lost more than 80 percent of their current habitat by around 2055 with mean global warming of 2°C. For a similar time frame and warming scenario, Souza et al. (2011) projected that 44 of 51 endemic Brazilian Atlantic forest bird species would lose their distribution area by 2050, which corresponds to a habitat reduction of 45 percent of the original area. The study assumes that the entire area of the Atlantic forest is suitable for these bird species. However, about 80 percent of the Atlantic forest is already deforested, and most remaining forest areas are fragmented and isolated. Twenty-six Cerrado bird species face 14–80 percent range contractions under a no-dispersal scenario, and they face a 5 percent range increase to a 74 percent range decrease under a full-dispersal scenario in a 3°C world (Marini et al. 2009).

##### Marsupials

Most of the 55 marsupial species found in Brazil inhabit forested areas and are therefore exposed to both climate change and land use change caused by deforestation. Loyola et al. (2012) found that marsupial species in Brazil face range contractions of

67 percent of their original habitat with mean global warming of approximately 2°C by 2050.

### Mammals

Schloss et al. (2012) projected that up to 39 percent of the mammals in the Neotropics would be unable to keep pace with climate-change velocity due to their limited dispersal abilities in a 4°C world. Torres, Jayat and Pacheco (2012) projected an at least 33 percent habitat loss for the maned wolf (*Chrysocyon brachyurus*) in Central South America with 2°C global warming by 2050.

### Plant Species

Plants are especially vulnerable to climate change because individual plants cannot migrate to avoid thermal stress. As a result, their dispersal mode will largely determine to what extent they may be able to adapt to changing climatic conditions. Moreover, plants directly respond to elevated atmospheric $CO_2$ levels (see Box 2.4)—but the degree to which some plant species may benefit from rising $CO_2$ levels is still being debated (Cox et al. 2013; Rammig et al. 2010).

Brazil is the country with the largest number of vascular plant species ( > 50,000) on Earth (ICSU-LAC 2010, p.57). Most future projections paint a bleak picture for plant biodiversity, mostly due to land-use change as a result of deforestation and, increasingly, the impacts of climate change. Simon et al (2013) projected a reduction in geographic distribution of 78 percent ( ± 7 percent) in a > 2°C world for 110 Brazilian Cerrado plant species. Feeley et al (2012) projected a loss of suitable habitat area in the Amazon region of between 8.2–81.5 percent in a 2°C world and 11.6–98.7 percent in a 4°C world, and a change in plant species richness between –4.1 percent to –89.8 percent in a 2°C world and –25.0 percent to complete loss for the studied species in a 4°C world. In Mexico, even common species are under threat, and great differences in species response (0.1–64 percent loss) to regional warming above 1.5°C in 2050 even among related tree species (e.g., oak trees) are being projected (Gómez-Mendoza and Arriaga 2007).

### Species Groups

Most studies on range contractions focus on single species or species groups; fewer studies have attempted to project the impact of future climate change at the community or biome level. Rojas-Soto et al. (2012) projected a reduction of 54–76 percent in the extent of the Mexican cloud forest with 2°C global warming by 2050. They concluded that this reduction forces tree communities to move about 200 m to higher elevations. Similarly, Ponce-Reyes et al. (2012) projected a 68 percent loss of suitable area for cloud forests in Mexico with a global warming of 3°C by 2080. Alarmingly, 90 percent of the cloud forest that is currently protected will not be climatically suitable for this ecosystem by 2080. As a consequence, climate change may lead to the extinction of 9 of the 37 vertebrate species restricted to Mexican cloud forests. With an increase of global mean temperature of 0.8–1.7°C by 2050, 2–5 percent of mammal species, 2–4 percent of bird species, and 1–7 percent of butterfly species in Mexico, as well as 38–66 percent of plant species in the Brazilian Cerrado, would go extinct (Thomas et al. 2004). At a warming of 1.8–2.0°C, these values increase to 2–8 percent, 3–5 percent, and 3–7 percent respectively. With an increase in global mean temperature of greater than 2°C, 44–79 percent of plant species in Amazonia are projected to go extinct (Thomas et al. 2004).

### *Synthesis*

Climate change induced negative effects on biodiversity, from range contractions to extinctions, are very likely in a warmer than 2°C world. Climate change impacts on local biodiversity by 2100 will depend on the balance between the number of species abandoning an area and those facing local extinctions versus the number of species invading that same area due to thermal stress. Species and species communities are possibly threatened by range contractions, extinctions, predator/prey disruptions, and phenology changes due to climate and land use changes. Their opportunity to survive in this changing environment lies in their capacity to adapt to these new conditions or to migrate to avoid them. As the adaptive capacity of affected species and ecosystems is hard to project or quantify, models need to use simplified approaches as implemented in bioclimatic envelope models, species-distribution models, and dynamic global vegetation models.

One clear trend regarding future warming levels is that the more temperatures are projected to increase, the more species diversity is affected. Mountainous regions in the tropics (e.g., cloud forests) are projected to become very vulnerable due to their high number of endemic and highly specialized species which might face mountaintop extinctions. Most models do not take biotic interactions (e.g., food-web interactions, species competition) and resource limitations into account. Therefore, the realized ecological niche of species within an ecosystem might be much smaller than what is potentially possible according to climatic and other environmental conditions leading to shifts in ecological zones.

## 3.4.5 Amazon Rainforest Dieback and Tipping Point

Old-growth rainforests in the Amazon basin store approximately 100 billion tons of carbon in their biomass (Malhi et al. 2006; Saatchi et al. 2011). Through evapotranspiration, Amazon rainforests recycle 28–48 percent of precipitation and contribute to local rainfall (van der Ent et al. 2010). A loss of these forest ecosystems due to climate change would release an enormous amount of carbon into the atmosphere and reduce their evapotranspiration potential (thereby reducing atmospheric moisture); this would lead to strong climate feedbacks (Betts et al. 2004; Costa and Pires 2010; Cox et al. 2004). These climate feedbacks, in combination with large-scale deforestation, put the Amazon rainforest on the list of potential tipping elments in the Earth system (Lenton et al. 2008).

## Factors Leading to Forest Dieback and Potential Feedbacks

### Observations of the Current Period

Current observations show that forests in Amazonia are adapted to seasonal drought (Davidson et al. 2012) mainly due to the ability to access deep soil water through deep rooting systems (Nepstad et al. 1994). It has been long debated, however, whether the productivity of tropical rainforests during the dry season is more limited by precipitation or by cloud cover. Depending on the method used, remote sensing or modeling, seasonal droughts were thought to enhance productivity either by more light entering the canopy through reduced cloud cover, or by the combined effects of several interconnected processes (Brando et al. 2010; Huete et al. 2006). These findings have been challenged by remote sensing experts who ascribe greening effects to saturation of the satellite sensor used (Samanta et al. 2011) or to changes in the optical constellation of the sensor (near-infrared reflectance) (Morton et al. 2014). Recent evidence from a large-scale and long-term experiment suggests that the feedbacks between climatic extreme events such as droughts and forest fires increase the likelihood of an Amazon dieback (Brando et al. 2014).

Extreme weather events in the Amazon may have several causes. The drought events in 2005 and 2010 were not related to El Niño but rather to high Atlantic sea-surface temperatures (Marengo et al. 2011). Cox et al. (2008) found the gradient between northern and southern tropical Atlantic lead to a warmer and drier atmosphere over the Amazon. Atypically low rainfall inflicted water stress on 1.9 million km² (2005) and 3.0 million km² (2010) of forest area (Lewis et al. 2011). As a result, approximately 2.5 million km² (2005) and 3.2 million km² (2010) of forest area were affected by increased tree mortality and reduced tree growth due to water stress (Lewis et al. 2011). These two droughts are thought to have reversed the currently assumed role of the intact forest as a carbon sink and lead to decreased carbon storage of approximately 1.6 Pg carbon (2005) and 2.2 Pg carbon (2010) compared to non-drought years (Lewis et al. 2011; Phillips et al. 2009).[34] The 2005 drought reversed a long-term carbon sink in 136 permanent measurement plots (Phillips et al. 2009).

Two multi-year rainfall exclusion experiments in Caxiuanã and Tapajós National Forest generated remarkably similar results of drought-induced tree mortality. These experiments demonstrated that once deep soil water is depleted, wood production is reduced by up to 62 percent, aboveground net primary productivity declines by 41 percent, and mortality rates for trees almost double (Brando et al. 2008; Costa and Pires 2010; Nepstad et al. 2007). Thus, an increase in extreme droughts in the Amazon region (medium confidence for Central South America in the IPCC SREX)(IPCC 2012) or a prolonged dry season (Fu et al. 2013) may have the potential to cause large-scale forest dieback and to increase atmospheric $CO_2$ concentrations.

Extreme drought events in combination with land use changes lead to an increased frequency in forest fires because the flammability of forests increases with a more open forest canopy (i.e., as it allows more radiation to dry out the forest surface and enhance fire spread) (Ray et al. 2005). Fires were twice as frequent in 2005 as during the average of the previous seven years and they were spatially concentrated in the arc of deforestation in the southern Amazon (Zeng et al. 2008). Increasing fires resulting from deforestation, pasture renewal, and other land-use-related activities increase the vulnerability of the Amazon rainforest to fire and cause changes in forest composition and productivity (Brando et al. 2012; Morton et al. 2013). This interplay of factors is thought to initiate a positive bidirectional feedback loop between fire and forest which could initialize forest transformation into savannahs and contribute to the Amazon tipping point (Nepstad et al. 2001, 2008). Basin-wide measurements show that the combined effects of fire and drought can change the Amazon into a carbon source (e.g., with 0.48 PgC emitted in 2010); it remains carbon-neutral, meanwhile, during wet years (Gatti et al. 2014).

Deforestation is feared to influence the lateral moisture transport from coastal to inland areas because convective precipitation is responsible for recycling precipitation locally. Walker et al. (2009) showed that the current distribution of conservation areas in the Amazon basin, which cover approximately 37 percent of the area, would be sufficient to maintain regional moisture transport and recycling of precipitation when considering different deforestation rates. Influences of dynamic vegetation on water fluxes and eventual carbon-climate feedbacks were not part of this study.

## Future Projections

### Water Stress

The Maximum Climatological Water Deficit (MCWD) (Aragão et al. 2007) is an indicator for drought intensity and plant water stress and correlates to tree mortality. For the period 2070–2099, 17 out of 19 GCMs project increased water stress for Amazon rainforests in a 3°C world (which implies a mean regional warming of 5°C) (Malhi et al. 2009). Ten of 19 GCM projections passed the approximate bioclimatic threshold from rainforest to seasonal forest (MCWD < –200 mm). Similarly, Zelazowski et al. (2011) projected water stress for forests to increase from 1980–2100 with an increase in global mean temperature of 2–4°C above pre-industrial levels. They found that humid tropical forests of Amazonia would retreat by 80 percent for two out of 17 GCMs. Seven other models projected at least a 10 percent contraction of the current extent of humid tropical forest.

### Changes in Forest Cover

Hirota et al. (2010) simulated potential changes in Amazon forest cover. At a regional temperature increase of 2°C, forest cover decreased by 11 percent along with a 20 percent reduction in precipitation in the Western Amazon forest (66°W). At a regional

[34] The combination of reduced uptake of carbon due to the drought and loss of carbon due to drought induced tree mortality and decomposition committed over several years.

temperature increase of 4°C, forest cover loss was 80 percent independent of precipitation reduction. With fire included, tree cover was even further reduced.

Cook and Vizy (2008) projected a 69 percent reduction in rainforest cover extent in a 4°C world. Cook et al. (2012) showed that, with a regional warming of 3–4°C (which corresponds to a mean global warming of 3°C), soil moisture was reduced by eight percent, leaf area index (i.e., corresponds to forest cover) decreased by 12.6 percent, and the land-atmosphere carbon flux increased by about 27.2 percent due to fire from 2070–2099 compared to 1961–1990. Cox et al. (2004) showed that a 4°C world could lead to a forest cover decrease of 10–80 percent. This finding was recently challenged by Good et al. (2013), who showed that an improved version of the Hadley model (HadGEM2-ES) projected only minimal changes in the Amazon forest extent due to forests surviving better in warmer and drier climates than previously thought. However, about 40 percent of the difference in forest dieback projections was associated with differences in the projected changes in dry-season length in the new simulations, as a result of improvements in the simulated autotrophic plant respiration, the soil moisture component, and a reduced gradient in the tropical Atlantic sea surface temperatures. This does not mean that the forest became more resilient in the updated model, but rather that the improved vegetation-climate feedback mechanisms impose less stress on the simulated forests so that tree mortality is reduced under warmer and drier climates (Good et al. 2013). In line with this, Cox et al. (2013) quantified a smaller risk (between 1–21 percent) of Amazon dieback when constraining projections based on current observations of the atmospheric $CO_2$ growth rate and assuming that the $CO_2$ fertilization effect is large.

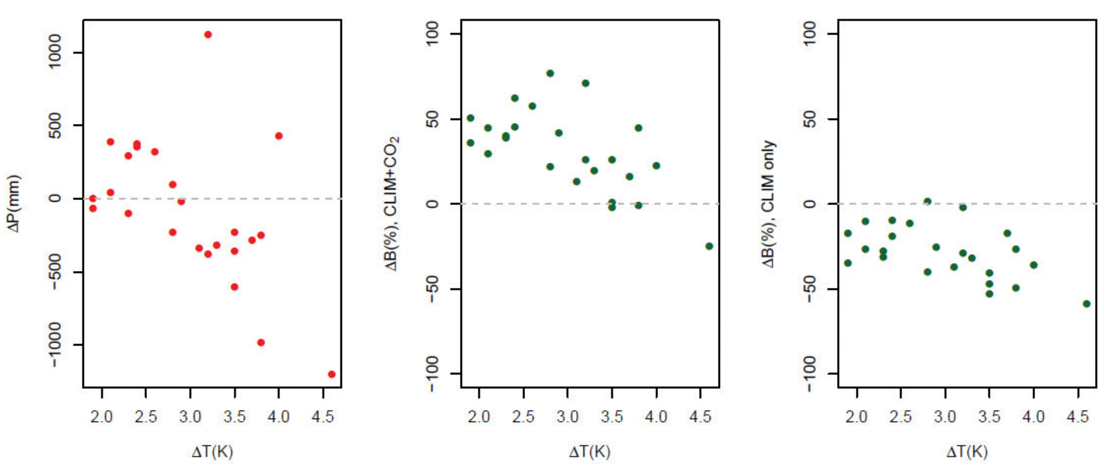
### Biomass Loss

Huntingford et al. (2013) showed that Amazon rainforest vegetation carbon generally increases in a 4°C world (and with regional temperature increases of up to 10°C). They conclude that there is evidence for forest resilience despite considerable uncertainties.

Previous studies, however, projected considerable losses in biomass. In a 4°C world, Huntingford et al. (2008) found that with a regional temperature increase of approximately 10°C from 1860–2100, vegetation carbon was reduced by about 7 kgC per $m^2$. Similarly, Fisher et al. (2010) simulated decreasing carbon stocks of 15–20 kgC per $m^2$ in 1950, 2.6–27 kgC per $m^2$ in 2050, and 1–10 kgC per $m^2$ in 2100 with a regional temperature increase of about 2–5°C from 1900–2100. Galbraith et al. (2010) found that vegetation carbon may either decrease or increase depending on the emissions scenario and vegetation model. In their simulations, vegetation carbon changed by −10 to +35 percent relative to 1983–2002 with a regional warming of 4–8°C from 2003 to 2100.

Rammig et al. (2010) showed that including the $CO_2$ fertilization effect resulted in an increase in biomass in Eastern Amazonia (EA) of 5.5–6.4 kgC per $m^2$, in Northwestern Amazonia (NWA) of 2.9–5.5 kgC per $m^2$, and in Southern Amazonia (SA) of 2.1–4.3 kgC per $m^2$ in a 3°C world (see also Vergara and Scholz 2010). The probability of a dieback was zero percent for all regions in this case. In contrast, climate-only effects without the buffering $CO_2$ fertilization effect resulted in biomass reduction in EA (−1.8 to −0.6 kgC per $m^2$), NWA (−1.2 to 0.6 kgC per $m^2$), and SA (−3.3 to −2.6 kgC per $m^2$) (Figure 3.20). The probability of biomass loss without $CO_2$ fertilization was projected to 86.4 percent (EA), 85.9 percent (NWA), and 100 percent (SA). The probability of a dieback (>25 percent biomass loss) was projected to be 15.7 percent

**Figure 3.20:** Simulated precipitation changes in Eastern Amazonia from the 24 IPCC-AR4 GCMs with regional warming levels of 2–4.5 K (left panel). Simulated changes in biomass from LPJmL forced by the 24 IPCC-AR4 climate scenarios assuming strong $CO_2$ fertilization effects (middle panel, CLIM+$CO_2$) and no $CO_2$ fertilization effects (CLIM only, right panel).




Source: Calculated from Rammig et al. (2010).

(EA), 1.1 percent (NWA), and 61 percent (SA) (Rammig et al. 2010). These results imply that understanding the still uncertain strength of the $CO_2$ fertilization effect is critical for an accurate prediction of the Amazon tipping point; it therefore urgently requires further empirical verification by experimental data from the Amazon region.

Deforestation and forest degradation, for example from selective logging (Asner et al. 2005), are also factors which crucially influence future changes in vegetation carbon. Gumpenberger et al. (2010) found relative changes in carbon stocks of –35 percent to +40 percent in a protection scenario without deforestation and –55 percent to –5 percent with 50 percent deforestation in a 4°C world. Poulter et al. (2010) found a 24.5 percent agreement of projections for a decrease in biomass in simulations with 9 GCMs in a 4°C world.

#### Large-Scale Moisture Transport

Several studies show that changes in moisture transport and regional precipitation are strongly linked to deforestation. Costa and Pires (2010) found in simulation runs with a coupled climate-vegetation model that precipitation was reduced in 9–11 of 12 months under different deforestation scenarios (based on Soares-Filho et al. 2006). Sampaio et al. (2007) performed simulations with a coupled climate-vegetation model for different agricultural regimes and deforestation scenarios of 20–100 percent for the Amazon basin (based on Soares-Filho et al. 2006). When replacing forest with pasture, they projected a 0.8°C increase in regional temperature and a 0.2 percent reduction in precipitation at 20 percent deforestation levels. At 40 percent deforestation levels, regional temperatures increased by 1.7°C and precipitation was reduced by –2.2 percent. At 50–80 percent deforestation, regional temperatures increased by 1.8–2–1°C and precipitation decreased by 5.8–14.9 percent. When replacing forest with soybeans at 50 percent deforestation, regional temperatures increased by 2.9°C and precipitation decreased by 4.6 percent. At 80–100 percent deforestation, regional temperatures increased by 3.7–4.2°C and precipitation decreased by 19.2–25.8 percent.

#### Fire

Studies projecting future fires in the Amazon are still scarce. Fires are projected to increase along major roads in the southern and southwestern part of Amazonia with a 1.8°C global warming by 2040–2050 (Silvestrini et al. 2011; Soares-Filho et al. 2012). High rates of deforestation would contribute to an increasing fire occurrence of 19 percent by 2050, whereas climate change alone would account for a 12 percent increase (Silvestrini et al. 2011). Drought and anthropogenic fire incidences could significantly increase the risk of future fires especially at the southern margin of the Amazon (Brando et al. 2014). If deforestation can be excluded in protected areas, future fire risk would be evenly reduced, emphasizing the management option to increase carbon storage when avoiding or reducing forest degradation (Silvestrini et al. 2011; Soares-Filho et al. 2012).

### *3.4.5.1 Synthesis*

Intensive research efforts over the past decades have enormously improved the understanding and interaction of processes linking climate, vegetation dynamics, land-use change, and fire in the Amazon. However, the identification of the processes and the quantification of thresholds at which an irreversible approach toward a tipping point is triggered (e.g., a potential transition from forest to savannah) are still incomplete.

Overall, the most recent studies suggest that the Amazon dieback is an unlikely, but possible, future for the Amazon region (Good et al. 2013). Projected future precipitation and the effects of $CO_2$ fertilization on tropical tree growth remain the processes with the highest uncertainty. Climate-driven changes in dry season length and recurrence of extreme drought years, as well as the impact of fires on forest degradation, add to the list of unknowns for which combined effects still remain to be investigated in an integrative study across the Amazon. A critical tipping point has been identified at around 40 percent deforestation, when altered water and energy feedbacks between remaining tropical forest and climate may lead to a decrease in precipitation (Sampaio et al. 2007).

A basin-wide Amazon forest dieback caused by feedbacks between climate and the global carbon cycle is a potential tipping point of high impact. Such a climate impact has been proposed if regional temperatures increase by more than 4°C and global mean temperatures increase by more than 3°C toward the end of the 21st century. Recent analyses have, however, downgraded the probability from 21 percent to 0.24 percent for the 4°C regional warming level when coupled carbon-cycle climate models are adjusted to better represent the inter-annual variability of tropical temperatures and related $CO_2$ emissions (Cox et al. 2013). This holds true, however, only when the $CO_2$ fertilization effect is realized as implemented in current vegetation models (Rammig et al. 2010). Moreover, large-scale forest degradation as a result of increasing drought may already impair ecosystem services and functions without a forest dieback necessarily to occur.

## 3.4.6 Fisheries and Coral Reefs

### *3.4.6.1 Vulnerability to Climate Change*

Significant impacts of human origin, such as changes in temperature, salinity, oxygen content, and pH levels, have been observed for the oceans over the past 60 years (Pörtner et al. 2014). Such changes can have direct and indirect impacts on fishery resources and food security (for example, as fish prey reacts sensitively to ocean acidification or habitat is lost due to coral reef degradation) (Turley and Boot 2010).

The Humboldt Current System off the coast of Peru and Chile sustains one of the richest fisheries grounds in the world and is highly sensitive to climate variability such as that resulting from ENSO. The Eastern Pacific region's fishery is dominated by catches of small pelagic fish which respond sensitively to changes in oceanographic conditions. Peru and Colombia are among the eight countries whose fisheries are most vulnerable to climate change (Allison et al. 2009; Magrin et al. 2014).

The Caribbean Sea and parts of the South Atlantic, in contrast to the Eastern Pacific, sustain vast coral reefs (see Section 3.4.6.2, Coral Reefs). The Caribbean Sea sustains a more diverse but less productive fishery (UBC 2011).

### Uncertain Climate Change Effects on the Intensity of Coastal Upwelling

Several effects of climate change on upwelling and related ecosystem functioning have been hypothesized—and they point in opposite directions. One hypothesis is that a decrease in productivity may be driven by a globally warmer ocean in the future, as observed under El Niño conditions. However, sea-surface temperatures have not been observed to increase in the Humboldt Current System over the last 60 years (Hoegh-Guldberg et al. 2014). The hypothesis is further contradicted by data indicating higher productivity during warm interglacial periods (Chavez and Messié 2009) and a projected weakening of trade winds and associated El Niño events (Bakun et al. 2010). However, particularly the latter projections are highly uncertain. As described in Section 2.3.2, El-Niño/Southern Oscillation, projections on the frequency and intensity of future El Niño events are uncertain.

An increase in productivity, in turn, has been hypothesized to occur due to a stronger land-sea temperature gradient—the land surface warms faster than the ocean waters—leading to stronger winds driving stronger upwelling (Bakun 1990; Chavez and Messié 2009). However, analysis has been unable to determine whether or not the recorded intensification of winds at the eastern sides of the world's oceans is due to inconsistencies in measurement techniques over long time scales. Comparison with non-upwelling regions, however, indicates that the wind intensification is more pronounced in upwelling regions (Bakun et al. 2010). Analysis of changes in coastal biomass shows an upward trend of waters within the Humboldt Current System for 1998–2007, particularly for the Peruvian coast. In contrast, the southern part of the California Current System (south of 30°N off the coast of Baja California) shows a negative trend (Demarcq 2009). Moreover, whether increased upwelling would lead to higher productivity depends on nutrient availability—and changing physical conditions may disturb the natural food web structure.

### Physiological Effects of Ocean Acidification on Marine Species

The IPCC states with high confidence that rising $CO_2$ levels will increasingly affect marine organisms (Pörtner et al. 2014). A meta-analysis of 228 studies revealed overall negative impacts of ocean acidification not only on calcification but also on survival, growth, development, and abundance (Kroeker et al. 2013). Wittmann and Pörtner (2013) conducted a meta-analysis of existing studies to determine responses for a range of future $CO_2$ concentrations. The ranges include 500–600 µatm, which is associated with warming of more than 2°C in 2100 and 851–1,370 µatm, which is associated with 4°C warming. They found differential responses for coral species, with 38 percent and 44 percent of all species studied exhibiting sensitivity to both scenarios. Echinoderms and mollusks both exhibit high sensitivity to ocean acidification as they have low metabolic rates and depend on calcium carbonate for shell formation. Wittmann and Pörtner (2013) stated that most species studied will be affected in a 4°C world, but that the effects will be visible before that. In fact, nearly 50 percent of all species studied show sensitivity to a 2°C warming. While crustaceans appear to be relatively resilient, with about a third of species affected in a 4°C scenario, the effects on fish are already significant in a relatively low $CO_2$ concentration scenario; more than 40 percent of species are affected. This figure nearly doubles for the high scenario. However, Wittmann and Pörtner (2013) stress that their investigation into fish species´ sensitivity is biased toward reef fish.

### Species Interaction and Ecosystem Effects

It is important to note that the effects of ocean acidification do not act in isolation; rather, they act in concert with such changes as rising sea-surface temperatures, changes in salinity, and decreasing nutrient availability due to enhanced stratification. These further interact with non-climatic pressures such as pollution and overfishing (Hoegh-Guldberg et al. 2014). For example, increasing temperatures may lead to a drastic narrowing of species' thermal tolerance window—with effects such as delayed spawning migration or mortality (Pörtner and Farrell 2008).

Sensitivity to ocean acidification can further narrow this tolerance window (Wittmann and Pörtner 2013). Such combined effects are to date little understood and knowledge remains limited due to limits on experimental settings and the limited ability to discern anthropogenic effects in a setting of high natural variability such as the Humboldt Current System (Hoegh-Guldberg et al. 2014). The expected synergistic effects of multiple pressures mean, however, that assessments remain conservative for a single or a subset of pressures (Wittmann and Pörtner 2013).

A further potential risk factor for biological productivity and fisheries is the effect of climate-induced changes on species interaction, which can occur due to the differential responses of species to changing environmental cues. For example, phytoplankton and zooplankton biomass changes may affect fish biomass (Taylor et al. 2012b). Different sensitivities to increasing $CO_2$ concentration may lead to remarkable shifts in species composition (Turley and Gattuso 2012). Similarly, asynchronous responses to warming may lead to mismatches in the predator-prey relationship. Such effects have been detected to modify species interactions at five trophic levels (Pörtner et al. 2014). For the Humboldt Current System, changes in the intensity of coastal upwelling add yet another factor that may endanger the balance of various species interactions. It has been hypothesized that the predator-prey relationship between phyto- and zooplankton could be disrupted due to excessive offshore transportation of zooplankton. If in such a scenario overfishing would not allow for small pelagic fish to control phytoplankton growth, sedimentation of organic matter may contribute to hypoxia, red tides, and the accumulation of methane (Bakun et al. 2010).

### Projections of Changes to Coastal Upwelling

The direction and magnitude of upwelling changes remains uncertain, particularly for the Humboldt Current System. Wang et al. (2010) showed that results diverge for different models. With approximately 1.5°C global warming in 2030–2039, projections show an overall increase in the decadal averaged upwelling index (July) for the California Current when compared to 1980–1989 for most of the GCMs analyzed. For the Humboldt Current System, however, there is very little agreement among models both in terms of direction and magnitude of change. Wang et al. (2010) observed that the factors driving coastal upwelling systems are too local to be captured by the coarse resolution of global models.

### Projected Changes to Fisheries Catch Potential

In response to changing oceanic conditions, including seawater temperature and salinity, fish stocks have been observed in, and are further expected to shift to, higher latitudes (Perry et al. 2005). This ultimately affects local fisheries in the tropics and subtropics. A further climate impact on the productivity of fisheries is the reduction in productivity at the base of the food chain due to the stronger stratification of warming waters (Behrenfeld et al. 2006). In fact, primary productivity has been shown to have declined by 6 percent since the early 1980s (Gregg 2003). Declining pH levels and increasing hypoxia may further negatively impact fisheries (Cheung et al. 2011).

No regional projections of future fishery catches appear to exist. A global study that considers the habitat preference of 1,066 commercially caught species and projects changes to primary productivity computes the expected 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) (Cheung et al. 2010).

Results of Cheung et al. (2010) for LAC indicate a mixed picture (see Figure 3.21). Concurrent with the expectation of fish populations migrating poleward into colder waters, the waters further offshore of the southern part of the Latin American continent are expected to see an up to 100 percent increase in catch potential. Catch potentials are expected to decrease by 15–50 percent along the Caribbean coasts and by more than 50 percent off the Amazonas estuary and the Rio de la Plata. Furthermore, the Caribbean waters and parts of the Atlantic coast of Central America are expected to see declines in the range of 5–50 percent, with the waters around Cuba, Haiti, the Dominican Republic, and Puerto Rico, as well as Trinidad and Tobago, St. Lucia, and Barbados, particularly severely affected. Along the coasts of Peru and Chile, fish catch is projected to decrease by up to 30°percent, but there are also increases towards the south.

There are, however, inherent uncertainties in the projections presented here. Cheung et al (2010) pointed out that important factors, such as expected declines in ocean pH (ocean acidification), direct human pressures, and local processes which escape the coarse resolution of global models, are not taken into account. Incorporating the effects of decreasing ocean pH and reduced oxygen availability in the northeast Atlantic yields catch potentials that are 20–30 percent lower relative to simulations not considering these factors (Cheung et al. 2011).

Taking into consideration the effects of species interaction on redistribution and abundance, Fernandes et al. (2013) report latitudinal shifts in the North Atlantic to be 20 percent lower than reported by the bioclimatic envelope model developed by Cheung et al. (2010). A further limitation of the studies is that results are given as 10-year averages and consequently do not take into consideration abrupt transitions as observed under El Niño conditions. It should also be noted that not all captured species are included in these calculations, with small-scale fisheries possibly not taken into account (Estrella Arellano and Swartzman 2010). Finally, it needs to be taken into account that local changes in fish population distribution are likely to affect the small-scale sector most severely, as artisanal fishers will not have the means to capture the benefits of higher productivity at higher latitudes further offshore.

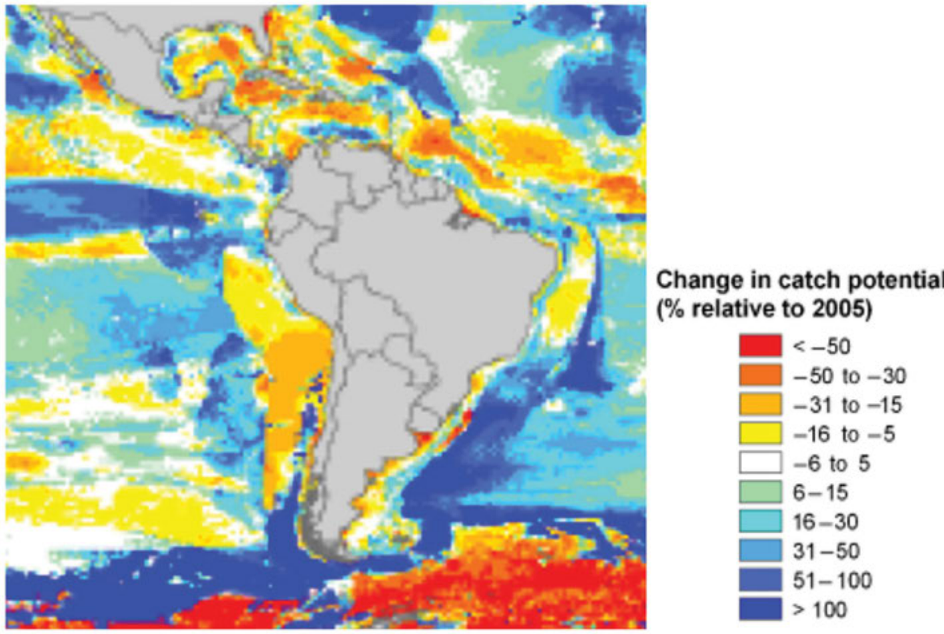
For the Exclusive Economic Zone of the Humboldt Current System, Blanchard et al. (2012) projected a 35 percent decline in

## Box 3.11: Freshwater Fisheries—Vulnerability Factors to Climate Change

The freshwater fishery of the Amazon River is an important source of protein for the local population. According to the FAO, annual per capita fish consumption in the Amazon basin may exceed 30 kg, which is significantly higher than in areas remote from freshwater sources where consumption has been estimated at around 9 kg per person per year (FAO 2010). As such, the river and its hydrological network provide an important source of proteins and minerals for the local population.

Those resources may be under threat from climate change (Ficke et al. 2007) as rising water temperatures may exceed species' temperature tolerance window. In addition, warmer waters are associated with higher toxicity of common pollutants (e.g., heavy metals) and lower oxygen solubility; this may negatively affect exposed organisms. In addition, "blackwaters" such as the Amazon varzèa lakes, depend on seasonal flooding for nutrient replenishment and for toxins to be flushed out. Reduced river flow and a reduced size of the flood plain may further lead to a reduced habitat for spawning (Ficke et al. 2007).

**Figure 3.21:** Change in maximum catch potential for Latin American and Caribbean waters.




Source: Cheung et al. (2010), Figure 1a.

phytoplankton and zooplankton density and similar magnitudes of change in the overall biomass of fish under 2°C global warming by 2050. Comparing the impacts of climate change with fishing pressure shows that climate impacts drive ecosystem change under low fishing rates ($0.2yr^{-1}$); under heavy fishing pressure ($0.8yr^{-1}$), climate effects become secondary.

Fisheries are in many cases at risk due to high fishing pressure, with many commercially caught species already showing signs of overexploitation. Climate change, by locally limiting productivity, has the potential to further aggravate this situation. While sustainable fisheries management can significantly reduce the risks of fisheries collapse, the uncertainty of climate impacts adds to the challenge of establishing the quantity of fish that can be caught at sustainable levels (maximum sustainable yield).

### *3.4.6.2 Coral Reefs*

Coral reefs provide ecosystem services which are particularly important at the local level for subsistence fisheries and tourism sector income (Hoegh-Guldberg et al. 2007). Healthy coral reefs also help to dampen the impact of coastal storm surges through the reduction of wave energy (Villanoy et al. 2012). In the face of rising sea-surface temperatures and declining pH-levels (see Section 2.3.8) as well as in concert with local stressors such as pollution, coral reefs and the services they provide are particularly vulnerable to climate change.

#### Vulnerability of Coral Reefs to Climate Change

Coral reefs are particularly vulnerable to the double effects of climate change on the oceans: rising temperatures and declining pH levels. This vulnerability is particularly visible in events of coral bleaching, where external stresses cause corals to expel their symbiotic algae (Hoegh-Guldberg 1999). Severe or prolonged bleaching events are often followed by disease outbreaks and can cause coral mortality (Eakin et al. 2010). Bleaching events on a large scale ("mass bleaching") have been linked to unusually high sea-surface temperatures, which exceed the temperature threshold of affected species. Other factors exerting stresses on coral reef systems which have been identified as causes for coral bleaching include pollution, overfishing, and the related shift in species composition (De'ath et al. 2012).

A prolonged period of unusually high sea-surface temperatures across the Caribbean reefs for more than seven months in 2005 caused the most extensive and most severe bleaching event recorded to date. Analyzing the concurrently high hurricane season during that period, Trenberth and Shea (2006) found that about half of the observed sea-surface temperature anomaly was linked to global warming. Following the warming events, bleaching continued in 2006 and was accompanied by disease and mortality. Mortality reached 50 percent in a number of locations, with the strongest effects recorded in the northern and central Lesser Antilles and less severe cases in the waters of Venezuela.

Hurricanes, while posing a direct threat to coral reef structures, have also been found to cool the surrounding waters and thereby reduce the warming signal and the risk of severe bleaching (Eakin et al. 2010). The effect of hurricanes on coral reefs may thus be positive in the sense that vertical mixing and upwelling caused by tropical cyclones may reduce heat stress for coral reefs. This effect was reconstructed for the 2005 anomaly, for which Carrigan and Puotinen (2014) found that nearly 75 percent of the assessed area experienced cooling from tropical cyclones. They estimated that this lead to around a quarter of reefs not experiencing stresses above critical thresholds, outweighing the negative effects of direct damage (e.g., through breakage). While they pointed out that the relatively frequent occurrence of tropical cyclones may have supported the development of relatively resistant coral reef species, it remains unclear whether such resistance will persist in the face of a projected increase in the intensity and frequency of tropical cyclones, particularly as such developments would be concurrent with changes to ocean chemistry deleterious to coral reefs. Dove et al. (2013) point out that expected reductions in reef net calcification, associated with changes in ocean chemistry under a high atmospheric $CO_2$ concentration, will significantly hinder the recovery of coral reefs after damages related to extreme events.

### Projections of Climate Change Impacts on Coral Reefs

Based on observations and laboratory experiments, thresholds have been identified which enable the projection of risk of bleaching events in the future. The decrease in calcium carbonate saturation and concurrent pH levels poses another threat to reef-building corals (see Section 2.3.8). Taking into consideration both the projected decrease in the availability of calcium carbonate and increase in sea-surface temperatures, Meissner et al. (2012) projected that most coral reef locations in the Caribbean sea and western Atlantic will be subject to a 60–80 percent probability of annual bleaching events with 2°C warming by 2050, with areas at the coast of Guyana, Suriname, and French Guiana being exposed to a 100 percent probability. In contrast, under 1.5°C warming by 2050, most locations in the Caribbean sea have a comparably low risk of 20–40 percent probability of annual bleaching events, with the waters of Guyana, Suriname, French Guiana, and the north Pacific being at slightly higher risk (up to 60 percent probability).

By the year 2100, almost all coral reef locations are expected to be subject to severe bleaching events occurring on an annual basis in a 4°C world. Exceptions are major upwelling regions, which experience a risk of 50 percent. Compared to impacts in the year 2050, the Caribbean sea experiences more locations under risk in 2100 despite no significant further increase in emissions and temperatures, highlighting the long-term impact of climate change on marine ecosystems even under emissions stabilization. A potentially limiting assumption made by Meissner et al. (2012) is that no changes in the frequency or amplitude of El Niño events is expected.

The study from Meissner et al. (2012) is based on a single Earth System Model. Van Hooidonk et al. (2013) used a large ensemble of climate models to analyze the onset of bleaching conditions for different emissions scenarios. With warming leading to a 2°C world, the median year in which bleaching events start to occur annually is 2046. While this median applies to most regions within the Caribbean, some parts experience bleaching 5–15 years earlier. These include the northern coast of Venezuela and Colombia as well as the coast of Panama. With warming leading to a 4°C world, the median year in which annual bleaching starts to occur is 2040 (with no earlier onset in the Caribbean region). Generally, the reefs in the northern waters of the Caribbean Sea appear to be less sensitive than those in the south. However, as Caldeira (2013) points out, those reefs at the higher latitude fringes of the tropical coral range (both north and south of the tropics) are likely to be more heavily affected by ocean acidification.

Buddemeier et al. (2011) computed coral losses in the Caribbean for three different scenarios, which would lead to a 2°C, 3°C, and 4°C world by 2100. Temperature trajectories diverge around 2050, by which time warming reaches about 1.2°C. A comparison of all trajectories shows little difference between scenarios in terms of coral cover. By 2020, live coral reef cover is projected to have halved from its initial state. By the year 2050, live coral cover is less than five percent; in 2100, it is less than three percent, with no divergence among emissions scenarios. Notably, a 5–10 percent live coral cover is assumed as the threshold below which the ecosystem no longer represents a coral reef (but is instead a shallow-water ecosystem that contains individual coral organisms). Assuming a scenario in which corals are able to adapt by gaining an additional 1°C of heat tolerance, the loss of live coral cover below five percent is prolonged by around 30 years. Buddemeier et al. (2011) noted that results can be extrapolated for the wider Southeast Caribbean, albeit with the caveat that the assumed high mortality rate of 50 percent was lower in regions outside the Virgin Islands.

The modeling projections of future bleaching events and loss of coral cover presented above are based on changes in marine chemistry and thermology. While the adaptive potential of coral reef species remains uncertain, it should be noted that further impacts impeding the resilience of coral reefs are not included in these future estimates. These include potential impacts that are likely to change in frequency and/or magnitude under future warming, such as hurricanes and the variability of extreme temperatures. Taking these uncertainties into account, Buddemeier et al. (2011) concluded that the presented projections are likely unduly optimistic, which leads the authors to predict that the "highly diverse, viable reef communities in the Eastern Caribbean seem likely to disappear within the lifetime of a single human generation." According to some estimates, a 90 percent loss of coral reef cover would lead to direct economic losses of $8.712 billion (2008 value) (Vergara et al. 2009).

Overall, while there are limitations to the projections of the state of coral reefs in the future, a bleak picture emerges from the available studies. Irrespective of the sensitivity threshold chosen, and indeed irrespective of the emissions scenario, by the year 2040 Caribbean coral reefs are expected to experience annual bleaching events. This is in accordance with Frieler et al. (2012) showing that, at the global scale, the global mean temperature at which almost 90 percent of coral reefs are at risk of extinction is 1.5°C above pre-industrial levels.

#### *3.4.6.3 Synthesis*

The rich fishery grounds of the Humboldt Current System in the Eastern Pacific react strongly to fluctuations in oceanic conditions related to the El Niño/Southern Oscillation (ENSO), during which the upwelling of nutrient-rich waters is suppressed by the influx of warm surface waters. Together with ocean acidification and hypoxia, which are very likely to become more pronounced under high-emissions scenarios, the possibility of more extreme El Niño events pose substantial risks to the world's richest fishery grounds. Irrespective of single events, the gradual warming of ocean waters has been observed and is further expected to affect fisheries particularly at a local scale. Generally, fish populations are migrating poleward towards colder waters. Projections taking into consideration such responses indicate an increase of catch potential by up to 100 percent in the south of Latin America. Off the coast of Uruguay, the southern tip of Baja California and southern Brazil the maximum catch potential is projected to decrease by more than 50 percent. Caribbean waters may see declines in the range of 5–50 percent, with the waters around Cuba, Haiti, the Dominican Republic, and Puerto Rico, as well as Trinidad and Tobago, St Lucia, and Barbados, particularly severely affected. Along the coasts of Peru and Chile, fish catch is projected to decrease by up to 30°percent, but there are also increases towards the south.

It stands to reason that the communities directly affected by local decreases in maximum catch potential would not gain from catch potentials increasing elsewhere. They may also be the ones whose livelihoods would be most affected by the expected deleterious effects of ocean acidification and warming on tropical coral reefs. Irrespective of the sensitivity threshold chosen and indeed irrespective of the emissions scenario, by the year 2040 Caribbean coral reefs are expected to experience annual bleaching events. While some species and particular locations appear to be more resilient to such events than others, it is clear that the marine ecosystems of the Caribbean are facing large-scale changes with far reaching consequences for associated livelihood activities as well as for the coastal protection provided by healthy coral reefs.

### 3.4.7 Human Health

The main human health risks in Latin America and the Caribbean include vector-borne diseases such as malaria, dengue fever, leishmaniasis, and fascioliasis, and food- and water-borne diseases such as cholera and childhood diarrheal disease. Many of these diseases have been found to be sensitive to changes in weather patterns brought about by ENSO. This indicates that disease transmission in LAC could prove highly responsive to changes in temperature and precipitation patterns induced by climate change. Extreme weather events, including heat waves, hurricanes, floods, and landslides, also cause injuries and fatalities in Latin America, and these in turn can lead to outbreaks of disease.

#### *3.4.7.1 Vector-Borne Diseases*

**Dengue fever** is widespread in Latin America, with much of the region providing highly suitable climatic conditions to the primary mosquito vector, *Aedes aegypti.* There has recently been a reemergence and marked increase in the incidence of dengue fever and dengue haemorrhagic fever in countries that had been declared free of the illness following successful elimination programs in the 1950s and 1960s (Tapia-Conyer et al. 2009).

Climate change is expected to play a contributing role in determining the incidence of the disease (Confalonieri et al. 2007), although it is often difficult to separate the impact of climate change from the impacts of urbanization and population mobility (Barclay 2008). In Brazil, the country with the largest number of cases in the world, a greater intensity of transmission of the disease has been observed during the hot, rainy months of the year (Teixeira et al. 2009). Between 2001–2009 in Rio de Janeiro, a 1°C increase in monthly minimum temperature was associated with a 45 percent increase in dengue fever cases the following month, and a 10 mm increase in precipitation with a 6 percent increase (Gomes et al. 2012). Analysis from Mexico points to a correlation between increases in the number of reported cases and increases in rainfall, sea-surface temperature, and weekly minimum temperature (Hurtado-Diaz et al. 2007). A study in Puerto Rico, based on analysis of a 20-year period, likewise finds a positive relationship between monthly changes in temperature and precipitation and monthly changes in dengue transmission (Johansson et al. 2009). Projections by Colon-Gonzalez et al (2013), holding all other factors constant, point to an upsurge in dengue incidence in Mexico of 12 percent by 2030, 22 percent by 2050, and 33 percent by 2080 with a warming scenario leading to a 3°C world in 2100; or 18 percent by 2030, 31 percent by 2050, and 40 percent by 2080 with a warming scenario leading to a 4°C world by 2100. In general, increases in minimum temperatures play the most decisive role in influencing dengue incidence, with a sharp increase observed when minimum temperatures reach or exceed 18°C (Colon-Gonzales et al. 2013).

It appears, however, that climatic conditions alone cannot account for rates of disease occurrence. Based on temperature-based mechanistic modeling for the period 1998–2011, Carbajo et al.(2012) found that temperature can estimate annual transmission risk but cannot adequately explain the occurrence of the disease on a national scale; geographic and demographic variables also appear to play a critical role.

**Malaria** is endemic in Latin America, and rates of transmission have increased over recent decades. This resurgence is associated in part with local environmental changes in the region, such as extensive deforestation in the Amazon basin (Moreno 2006). Periodic epidemics have also been associated with the warm phases of ENSO (Arevalo-Herrera et al. 2012; Mantilla et al. 2009; Poveda et al. 2011).

It is possible that high temperatures could cause malaria to spread into high altitude cities (e.g., Quito, Mexico City) where it has not been seen for decades (Moreno 2006). Evidence shows an increasing spread of malaria to higher elevations in northwest Colombia during the last three decades due to rising temperatures, indicating high risks under future warming (Siraj et al. 2014). The connection between malaria and climate change, however, is unclear given the complexity of factors involved. Indeed, it is likely that the effect of climate change on malaria patterns will not be uniform. While incidence could increase in some areas, it is also possible that it may decrease in others—for example, in the Amazon, in Central America, and elsewhere where decreases in precipitation are projected (Haines et al. 2006) (see Section 3.3.3, Regional Precipitation Projections).

Caminade et al. (2014) projected a lengthening of the malaria transmission season in the highlands of Central America and southern Brazil by the 2080s, but a shortening in the tropical regions of South America. This spatial differentiation is significantly more pronounced with warming leading to a 4°C world than to a 2°C world.

Earlier projections, however, offer mixed results. Béguin et al. (2011) projected an expansion of malarial area by 2050 in Brazil and isolated areas near the west coast of the continent under approximately 2°C of global warming, although this is only if climatic and not socioeconomic changes are taken into account. Van Lieshout et al. (2004), in contrast, found reductions in the size of the population exposed to malaria for at least three months of the year in all the scenarios they considered, and a reduction in exposure to malaria for at least one month of the year in a 4°C world (but not in a 3°C world). This study, meanwhile, projects an expansion of the malarial zone southward beyond its current southernmost distribution in South America—a finding consistent with Caminade et al. (2014).

**Leishmaniasis** is a skin disease carried by sandflies that takes two main forms: cutaneous and visceral. Both are found through much of the Americas from northern Argentina to southern Texas, excluding the Caribbean states (WHO 2014). A spatial analysis by Valderrama-Ardilla et al. (2010) of a five-year outbreak of cutaneous leishmaniasis in Colombia beginning in 2003 identified temperature as a statistically significant variable. The study concluded, however, that climatic variables alone could not explain the spatial variation of the disease. A positive association has been reported between the ENSO cycle and annual incidence of cutaneous leishmaniasis in Colombia (Gomez et al. 2006) and visceral leishmaniasis in Brazil (Franke et al. 2002). A study from Colombia of both types of the disease also identified an increase in occurrence during El Niño and a decrease during La Niña (Cardenas et al. 2006). These findings suggest that an increased frequency of drought conditions is likely to increase the incidence of leishmaniasis (Cardenas et al. 2006).

**Fascioliasis,** a disease caused by flatworms and carried by snails as an intermediate host, is a major human health problem in the Andean countries of Bolivia, Peru, Chile, and Ecuador (Mas-Coma 2005). Cases have also been reported in Argentina, Peru, Venezuela, Brazil, Mexico, Guatemala, and Cuba (Mas-Coma et al. 2014). The host infection incidence of fascioliasis is strongly dependent on weather factors, including air temperature, rainfall, and/or potential evapotranspiration. Temperature increases associated with climate change may lead to higher infection and transmission rates and cause an expansion of the endemic zone, while increases in precipitation could, for example, increase the contamination risk window presently linked to the November-April rainy season (Mas-Coma et al. 2009).

#### *3.4.7.2 Food- and Water-Borne Diseases*

**Cholera** is transmitted primarily by fecal contamination of food and water supplies. Outbreaks are therefore often associated with warm temperatures, flooding, and drought, all of which can aid contamination. Climatic variables have been shown to be decisive in determining the extent of outbreaks (Koelle 2009). A recent study of the relationship between rainfall and the dynamics of the cholera epidemic in Haiti, for example, shows a strong relationship whereby increased rainfall is followed by increased cholera risk 4–7 days later (Eisenberg et al. 2013). In South America, ENSO can be a driving factor in cholera outbreaks in coastal areas because the El Niño phase provides warm estuarine waters with levels of salinity, pH, and nutrients suitable for the blooming of the *V. Cholerae* pathogen (Martinez-Urtaza et al. 2008; Salazar-Lindo 2008).

Rates of **childhood diarrheal disease** have also been shown to be influenced by ambient temperature—and by ENSO in particular. This was observed during the 1997–1998 El Niño event in Peru. During that particularly warm winter, in which ambient temperatures reached more than 5°C above normal, hospital admissions for diarrheal disease among children increased by 200 percent over the previous rate (Checkley et al. 2000). The relative risk of diarrheal disease in South America is expected to increase by 5–13 percent for the period 2010–39 with 1.3°C warming, and by 14–36 percent for the period 2070–99 with 3.1°C warming (Kolstad and Johansson 2011).

#### *3.4.7.3 Impacts of Extreme Temperature Events*

**Unusually high or low temperatures** can potentially increase morbidity and mortality, particularly in vulnerable groups such as the elderly and the very young. A strong correlation has been found between unusually cold periods and excess deaths in Santiago, Chile, for example. In a time-series regression analysis, Muggeo and Hajat (2009) estimated a 2.4 percent increase in all-cause deaths among the above-65 age group for every 1°C decrease below a cold threshold identified in their model. Cold-related risks to human health would therefore be reduced if climate change results in a reduction in extreme cold events.

Urban populations tend to be the most vulnerable to extreme heat events due to the urban heat island effect, in which the built environment amplifies temperatures. In northern Mexico, heat waves have been correlated with increases in mortality rates (Mata and Nobre 2006); in Buenos Aires, 10 percent of summer deaths are associated with heat strain (de Garin and Bejaran 2003). Excessive heat exposure can cause or exacerbate a range of health conditions, including dehydration, kidney disease, and cardiovascular and respiratory illnesses (Kjellstrom et al. 2010). Increased rates of hospital admissions of kidney disease patients have been documented during heat waves (Kjellstrom et al. 2010). Heat stress has been identified as a particular danger for workers in Central America and one that coincides with high rates of kidney disease in some populations (Kjellstrom and Crowe 2011).

#### *3.4.7.4 Impacts of Flooding and Landslides*

**Torrential rain and resulting floods** are among the main natural hazards in the region and cause widespread injury and loss of life, livelihood, and property (Mata and Nobre 2006). Catastrophic flooding has affected Mexico, Venezuela, Colombia, Brazil, Chile, Argentina, and Uruguay in recent years (WHO/WMO 2012). Flooding can have multiple indirect health impacts, including the spread of water-borne disease through water supply contamination and via the creation of stagnant pools that serve as habitats for disease vectors such as malaria and dengue mosquitoes. Landslides and mudslides can also be a consequence of flooding; these tend to be exacerbated by factors such as deforestation and poor urban planning. Flash floods and landslides are a particular danger for informal settlements located on steep slopes and on alluvial plains (Hardoy and Pandiella 2009).

**Glacial lake outburst floods** (see Box 3.4) also pose a risk to populations located in the Andean region (Carey et al. 2012). The historical impacts of glacial lake outburst floods in Peru's Cordillera Blanca mountain range illustrate the potential for catastrophic loss of life during periods of glacial retreat; many thousands of deaths have resulted from flooding, most notably in incidents in 1941, 1945, and 1950 (Carey et al. 2012). The projection of further glacial melting in the Andes (see Section 3.4.1, Glacial Retreat and Snowpack Changes) means that flooding continues to pose a risk to human populations.

#### *3.4.7.5 Synthesis*

The literature on the potential climate change impacts on human health in the LAC region shows increased risks of morbidity and mortality caused by infectious disease and extreme weather events. Observed patterns of disease transmission associated with different parts of the ENSO cycle seem to offer valuable clues as to how changes in temperature and precipitation might affect the incidence of a particular disease in a particular location.

Projections of how malaria incidence in LAC could be affected by climate change over the rest of the century are somewhat inconsistent, with some studies pointing to increased incidence and others to decreased incidence. Such uncertainty also characterizes studies of the relationship between climate change and malaria globally and reflects the complexity of the environmental factors influencing the disease. Little quantitative data is available on the future impacts of extreme weather events on human health, although studies based on historical data, such as that of Muggeo and Hajat (2009), have revealed a link between extreme temperatures and increased rates of mortality in vulnerable sub-populations.

### 3.4.8 Migration

While migration is not a new phenomenon in the region, it is expected to accelerate under climate change. There are many areas in LAC prone to extreme events, including droughts, floods, landslides, and tropical cyclones, all of which can induce migration. Faced with severe impacts, migration might seem like the only option for finding alternative livelihoods (Andersen et al. 2010). However, migration typically causes an economic strain on both internal and external migrants (Raleigh et al. 2008), and not everyone whose livelihood is threatened can afford to migrate. The very poorest who do not have the necessary resources to migrate can get trapped in a situation of ever-increasing poverty.

The transition from temporary to permanent migration resulting from climate events can be facilitated by the existence of strong migration ties and networks (e.g., between LAC and the United States) (Deprez 2010). There are also important pull factors, which have been a major determinant of emigration in the past, including more and better paid job opportunities and better access to services. They incentivize migration, particularly to North America or to countries within LAC with stronger economies. The question to be assessed over time is whether climate change will make push factors more important than pull factors.

The scientific literature on the interaction between migration and climate change is limited in terms of future projections. There is, however, a growing body of literature on the demographic, economic, and social processes of the interactions of climate and migration (Piguet et al. 2011; Tamer and Jäger 2010). Migration is considered an adaptive response to maintain livelihoods under conditions of change. Assunção and Feres (2009) show that an increase in poverty levels by 3.2 percent through changes in agricultural productivity induced by regional warming of 1.5°C in 2030–2049 is reduced to two percent if sectoral and geographic labor mobility is allowed for. This means that migration can reduce the potential impact of climate change on poverty (Andersen et al. 2010).

The projections of environmentally-induced migration agree that most of the movement is likely to occur within the same country or region (Deprez 2010). The largest trend in migration continues to be major movements from rural areas to urban areas. Given the well-established migration channels between most LAC countries and the United States, however, the impacts of climate change may increase South-North migration flows.

There are no official statistics to show how many migrants in LAC are moving in response to climate-related or other environmental factors (Andersen et al. 2010). Although functioning as an adaptive strategy, environmentally-induced migration has strong negative impacts on transitory areas and final destinations. For example, the International Organization for Migration reports that "rapid and unplanned urbanization has serious implications for urban welfare and urban services", particularly in cities with "limited infrastructure and absorption capacity" (IOM 2009). For areas of origin, the general consensus for LAC seems to be that the impact of environmentally induced migration is overwhelmingly negative (Deprez 2010).

#### *3.4.8.1 Drought*

The effects of drought on migration have not been fully researched. Perch-Nielsen et al. (2008) explained that drought is the "most complex and least understood natural hazard," and that there are a number of adaptive measures households might take before resorting to migration. Nevertheless, scenarios based on projections of Mexico–United States migration rates (Feng et al. 2010) and of Brazilian internal migration (Barbieri et al. 2010) suggest that drought will lead to increased emigration along established migration routes and the depopulation of rural areas (Faist and Schade 2013). Other examples of drought-induced migration include the flow of migrants from Brazil's and Argentina's northeast regions to the state capitals and to the south-central regions (Andersen et al. 2010). Examples indicate that drought-induced migration is already occurring in some regions. In Northeastern Brazil, a primarily agricultural region, spikes in the rate of migration to rapidly growing coastal cities or to the country's central and southern regions have been observed following decreases in crop yields in years of severe drought (Bogardi 2008). Barbieri et al. (2010) projected emigration rates in Brazil from rural areas and found that depopulation is expected to occur—especially with increasing temperatures. This study, meanwhile, finds the biggest increase in migration coming from productive agricultural areas that support a large labor force.

#### *3.4.8.2 Sea-Level Rise and Hurricanes*

Projections considering the impacts of sea-level rise on migration in Latin America and the Caribbean are sparse (Deprez 2010). There is more research, however, on the impact of hurricanes. Although projections posit that migration resulting from hurricanes will continue to be mostly temporal and internal (Andersen et al. 2010), stronger hurricane impacts in the Caribbean will increasingly drive households that have repeatedly suffered from these events to consider permanent domestic, regional, or international migration (ECLAC 2001). In 1998, Hurricane Mitch affected several Central American countries and displaced up to two million people either temporarily or permanently. The impact was highly differentiated by country, with much lower displacement rates in Belize compared to Nicaragua, Honduras, and El Salvador, and a 300 percent increase in international emigration from Honduras (Glantz and Jamieson 2000; McLeman and Hunter 2011). Although the number of migrants has decreased over time, it has so far remained above the level prior to the hurricane (McLeman 2011).

#### *3.4.8.3 Exacerbating Factors*

The largest level of climate migration is likely to occur in areas where non-environmental factors (e.g., poor governance, political persecution, population pressures, and poverty) are already present and already putting migratory pressures on local populations. In addition, poverty and an unequal geographical population distribution heighten people's vulnerability to biophysical climate change impacts, thus compounding the potential for further migration (Deprez 2010).

#### *3.4.8.4 Social Effects of Climate-Induced Migration*

Similar to traditional migrants, climate migrants with more education and skills are able to benefit the most from migration. Benefits to migrants and their families can include, for example, the possibility of finding better jobs. But migration can also have a strong negative social impact on those who stay behind, particularly on the poorest who typically do not have the resources to migrate and therefore risk being trapped in an adverse situation with limited coping strategies (Andersen et al. 2010). In addition, climate-change-induced labor migration can have implications on families left behind (e.g., challenges to children resulting from being raised in single parent homes with limited economic resources). In addition, climate change may induce greater levels of female migration; in the context of gender-based discrimination, these women may face more challenges settling down and finding adequate housing and stable jobs (Deprez 2010).

Labor migration can also provide benefits to migrants and their families. Migration can generate an increase in a family's financial assets, as work in the new location often pays better. This contributes to better living conditions if the family is able to migrate together or generates remittances that can be sent back to help the family left behind.

Despite some benefits, climate migrants face significant risks. For example, the cost of migration (including travel, food, and housing) can be very high and result in a worse financial situation for the family. There is also evidence that migrants' working and housing standards can, in some cases, be very poor (such as in marginalized areas, informal settlements, and slums) with possible negative effects on health (Andersen et al. 2010). Further, migrants who do not have networks or social capital in their new location can be socially isolated or discriminated against, resulting

## Box 3.12: Distress Migration during Hurricane Mitch

A typical example of distress migration took place when Hurricane Mitch struck Central America in 1998. Honduras evacuated 45,000 citizens from Bay Island. The government of Belize issued a red alert and asked citizens on offshore islands to leave for the mainland. Much of Belize City was evacuated. Guatemala issued a red alert as well. By the time Mitch made landfall those evacuated along the western Caribbean coastline included 100,000 in Honduras, 10,000 in Guatemala, and 20,000 in the Mexican state of Quintana Roo. Despite this, nearly 11,000 people were killed and more than 11,000 were still missing by the end of 1998. In all, 2.7 million were left homeless or missing. The flooding caused damage estimated at over $5 billion (1998 dollars; $6.5 billion in 2008 dollars). Source: Andersen et al. (2010).

in tensions or conflict. In addition, ties to families and networks in the communities of origin may deteriorate while they are away (Andersen et al. 2010).

In the case of climate-related evacuations, the social effects are mostly negative (see Box 3.12: Distress Migration during Hurricane Mitch). These include serious damage to physical assets (e.g., housing and livestock), and to other natural resources in the community of origin. In many cases, natural disasters can also contribute to financial and health problems (Andersen et al. 2010).

Migration contributes strongly to structural and sociodemographic change in LAC cities. Migrants tend to come from similar locations and settle in the same areas which usually are marginal areas in urban areas where they might have social capital or social networks (Vignoli 2012). This contributes to creating social vulnerability to climate change by increasing spatial segregation at the destination, or by modifying social networks of migrant households in their origin (Pinto da Cunha 2011; Vignoli 2012). As a result, immigrant populations may lack the knowledge of disaster risk management plans, especially if they are new to urban areas and had not encountered disaster management plans in the rural areas where they migrated from (Adamo 2013).

### 3.4.9 Human Security

The LAC region is considered to be at low risk of armed conflict, with the incidence of armed conflicts declining substantially in the last 15 years (Rubin 2011). With the downfall of many military regimes in the 1980s, and continued economic integration, the region has achieved relative stability (Rubin 2011). However, in the context of high social and economic inequalities and migration flows across countries, disputes regarding access to resources, land, and wealth are persistent.

Several countries in the region have also faced political instability in the past few years. For example, Bolivia has seen some internal social movements calling for the independence of some regions; and there are important challenges related to the drug trade which has become increasingly violent, particularly in Mexico (Necco Carlomagno 2012). In fact, the activities of criminal groups and organized crime syndicates in countries like Brazil and Mexico are a major source of some of the most significant conflicts (Rubin 2011).

Climate change could aggravate these situations, further increasing conflicts over the use of resources. Socioeconomic disparities could be exacerbated, and in the worst case scenario, government capacities could be insufficient to face these along with natural disasters and climate-related challenges (McLeman 2011). In some Latin American countries where criminal organizations already have significant power, such security gaps can enable them to increase their influence, further weakening the capacity of the state (Carius and Maas 2009). It is important to note that in the past, environmental degradation has often been used as a pretext for conflicts that are in fact caused by underlying ethnic tensions and injustices associated with an unequal geographical distribution of the population and income inequality (Deprez 2010).

In this context, Rubin (2011) suggests four ways in which climate change could increase the risk of conflict in LAC:

- *More resource scarcity.* Climate change is likely to exacerbate resource scarcities. Increasing scarcity of food, water, forests, energy, and land could intensify competition over the remaining resources, triggering internal unrest and even border conflicts.
- *More migration*. The LAC region has important migration dynamics that are being exacerbated by climate change as households face increased resource scarcities, rising sea levels, and more (and more intense) natural disasters. Larger flows of migrants could potentially destabilize destination countries.
- *Increasing instability*. Climate change and variability may undermine the capacity of the state by increasing the cost of infrastructure in remote rural areas, limiting the reach of the state. This could be aggravated by the rising costs of disaster management (e.g., an increase in the level of agricultural subsidies needed to maintain adequate food production) as well as by the general need for increased adaptation spending. These limits in state capacity might result in a weakening of the relationship between the state and its citizens.
- *Increasing frequency and intensity of natural disasters.* The chaotic conditions that follow in the wake of natural disasters may provide opportunities for rebel groups to challenge the government's authority.

The empirical literature is inconclusive regarding the linkages between climate change and an increasing risk of conflict globally.

Rubin (2011) suggests, however, that while resource scarcity in isolation from other socioeconomic factors does not necessarily increase the risk of conflict, it often acts as a catalyst or driver, amplifying the existing (often traditional) causes of conflict. In this sense, Haldén (2007) notes that disparities in standards of living and income can be problematic for several reasons: (1) disparities and divisions might by themselves impede growth and undermine adaptation strategies; (2) substantial inequality might also destabilize societies and increase the risk of conflict in the light of climate change and variability; and (3) the differences between large segments of the populations imply that climate change will have very unequal impacts on the population, further exacerbating tensions. This is particularly relevant in the LAC region, which has one of the most unequal income distributions in the world (Fereira et al. 2013).

Large inequalities among groups (differentiated along ethnic, religious, political, or geographical lines) increase the risk of violent conflict and high individual income inequality is a driver of crime (Dahlberg and Gustavsson 2005; Fajnzylber et al. 2002; Østby 2007). In the case of Bolivia, for example, highly unequal distributions of natural resources create tensions among regions. In response to the nationalization of gas and oil reserves, the resource-rich regions of Santa Cruz, Tarija, Beni, and Pando (comprising 35 percent of the Bolivian population) unsuccessfully sought autonomy. Violent disputes erupted between the government and the regions seeking autonomy (Rubin 2011); this has since subsided due to the 2010 Autonomies Law and other agreements.

Relatively small populations can have a tremendous impact on the environment (Hoffman and Grigera 2013). There are examples–notably in the Amazon basin—where the rural poor have turned to illicit extractive activities (e.g., illegal logging) because they lack legal or formal alternatives. The effects of climate change and environmental degradation, along with the rapid growth of the extractive industry, is expected to take the greatest toll on the most vulnerable—small-hold farmers, indigenous populations, and the poor (Hoffman and Grigera 2013). The resulting increase in resource competition, (particularly for water and land)—together with increasing market pressure on landholders with tenuous legal tenure—is expected to exacerbate existing inequities and tensions surrounding the proper and equitable allocation of the region's natural wealth (Hoffman and Grigera 2013).

Climate change could also increase violence in small communal or household settings. One example is gender-based violence, which is already widespread in Latin America (Morrison et al. 2004). Although there is little research on this topic, there are some studies (e.g., Harris and Hawrylyshyn 2012) which indicate that climate change (by transforming livelihoods and social structures) could spur social violence in non-conflict situations. Moser and Rogers (2005) showed how rapid socioeconomic changes might have a destabilizing effect not only on societies but also within families, leading to an increased risk of domestic violence.

## 3.4.10 Coastal Infrastructure

Coastal areas, infrastructure, and cities are all vulnerable to climate change. This is particularly true for the Caribbean region due to its low-lying areas and the population's dependence on coastal and marine economic activities (Bishop and Payne 2012). Tropical cyclones and sea-level rise represent the main risks as their combination can severely affect economic development (and have generated significant losses and damages in past decades). For example, category 5 Tropical Cyclone Ike generated approximately \$19 billion in damages, including \$7.3 billion in Cuba alone (Brown et al. 2010).

Overall losses induced by climate change stressors such as increased wind speed, storm surge, and coastal flooding could amount to 6 percent of GDP in some Caribbean countries (CCRIF 2010). Climate change-related impacts, including local sea-level rise, increased hurricane intensity, and modified precipitation and temperature patterns could increase current economic losses by 33–50 percent by the 2030s (CCRIF 2010).

### *3.4.10.1 Impacts of Sea-Level Rise on Coastal Cities*

Several studies (Brecht et al. 2012; Hallegatte et al. 2013; Hanson et al. 2011) have recently estimated the potential costs of sea-level rise, and the modification of storm patterns and land subsidence (which is not induced by climate change), for coastal cities in LAC. Hallegatte et al. (2013) found that, by 2050, coastal flooding could generate approximately \$940 million of mean annual losses in the 22 largest coastal cities in the region with a sea-level rise of 20 cm, and about \$1.2 billion with a sea-level rise of 40 cm (Table 3.8). The study likely underestimates the overall impact as it only assesses the costs of climate change on the largest coastal cities.

### *3.4.10.2 Impacts on Port Infrastructure*

Port infrastructures are particularly vulnerable to the direct and indirect consequences of climate change (Becker et al. 2013). Becker et al. (2013) identified sea-level rise, higher storm surges, river floods, and droughts as the main direct impacts, and coastal erosion, which could undermine port buildings and construction, as one of the indirect impacts of climate change. The potential increase in tropical cyclone intensity may increase ships' port downtime and, therefore, increase shipping costs (Chhetri et al. 2013; Esteban et al. 2012).

Port infrastructure is crucial to economic development as international trade is principally channeled through ports. Furthermore, in Caribbean countries, port infrastructure plays a very significant role as they often are the only vector for trade in goods and assets (Bishop and Payne 2012). Impacts on seaports will also have indirect consequences on local economies as import disruptions generate price increases for imported goods and export disruptions lead to revenues and incomes decreasing at the national level (Becker et al. 2012).

**Table 3.8:** Projected losses from sea-level rise under two different sea-level-rise scenarios and land subsidence in the largest LAC cities.

| | 20 CM SEA-LEVEL RISE AND SUBSIDENCE (NO ADAPTATION) | | 40 CM SEA-LEVEL RISE AND SUBSIDENCE (NO ADAPTATION) | |
|---|---|---|---|---|
| URBAN AGGLOMERATION | MEAN ANNUAL LOSS (M$) | MEAN INCREASE DUE TO SLR AND SUBSIDENCE COMPARED TO CURRENT LOSSES | MEAN ANNUAL LOSS (M$) | MEAN INCREASE DUE TO SLR AND SUBSIDENCE COMPARED TO CURRENT LOSSES |
| **La Habana (Cuba)** | 9 | 5939% | 21 | 13660% |
| **Port-au-Prince (Haiti)** | 8 | 1090% | 11 | 1482% |
| **San Juan (Puerto Rico)** | 1.680 | 2365% | 4.238 | 6118% |
| **Santo Domingo (Dominican Republic)** | 263 | 1166% | 410 | 1880% |
| **Baixada Santista (Brazil)** | 274 | 3041% | 467 | 5256% |
| **Barranquilla (Colombia)** | 87 | 1782% | 102 | 2106% |
| **Belém (Brazil)** | 93 | 698% | 586 | 4955% |
| **Buenos Aires (Argentina)** | 161 | 268% | 592 | 1257% |
| **Panama City (Panama)** | 431 | 916% | 451 | 962% |
| **Fortaleza (Brazil)** | 52 | 2762% | 108 | 5814% |
| **Grande Vitória (Brazil)** | 2.643 | 1289% | 10.096 | 5208% |
| **Guayaquil (Ecuador)** | 31.288 | 1012% | 32.267 | 1047% |
| **Lima (Peru)** | 39 | 1009% | 48 | 1254% |
| **Maceió (Brazil)** | 54 | 887% | 283 | 5025% |
| **Maracaibo (Venezuela)** | 67 | 1086% | 588 | 10238% |
| **Montevideo (Uruguay)** | 50 | 258% | 180 | 1181% |
| **Natal (Brazil)** | 150 | 1505% | 487 | 5100% |
| **Porto Alegre (Brazil)** | 71 | 641% | 483 | 4918% |
| **Recife (Brazil)** | 259 | 1279% | 970 | 5063% |
| **Rio de Janeiro (Brazil)** | 411 | 1088% | 1.803 | 5108% |
| **Salvador (Brazil)** | 245 | 4903% | 262 | 5248% |
| **San Jose (Costa Rica)** | 10 | 551% | 67 | 4133% |
| **Total** | **2769.6** | | **6164.4** | |

Source: Hallegatte et al. (2013).

### *3.4.10.3 Impacts on Tourism Activities*

Tourism in the region, especially beach tourism in the Caribbean, is projected to be affected by the impacts of climate change (Hyman 2013). The total contribution of travel and tourism in the Caribbean was about 14 percent of the regional GDP and directly supported approximately 650,000 jobs (World Travel and Tourism Council 2013). As a result, the impact of climate change on tourism could detrimentally affect regional economic development (Simpson et al. 2011, 2010).

Beach tourism is particularly exposed to several direct and indirect climate change stressors, including sea-level rise, modified tropical storm pattern, heightened storm surges, and coastal erosion (Simpson et al. 2011). In a study comparing the vulnerability of four different tourist destinations in Jamaica, Hyman (2013) found that coastal tourist resorts are two-to-three times more exposed to climate change-related stressors than inland touristic resorts.

### *3.4.10.4 Impacts of Tropical Cyclones*

Although projections on tropical cyclone frequency are still uncertain, they indicate an augmentation of the number of Category 4 and 5 high-intensity tropical cyclone on the Saffir-Simpson scale (see Chapter 3.3.6, Tropical Cyclones/Hurricanes). The losses and damages associated with tropical cyclones making landfall are also projected to change (Hallegatte 2007; Mendelsohn et al. 2011). Quantifying the future impact of tropical cyclones and their associated costs is complex as it involves not only climate model projections but also projections of socioeconomic conditions and potential adaptation measures.

In a scenario leading to a 4°C world and featuring a 0.89–1.4 m sea-level rise, tropical cyclones in the Caribbean alone could generate an extra $22 billion and $46 billion in storm and infrastructure damages and tourism losses by 2050 and 2100, respectively, compared to a scenario leading to a 2°C world (Bueno et al. 2008). The sea-level rise assumed in this study is based on semi-empirical sea-level rise projections (Rahmstorf 2007) and is higher than the upper bound projected in Section 3.3.7, Regional Sea-level Rise. Curry et al. (2009) project that cumulative losses induced by tropical cyclones in the Caribbean, Central America, and Mexico are going to increase to about $110 and $114 billion during the period 2020–2025. These numbers assume an increasing tropical cyclone intensity of 2 percent and 5 percent, respectively, compared to average values from 1995–2006. The majority of the costs, approximately $79 billion in cumulative losses, would incur in Mexico (Table 3.9). The estimates of Curry et al. (2009) take into account GDP and population projections but not potential adaptation measures.

**Table 3.9:** Cumulative loss for the period 2020–2025 for Latin American and Caribbean sub-regions exposed to tropical cyclones under scenarios A1 (constant frequency, intensity increased by 2 percent) and A2 (constant frequency, intensity increased by 5 percent).

| SUB-REGION | SCENARIO A1 (IN MILLION US$) | SCENARIO A2 (IN MILLION US$) |
|---|---|---|
| **Mexico** | 79.665 | 79.665 |
| **Central America and Yucatan**[35] | 5.128 | 5.847 |
| **Greater Antilles**[36] | 22.771 | 26.041 |
| **Lesser Antilles**[37] | 1.813 | 2.073 |
| **Bahamas, The** | 985 | 1.241 |
| **Total** | 110.362 | 114.867 |

The data and calculations are based on Curry et al. (2009). Please note that the scenarios named here 'A1' and 'A2' are not SRES scenarios but based on Emanuel (2005) and Webster et al. (2005).

## 3.4.11 Energy Systems

Energy access is a key requirement for development, as many economic activities depend on reliable electricity access (Akpan et al. 2013). At the individual and household level, electricity access enables income-generating activities, increases safety, and contributes to human development (Deichmann et al. 2011). In LAC, the population generally has extended access to electricity in rural and urban areas (apart from Haiti, where only 12 percent of the rural population and 54 percent of the urban population had access to electricity in 2010) (World Bank 2013z).

Climate change is projected to affect electricity production and distribution both globally and in the region (Sieber 2013). This challenges the LAC countries, which will have to increase or at least maintain electricity production at the current level to support economic development and growing populations.

The effects of extreme weather events and climate change could lead to price increases and/or power outages (Ward 2013). Thermal electricity and hydroelectricity are projected to be most vulnerable. Three types of climate-change-related stressors could potentially affect thermal power generation and hydropower generation: Increased air temperature (which would reduce thermal conversion efficiency); decreased available volume and increased temperature of cooling water; and extreme weather events (which could affect the production plants, the distribution systems, and grid reliability) (Han et al. 2009; Sieber 2013).

### *3.4.11.1 Current Exposure of the LAC's Energy Systems*

LAC countries have a diverse energy mix (Table 3.10). The majority of the South American countries heavily rely on hydroelectricity(almost 100 percent, for example, in Paraguay); Central American countries use thermal electric sources and hydroelectricity. Caribbean countries, meanwhile, rely on thermal electric sources for electricity production. Between 91 percent (for Jamaica) and 55 percent (for Cuba) of the electricity consumed is generated from these sources.

With a projected change in water availability, from decreasing precipitation and river runoff and/or increasing seasonality and shrinking snow caps and decreasing snow fall in the Latin American mountainous regions, thermal electricity plant cooling systems may become less efficient and electricity production could be affected (Mika 2013; Sieber 2013). Hydroelectric power generation is similarly affected (Hamududu and Killingtveit 2012).

### *3.4.11.2 Impacts of Climate Change on Energy Supply*

There are limited studies specifically quantifying the impacts of climate change on thermal electricity and hydroelectricity generation in LAC. As the larger share of the electricity produced in the

[35] Belize, Costa Rica, El Salvador, Guatemala, Honduras, and Nicaragua.
[36] Cuba, Dominican Republic, Haiti, Jamaica, and Puerto Rico.
[37] Antigua and Barbuda, Barbados, Dominica, Grenada, St. Kitts and Nevis, St. Lucia, and St. Vincent and the Grenadines.

**Table 3.10:** Electricity production from hydroelectric and thermoelectric sources, including natural gas, oil, coal, and nuclear in 2011 in the Latin American and Caribbean countries.

| COUNTRY OR REGION | ELECTRICITY POWER CONSUMPTION (KWH PER CAPITA) | ELECTRICITY PRODUCTION FROM HYDROELECTRIC SOURCES (% OF TOTAL) | ELECTRICITY PRODUCTION FROM THERMOELECTRIC SOURCES (% OF TOTAL) | ELECTRICITY PRODUCTION FROM OTHER SOURCES (% OF TOTAL) |
|---|---|---|---|---|
| **Caribbean** | | | | |
| Cuba | 1326.6 | 0.56 | 54.89 | 44.55 |
| Dominican Republic | 893.31 | 11.79 | 87.99 | 0.21 |
| Haiti | 32.49 | 16.71 | 78.97 | 4.32 |
| Jamaica | 1549.23 | 1.96 | 91.81 | 6.22 |
| Trinidad and Tobago | 6331.94 | – | 100 | – |
| **Latin America** | | | | |
| Argentina | 2967.39 | 24.36 | 73.97 | 1.66 |
| Bolivia | 623.37 | 32.50 | 64.10 | 3.41 |
| Brazil | 2437.96 | 80.55 | 12.77 | 6.68 |
| Chile | 3568.08 | 31.97 | 60.40 | 7.63 |
| Colombia | 1122.73 | 79.06 | 17.64 | 3.30 |
| Costa Rica | 1843.94 | 72.56 | 8.78 | 18.66 |
| Ecuador | 1192.28 | 54.93 | 42.27 | 2.79 |
| El Salvador | 829.57 | 34.64 | 34.06 | 31.30 |
| Guatemala | 539.08 | 39.84 | 33.10 | 27.07 |
| Honduras | 707.76 | 39.50 | 56.51 | 3.99 |
| Nicaragua | 521.58 | 11.61 | 65.99 | 22.41 |
| Panama | 1829.01 | 52.16 | 47.55 | 0.29 |
| Paraguay | 1228.19 | 100.00 | 0.00 | 0.00 |
| Peru | 1247.75 | 55.00 | 43.13 | 1.87 |
| Uruguay | 2810.12 | 62.64 | 28.10 | 9.26 |
| Venezuela, RB | 3312.68 | 68.55 | 31.45 | 0.00 |
| **Mexico** | **2091.69** | **12.26** | **84.13** | **3.62** |

Sources: World Bank (2013e, f, g, h, i, j). – means not available.

region originates from hydropower, general impacts of climate change on thermal electric generation plants are discussed in Section 4.4.6, Energy Systems.

## Hydropower

Hydropower produces the larger share of electricity in the LAC region (see Table 3.10). The core natural resource for hydroelectricity is river runoff, which has to be inter- and intra-annually stable to allow hydropower installations to produce electricity most efficiently (Hamududu and Killingtveit 2012; Mukheibir 2013). In Peru it is estimated that a 50 percent reduction in glacier runoff would result in a decrease in annual power output of approximately 10 percent, from 1540 gigawatt hours (GWh) to 1250 GWh (Vergara et al. 2007).

Hamududu and Killingtveit (2012) found that production will increase by 0.30 TWh (or 0.03 percent) in the Caribbean compared to 2005 production levels, and by 0.63 TWh (or 0.05 percent) in South America, under 2°C global warming by the middle of the 21st century. Maurer et al. (2009) projected the impacts of climate change on the Rio Lempa Basin of Central America (flowing through Guatemala, Honduras, and El Salvador and into the Pacific—see Table 3.11). They concluded that an increase in frequency of

**Table 3.11:** Projected temperature and hydrologic changes in the Rio Lempa River during the period 2040–2069 and 2070–2099 relative to the period 1961–1990 for hydrological change and pre-industrial levels for temperature changes.

| IMPACT/PERIOD | SCENARIO | 2040–2069 | 2070–2099 |
|---|---|---|---|
| **Temperature increase above pre-industrial levels** | B1 | +1.8°C | +2.2°C |
| | A2 | +2.1°C | +3.4°C |
| **Precipitation change relative to 1961–1990 (median change)** | B1 | – | –5% |
| | A2 | – | –10.4% |
| **Reservoir inflow relative to 1961–1990 (median change)** | B1 | – | –13% |
| | A2 | – | –24% |
| **Frequency of low flow relative to 1961–1990 (median change)** | B1 | +22% | +33% |
| | A2 | +31% | +53% |

Source: Maurer et al. (2009).

low-flows in scenarios leading to a 2°C world and a 3°C world implies a proportional decrease in hydropower capacity for the two main large reservoirs used for hydroelectricity generation in El Salvador (Cerron Grande and 15 Setiembre). Low-flow frequency is a key indicator of the economic viability of hydropower infrastructures as it determines the firm power, which is the amount of "energy a hydropower facility is able to supply in dry years" (Maurer et al. 2009). The projected increase in low-flow frequency could therefore reduce the economic return from the existing facility and reduce the return on investments in future hydroelectric infrastructures (Maurer et al. 2009).

For Brazil, de Lucena et al.(2009) project that average annual river flows will decrease by 10.80 percent with 2.9°C global warming, and by 8.6 percent with 3.5°C global warming, by 2071–2100. This decrease in annual flow will lead to a decrease in firm power of 3.2 and 1.6 percent, respectively, during this time period compared to production level for 1971–2000. For the Rio Grande river basin, average river flow could be between –20 and +18 percent with a global warming of 2.1°C depending on the different GCM chosen. This difference between the lowest and the highest estimates highlights the limitations of the current models to project the potential hydropower production from dams built on this river basin and reflects that projections vary from one GCM to another (Nóbrega et al. 2011). Popescu et al. (2014) showed an increase in the maximum hydropower energy potential for the La Plata Basin of between 1–26 percent with a global warming of 1.8°C by 2031–2050 (see Table 3.12). There were also great disparities in the sub-basin projections depending on the model used. The La Plata basin is one of the most economically important river basins in Latin America (being part of Argentina, Bolivia, Brazil, Paraguay, and Uruguay). It has a major maximum hydropower energy potential, producing on average 683,421 GWh per year during the period 1991–2010 and 76 percent of the 97,800 MW total electricity generation capacity of the five countries in the La Plata basin (Popescu et al. 2014).

The results of these studies, however, need to be interpreted with care. For example, the significant decrease in hydropower capacity at the micro-level as projected by Maurer et al. (2009) strongly contrasts with the results of Hamududu and Killingtveit (2012), who projected an increase in hydropower generation at the macro-level. The Hamududu and Killingtveit study may be limited for several reasons. First, it does not take into account seasonality and the impacts of climate change on the timing of river flows. Second, changes in hydrology and temperatures are accounted for at the country level but not at the river basin level; this does not take into account potential spatial variability and changes occurring over short distances. Third, the study does not consider the potential impacts of floods and droughts, which have very significant impacts on hydroelectricity generation and are projected to occur more frequently and with a greater intensity in the coming decades (Marengo et al. 2012, 2013; Vörösmarty et al. 2002) (see also Section 3.4.2, Water Resources, Water Security, and Floods). Finally, the study does not consider the impacts on river runoff from decreasing snow cover and snowfall in the Latin American mountainous regions (Barnett et al. 2005; Rabatel et al.

**Table 3.12:** Maximum hydropower energy potential for the La Plata Basin with present, near future, and end-of-century climate conditions for two climate models (PROMES-UCLM and RCA-SMHI).

| SCENARIO | PRESENT CLIMATE 1991–2010 | FUTURE CLIMATE 2031–2050 (1.8°C IN SCENARIO A1B) | | END OF CENTURY 2079–2098 (3.2°C IN SCENARIO A1B) | |
|---|---|---|---|---|---|
| | ENERGY (GWH/YEAR) | ENERGY (GWH/YEAR) | VARIATION TO PRESENT | ENERGY (GWH/YEAR) | VARIATION TO PRESENT |
| **PROMES-UCLM** | 683,421 | 688,452 | 1.01 | 715,173 | 1.05 |
| **RCA-SMHI** | | 861,214 | 1.26 | 838,587 | 1.23 |

Source: Popescu et al. (2014).

2013; Vuille et al. 2008). These limitations could potentially explain why their results are different from those of Maurer et al. (2009), who use monthly precipitation rates to calculate annual inflows.

Further research is needed to adequately inform decision makers in the region on the impacts of climate change on hydropower generation. Similarly to Hamududu and Killingtveit (2012), de Lucena et al. (2009) only accounted for the average behavior of flows and did not integrate potential change in seasonality or the effects of extreme dry or wet events on hydropower generation. In this context, projections for hydropower production in Brazil by de Lucena et al. (2009) may underestimate the potential impacts of climate change. The projections by Popescu et al. (2014) only estimated a maximum hydropower potential, but this does not mean that more hydropower electricity will be produced from existing or future installations. For example, the specifications for existing dams (e.g., reservoir size, dam height, and so forth) may not be sufficient to efficiently manage projected excess flows.

Despite these uncertainties, there are some clear climate change impacts on hydropower. Mukheibir (2013) inventoried the climate-related stressors that are projected to affect hydroelectricity generation. He separated climate-change-related stressors into three categories: (1) long-term trends or gradual changes induced by climate change; (2) increases in extreme climate variability; and (3) indirect climate change impacts (Table 3.13). These stressors could potentially reduce firm energy and increase variability and uncertainty of supply in the energy sector (Ebinger and Vergara 2011).

**Table 3.13:** Climate change-related stressors projected to affect hydroelectricity generation.

| CATEGORY OF CLIMATE-CHANGE-RELATED STRESSORS | CLIMATE-CHANGE-RELATED STRESSORS |
|---|---|
| Long term trends or gradual changes induced by climate change | Reduction in average precipitation<br>Increase in average precipitation<br>Increase in average temperature |
| Increase in extreme climate variability | Drought<br>Flooding |
| Indirect climate change impacts | Water scarcity<br>Siltation through land degradation |

Source: Mukheibir (2013).

### Oil and Gas

Some LAC countries, such as the Republica Bolivariana de Venezuela, Brazil, and Mexico, benefit from significant oil and/or gas reserves. For example, Venezuela is the world's tenth largest exporter of oil and Mexico was the ninth biggest producer in 2013 (EIA 2014a). The production of gas and oil in LAC countries contributed 7.38 percent in 2012 and 12.01 percent in 2013 to global production (Table 3.14). Furthermore, some countries in the region have a very significant share of their GDP originating

**Table 3.14:** Natural gas production for LAC countries in 2012 and oil production in 2013.

| | NATURAL GAS PRODUCTION IN 2012 (IN BILLION CUBIC FEET) | OIL PRODUCTION IN 2013 (IN THOUSANDS OF BARRELS PER DAY) |
|---|---|---|
| **Argentina** | 1,557.39 | 707.91 |
| **Bolivia** | 652.27 | 64.46 |
| **Brazil** | 910.77 | 2,712.03 |
| **Chile** | 42.98 | 15.57 |
| **Colombia** | 1,110.30 | 1,028.47 |
| **Cuba** | 38.00 | 48.73 |
| **Ecuador** | 54.39 | 527.03 |
| **Mexico** | 1,684.42 | 2,907.83 |
| **Peru** | 639.91 | 174.96 |
| **Trinidad and Tobago** | 1,504.74 | 118.12 |
| **Venezuela, RB** | 2,682.81 | 2,489.24 |
| **Total LAC region** | 10,878.68 | 10,851.42 |
| **LAC percentage of global production** | 7.38% | 12.01% |

The LAC countries not displayed in the table produce little oil or natural gas. Source: EIA (2014a; b).

from oil and natural gas rents (defined as the difference between value of natural gas or oil production and the total cost of production); in Venezuela and Trinidad and Tobago, for example, about 30 percent of 2012 GDP in 2012 came from oil and gas rents (World Bank 2013e; f). The assessment of climate change impacts on oil and gas presented here focuses on direct impacts and does not consider the possible decrease in fossil fuel assets value induced by future mitigation policies, which would contribute to a reduction in fossil fuel demand at the global level (IPCC 2014d).

Off-shore platforms and on-shore infrastructures are susceptible to climate related impacts, such as sea-level rise and coastal erosion that could damage extraction, storage and refining facilities (Dell and Pasteris 2010) and also to extreme weather events such as tropical cyclones which could lead to extraction and production disruption and platform evacuation (Cruz and Krausmann 2013). For example, in the aftermath of tropical cyclones Katrina and Rita in 2005, 109 oil platforms and five drilling rigs were damaged leading to interruptions in production (Knabb et al. 2005). Cozzi and Gül (2013) identify two key climate related risks for the LAC region: sea-level rise and an increase in storm activity (particularly for Brazil). These risks would mainly lead to an increase in the shutdown time of coastal refineries and an increase in offshore platform costs, which will have to be more resistant to high-speed winds associated with tropical cyclones (Cozzi and Gül 2013).

#### Wind and Solar Energy

Solar and wind energy sources play an important role in climate change mitigation strategies to reduce global emissions from fossil fuel combustion. Even though wind and solar energy still play a very minor role in LAC, significant development of the sector is projected (Bruckner et al. 2014). In this context, a more precise understanding of the effect of climate change on these energy sources is of great significance.

For wind energy, the main climate change impact relates to changing wind patterns and how climate change will affect inter- and intra-annual variability and geographical distribution of wind (Arent et al. 2014). Despite significant progress, GCMs and RCMs still do not produce very precise projections for inter-annual, seasonal, or diurnal wind variability (Arent et al. 2014). Furthermore, specific studies estimating the effects of climate change on wind patterns and therefore wind energy in LAC are still missing (Pryor and Barthelmie 2013). However, drawing on conclusions from Pryor and Barthelmie (2013) for the United States and Europe stating that "generally, the magnitude of projected changes over Europe and the contiguous USA are within the 'conservative' estimates embedded within the Wind Turbine Design Standards," it can be assumed that future climate change may not significantly affect wind energy supply. Pryor and Barthelmie (2013) nonetheless highlight the need for more research in this area to better quantify the effects of long-term climate change and extreme events on wind energy supplies.

Solar energy installations are subject to two types of climate-related impacts: reduced insulation induced by cloudiness, which decreases heat or electricity output, and extreme weather events such as windstorms or hail, which could damage production units and their mounting structures (Arent et al. 2014). According to Arent et al. (2014), gradual climate change and extreme weather events "do not pose particular constraints to the future deployment of solar technologies." Studies estimating projected impacts of climate change and extreme weather events on solar energy outputs are not available.

### 3.4.11.3 Impacts of Tropical Cyclones on Power Outages

The Caribbean and Central American regions are particularly exposed to the impacts of tropical cyclones and a higher frequency of high-intensity tropical cyclones is projected (see Section 3.3.6, Tropical Cyclones/Hurricanes). Strong winds, heavy precipitation, and floods associated with tropical cyclones have the capacity to disrupt and even damage essential power generation and distribution infrastructures leading to power outages. A growing number of studies have developed models to estimate and forecast the risks of power outages to energy systems in order to improve disaster assistance and recovery (Cao et al. 2013; Han et al. 2009; Nateghi et al. 2013; Quiring et al. 2013). However, studies and models specifically quantifying or taking into account the projected effect of climate change on tropical cyclones intensity and frequency and the potential disruptions to power generation and distribution in the Caribbean and Central American countries are lacking.

### 3.4.11.4 Effects of Climate Change on Energy Demand

Climate change will also affect energy demand. Increasing temperatures and heat extremes (see Sections 3.3.1, Projected Temperature Changes, and 3.3.2, Heat Extremes) lead to a higher demand for air conditioning (Cozzi and Gül 2013); on the other hand, demand for heating may decrease. At the global level, Isaac and van Vuuren (2009) estimated that by 2100 in a 4°C world the number of cooling degree days will rise from 12,800 during the period 1971–1991 to 19,451, (a 51.9 percent increase) while demand for heating (measured in heating degree days) was projected to remain almost constant. At the regional level, they project that by 2100 demand for heating is going to decrease by 34 percent compared to the 1971–1991 period—from 364 to 240 heating degree days. They project the demand for cooling to increase by 48 percent, from 1802 to 2679 cooling degree days.

### 3.4.11.5 Synthesis

The assessment of the current literature on climate change impacts on energy in LAC shows that there are only a few studies, most of which make strong assumptions about key issues such as seasonality of water supply for hydropower. These studies are more qualitative than quantitative, and important gaps remain. However, in general substantial climate change impacts can be expected for the energy sector. There is also a lack of studies with respect to the impacts of climate change impacts on renewable energies. In general, the impacts of climate change on energy demand is less well studied than those on energy supply—and, yet, demand and supply interact in a dynamic way. For example, the concomitant increase in energy demand during heat extremes and the decrease of energy supply through reduced river flow and low efficiencies may put existing energy systems under increasing pressure in the future.

## 3.5 Regional Development Narratives

In this section, implications of climate change for regional development are discussed in order to relate climate change impacts to existing and future vulnerabilities in the LAC region. The development narratives are split into overarching development narratives across the region and in sub-regional development narratives. It is important to note that each development narratives presents only one of the many possible ways in which climate change can put key development trajectories at risk. Table 3.15 summarizes the key climate change impacts under different warming levels in the Latin American and the Caribbean region and Figure 3.22 summarizes the key sub-regional impacts.

### 3.5.1 Overarching Development Narratives

#### *3.5.1.1 Changes to the Hydrological Cycle Endanger the Stability of Freshwater Supplies and Ecosystem Services*

An altered hydrological system due to changing runoff, glacial melt, and snowpack changes will affect the ecosystem services that the rural population depends on, freshwater provisioning in cities, and major economic activities such as mining and hydropower.

Throughout the 20th century the tropical glaciers in the Central Andes have lost large amounts of their volume (see Section 3.4.1, Glacial Retreat and Snowpack Changes). As land surface temperatures rise, this trend is expected to accelerate possibly leading to an almost complete deglaciation of 93–100 percent in a 4°C world. In concert with decreasing snowpack, changes to precipitation patterns, and higher evaporation, increasing glacial melt will impact the timing and magnitude of river flows. In general, runoff is projected to increase during the wet season, increasing flood risk (see Section 3.4.2, Water Resources, Water Security, and Floods). Accelerated melting rates may lead to a localized short-term surge in water supply that might lead to unsustainable dependency (Vuille 2013). For example, in the area known as Callejon de Huaylas in the central highlands of Peru, climate-change-induced glacier retreat will add water stress to an area in which agriculture has already shifted toward more water-intensive irrigated crop production since the 1990s (Bury et al. 2011). As the glacier reservoirs gradually disappear, however, runoff will tend to decrease (particularly in the dry season). The peak in runoff is expected to be reached in about 20–50 years from now (Chevallier et al. 2011) if it has not yet peaked already (Baraer et al. 2012).

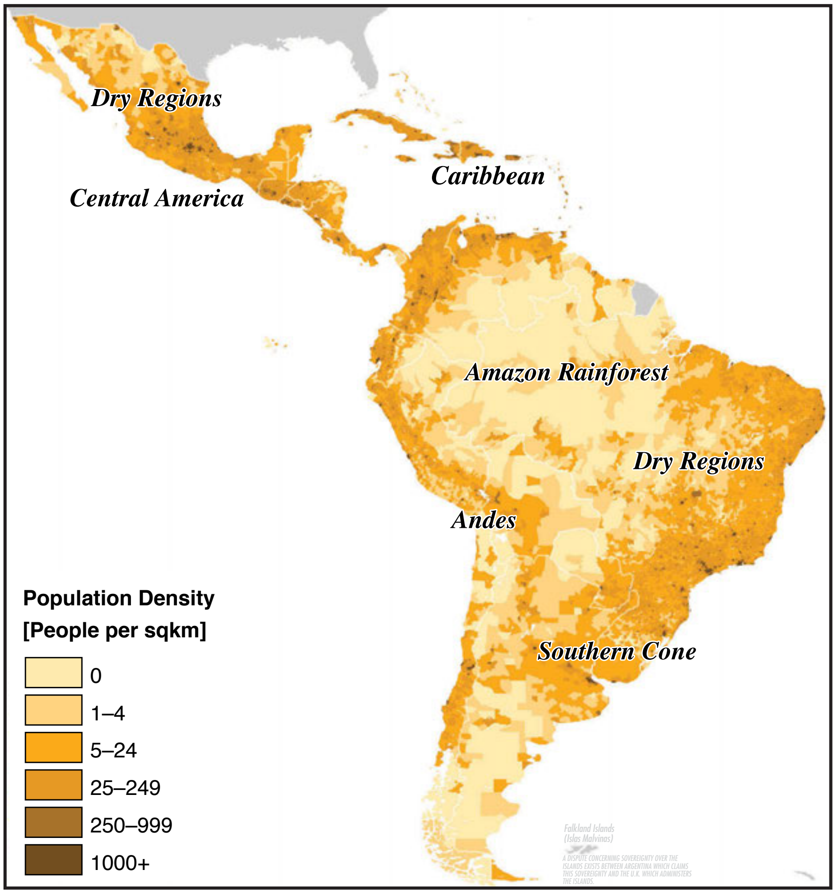
Changes to river flow translate into risks to stable water supplies for much of the region. Diminishing downriver water flow will also undermine hydropower generation; crucial to the economic development of the continent (Hoffman and Grigera 2013) (see also Section 3.4.11). Current studies project that by 2050, up to 50 million people in the vast lowland area fed by Andean glacial melt, will be affected by the loss of dry season water for drinking, agriculture, sanitation, and hydropower (Cushing and Kopas 2011). Deforestation and land degradation can furthermore alter the water cycle and possibly endanger water availability (Buytaert et al. 2006; Viviroli et al. 2011).

Changes to the seasonal cycle of water availability affect the ecosystems that rely on a stable water supply. Consequently ecosystem services are put at risk. For example, freshwater fisheries may be exposed to climate-related risks as decreasing river flows reduce the floodplain for spawning and the natural seasonal flooding of lakes is reduced. A projected decrease in annual precipitation and increasing risk of drought will in turn increase the risk of large-scale forest degradation, not only in the Amazon, with a loss of associated ecosystem services.

In the Andes in particular, water stress will reduce pasture land availability in the dry season and increase the potential for conflict over land use (Kronik and Verner 2010). Social conflicts over water rights and water access may increase in the Peruvian Andes between farming communities and mining companies. Moreover, higher river flow peaks can lead to landslides and devastating floods associated with glacial lake outburst (Chevallier et al. 2011)—with direct consequences for human lives and settlements.

Cities are highly vulnerable as continuous urbanization and population growth increases water demand (Hunt and Watkiss 2011) and as they depend on ecosystem services provided by surrounding areas. The high Andean moorlands (known as *páramos*—see Box 3.10, Critical Ecosystem Services of High Andean Mountain Ecosystems), which are key ecosystems able to stock large amounts of carbon on the ground and act as water regulators, are threatened by temperature rise, precipitation changes, and increasing human activity. Major population centers, such as Bogota and Quito, rely on páramo water as a significant supply source. The melting of the Andean glaciers, increasingly unpredictable seasonal rainfall patterns, and the overuse of underground reserves are affecting the urban centers of the highlands (e.g., La Paz, El Alto, and Cusco),

**Figure 3.22:** Sub-regional risks for development in Latin America and the Caribbean (LAC) under 4°C warming in 2100 compared to pre-industrial temperatures.




### Central America & the Caribbean

Higher ENSO and tropical cyclone frequency, precipitation extremes, drought, and heat waves. Risks of reduced water availability, crop yields, food security, and coastal safety.

*Poor exposed to landslides, coastal erosion with risk of higher mortality rates and migration, negative impacts on GDP where share of coastal tourism is high.*

### Amazon Rainforest

Increase in extreme heat and aridity, risk of forest fires, degradation, and biodiversity loss.

*Risk of rainforest turning into carbon source. Shifting agricultural zones may lead to conflict over land. Risks of species extinction threatening traditional livelihoods and cultural losses.*

### Andes

Glacial melt, snow pack changes, risks of flooding, and freshwater shortages.

*In high altitudes women, children, and indigenous people particularly vulnerable; and agriculture at risk. In urban areas the poor living on steeper slopes more exposed to flooding.*

### Dry Regions

Increasing drought and extreme heat events leading to cattle death, crop yield declines, and challenges for freshwater resources.

*Risks of localized famines among remote indigenous communities, water-related health problems. Stress on resources may lead to conflict and urban migration.*

### Southern Cone

Decreasing agricultural yields and pasture productivity, northward migration of agro-ecozones.

*Risks for nutritious status of the local poor. Risks for food price increases and cascading impacts beyond the region due to high export share of agriculture.*

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Data sources: Center for International Earth Science Information Network, Columbia University; United Nations Food and Agriculture Programme; and Centro Internacional de Agricultura Tropical—(2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socio-economic Data and Applications Center (SEDAC). This map was reproduced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

which rely to some extent on glacial melt for dry season water supplies and are already facing dire shortages. The arid coastal plain of Peru faces similar challenges. Water shortage has become a huge risk and a source of tension in Lima, which is dependent on water from the Andes. In Santiago de Chile, meanwhile, an estimated 40 percent reduction in precipitation will impact water supplies in a city that is expecting a 30 percent population growth by 2030 (Heinrichs and Krellenberg 2011). Quito is another city that will face water shortages as a result of glacier retreat (Hardoy and Pandiella 2009).

Freshwater in coastal areas is particularly exposed to the risks associated with sea-level rise. Here, a substantial section of the population is exposed to repeated flooding, contamination of groundwater by salt water, and constraints on the availability and quality of drinking water (Magrin et al. 2007). Low-income groups who already lack adequate access to water will be even less able likely to obtain it unless there is a considerable improvement in the provision of basic services.

#### 3.5.1.2 Climate Change Places at Risk Both Large-Scale Agricultural Production for Export and Small-Scale Agriculture for Regional Food Production

Latin America and the Caribbean is a climatically highly heterogeneous region. As a result, agricultural production systems and their outputs differ greatly among climatic zones and countries, as will the impacts of climate change on agricultural production. Despite the relatively low contribution of agriculture (10–12 percent) to the total GDP, agriculture plays a vital role for the LAC economy, with 30–40 percent of the labor force engaged in the agricultural sector (IAASTD 2009). However, the numbers and proportion of the sector comprised by subsistence and commercial agriculture, differ greatly among the LAC countries.

Climate change is expected to have different impacts over different timeframes (see Section 3.4.3, Climate Change Impacts on Agriculture). In the short run, expected changes in agricultural outputs in the region are likely to be heterogeneous, with some regions and crops seeing gains and others losses (Table 3.15). In the long run, however, larger reductions in agriculture are expected with important impacts on livelihoods (Calvo 2013; Sanchez and Soria 2008; Samaniego 2009) despite uncertainties with regard to the importance of $CO_2$ fertilization and potential adaptation. Overall, the potential risks estimated for the agricultural sector in LAC are substantial, particularly during the second half of the 21st century.

By putting agricultural production at risk, climate change threatens an important regional export. LAC plays a vital role in global agriculture (IFPRI 2012). The two biggest exporters of agricultural products in Latin America are Brazil and Argentina (Chaherli and Nash 2013). Agricultural production in LAC countries has increased by roughly three percent per annum since the early 1990s (IFPRI 2012). In LAC, large parts of agriculture are rain-fed and therefore very vulnerable to climatic variations such as droughts and changing precipitation patterns. Only 10.5 million ha of agricultural area are irrigated, amounting to roughly 0.6 percent of the total agricultural area. Of those 10.5 million ha of irrigated area, 3.5 million are located in Brazil, amounting to 1.3 percent of Brazil's agricultural area (FAOSTAT 2013; Oliveira et al. 2009). Changing precipitation patterns and extreme events could therefore affect important parts of the economy. Moreover, Hoffman and Grigera (2013) calculate that for the Amazon and Cerrado regions, shifting rainfall patterns and temperature rises due to climate change will lead to more frequent droughts and forest fires in the dry season and floods in the rainy season, threatening the growth of monoculture agribusiness and the livelihoods of small-holder farmers and ranchers.

Besides the implications of climate change for large-scale agriculture, there is also evidence that climate change will strongly affect small-to-medium-scale agriculture and regional food security as well as indigenous communities. This is particularly true for rural communities who heavily rely on subsistence farming and the urban poor who are most hard-hit by rising food prices. A projected 15–50 percent decline in fishery catch potential along the Caribbean coast, and by more than 50 percent off the Amazonas estuary and the Rio de la Plata (Cheung et al. 2010), together with widespread coral reef loss, further adds to the challenge of maintaining a healthy diet for the poorest in the region. Coral reef loss and more frequent extreme events could also affect the viability of the tourism industry, with significant implications for livelihoods across different socio-economic groups.

Overall undernourishment in the region has decreased. In 1990, roughly 65 million people (14.6 percent of the population) were undernourished; by 2012, the number decreased to 49 million people (8.3 percent of the population) (FAO 2012a). The LAC countries most affected by undernourishment are Haiti, Bolivia, Guatemala, Nicaragua, and Paraguay. In all five countries more than 20 percent of the population are undernourished (FAO 2012a). However, population growth and changing nutritional patterns are expected to increase global food demand by 60 percent by 2050 (FAO 2012a). As a result, increased agricultural production is essential to maintain the currently positive trend of decreasing undernourishment. The expected negative effects of climate change on agriculture (Table 3.15) will make the challenge of achieving food security in LAC all the more difficult. According to one study, without adaptation measures climate change is likely to stall the projected decline in child undernourishment in LAC by 5 percent by 2050 (Nelson et al. 2009). This study does not take into account the impacts on food resources other than agricultural crops; it therefore may underestimate the multidimensional impacts that climate change has on food security.

There are potentially direct consequences of climate change on the levels of poverty and food security in the region. According to an exploratory modeling study by Galindo et al. (2013) an average decline of six percent in agricultural production due to climate change by 2025 would result in 22.6 percent and 15.7 percent fewer people overcoming the $1.25 and $2 per day poverty lines respectively, given losses in livelihoods. This means a total of 6.7–8.6 million people who would remain under the poverty line as a result of climate change impacts on agriculture. In addition, important indirect effects resulting from reductions in agricultural yields include risks to agro-industrial supply chains. Given the exploratory nature of this study, however, exact numbers have to be interpreted with care.

#### 3.5.1.3 A Stronger Prevalence of Extreme Events Affects Both Rural and Urban Communities, Particularly in Coastal Regions

A changing frequency and intensity of extreme events, such as drought, heat extremes, tropical cyclones, and heavy precipitation, will have strong implications for the urban and rural populations of the region, with particular vulnerability patterns shaping the risks of different population groups.

The LAC region is heavily exposed to the effects of strong ENSO events, including extreme precipitation and disastrous flooding, especially in the Andes and Central America where steep terrains are common (IPCC 2012; Mata et al. 2001; Mimura et al. 2007; Poveda et al. 2001). Glacial lake outbursts present a further permanent hazard for Andean cities (Chevallier et al. 2011). Along the Caribbean and Central American coasts, tropical cyclones and rising sea levels expose the population to storm surges and coastal inundation (Dilley et al. 2005; Woodruff et al. 2013). Although the scientific evidence is limited, there are studies indicating an increase of 80 percent in the frequency of the strongest category 4 and 5 Atlantic Tropical Cyclones (Bender et al. 2010; Knutson et al. 2013) and a doubling in the frequency of extreme El Niño events above 20th century levels (Cai et al. 2014). The latter two projections are especially worrisome as they concur with a sea-level rise up to 110 cm (see Section 3.3.7, Regional Sea-level Rise). A poleward migration of tropical cyclones as recently observed (Kossin et al. 2014) could potentially lead to less damage to tropical coasts but countries would also benefit less from the water replenishment that cyclone rainfall brings and areas currently less exposed to tropical cyclones would face additional risks.

The vulnerability of people exposed to extreme events is shaped by a multitude of non-climatic factors. Some socioeconomic factors shaping vulnerability are the same for rural and urban populations, including social marginalization and limited access to resources. However, conditions such as dense and poorly constructed housing in urban areas or high, direct dependence on ecosystem services among rural indigenous populations result in specific vulnerability patterns for different population groups.

Despite these differences in vulnerabilities, climate impacts also act along an urban-rural continuum. For example cities depend on the surrounding landscape to provide ecosystem services and the rural population benefits from remittances sent from urban to rural areas. However, the effectiveness of remittances in supporting adaptive capacity under rising impacts is open to question, as both demand on the receiving end and exposure to climate risks on the sending end are expected to rise.

The rural poor are likely to feel the impacts of climate change and variability most directly given their dependency on rain-fed agriculture and other environmental resources (e.g., forests and fish) which are particularly susceptible to the effects of climate change in general and extremes in particular. Moreover, these populations have limited political voice and are less able to leverage government support to help curb the effects of climate change (Prato and Longo 2012; Hardoy & Pandiella, 2009). Rural poverty in the LAC region has declined considerably over the past two decades—both in terms of the numbers of people who live in poverty and the rate of poverty among rural populations—with many countries in the region showing positive trends both in poverty reduction and in a better distribution of income. That said, many rural people in the region continue to live on less than $2 per day and have poor access to financial services, markets, training, and other opportunities. There is a strong concentration of extreme poverty among landless farmers and indigenous peoples, particularly among women and children; indeed, close to 60 percent of the population in extreme poverty live in rural areas (RIMISP 2011).

Extreme events will also strongly impact the urban poor as urban areas are also a focal point of climate change impacts from extreme events (Vörösmarty et al. 2013). In 2010, the urban population accounted for 78.8 percent of the total population (ECLAC 2014). National economies, employment patterns, and government capacities—many of which are highly centralized—are also very dependent on large cities; this makes them extremely vulnerable to the effects of extreme events (Hardoy and Pandiella 2009).

Urbanization in the region includes unplanned, haphazard expansion of cities (ONU-Habitat 2012) over floodplains, mountain slopes, or areas prone to flooding or affected by seasonal storms, sea surges, and other weather-related risks (Hardoy and Pandiella 2009). Houses in informal settlements are frequently built with inadequate materials, which make them damp and cold in the winter and very hot in the summer (Hardoy and Pandiella 2009). Hence, there are concentrations of low-income households at high risk from extreme weather (Hardoy et al. 2001). For example, an estimated 1.1 million people live in the favelas of Rio de Janeiro that sprawl over the slopes of the Tijuca mountain range, making them particularly at risk from mudslides (Hardoy and Pandiella 2009).

Moreover, most low-income people live in housing without air conditioning or adequate insulation; during heat waves, the very young, pregnant women, the elderly, and people in poor health are particularly at risk (Bartlett 2008) (see also Section 3.4.7, Human Health). In northern Mexico, heat waves have been correlated with increases in mortality rates; in Buenos Aires, 10 percent of summer deaths are associated with heat strain; in Peru, records show a correlation between excessive heat and increases in the incidence of diarrhea (Mata and Nobre 2006). Such effects may be compounded by a climate-change-related increase in the broad geographic areas and microclimates in which certain vector-borne diseases, such as malaria and dengue fever, can flourish (Costello et al. 2009).

Adverse socioeconomic conditions in concert with exposure to climate change impacts undermine the development of adaptive capacity. People living in informal urban settlements without legal tenure rights—who are generally from poor and socially excluded communities (including marginalized ethnic groups)—in principle have limited means or incentive to attempt to climate-proof their houses (Moser et al. 2010). A lack of accountability to the citizens and a very limited scope for public participation in decision making means that poorer areas are deprioritised for infrastructural upgrading, and thus frequently have inadequate infrastructure (e.g., storm drains) to cope with extreme events (Hardoy and Pandiella 2009). Furthermore, the impacts of extreme weather events are often more severe in areas that have been previously affected or have not yet been fully recovered from previous a previous extreme event; these cumulative effects are difficult to overcome (Hardoy and Pandiella 2009; Hardoy and Romero Lankao 2011). Damage to housing as a result of extreme weather can lead to loss of key assets used in urban informal sector businesses (Moser et al. 2010), further undermining the buildup of resilience and increasing the risk of poverty traps.

## 3.5.2 Sub-regional Development Narratives

### *3.5.2.1 Central America and the Caribbean—Extreme Events as a Threat to Livelihoods*

In a 4°C world, the Central American and Caribbean countries are projected to be at risk from higher ENSO and tropical cyclone frequency, drought and heat extremes, and precipitation extremes (Table 3.15). The impacts of tropical cyclones will be exacerbated by rising sea levels fostering storm surges. Moreover, by the year 2040, Caribbean coral reefs are expected to experience annual bleaching events due to sea-level rise, ocean warming, and sedimentation from flood events, which will diminish the coastal protection provided by healthy coral reefs. Altogether these impacts may augment impacts on coastal infrastructure (including beach erosion), thus threatening transport, settlements, and tourism. In combination with an up to 50 percent decrease in fish catch potential under a 4°C world (Cheung et al. 2010), damage to coral reefs threatens artisanal fisheries that support local livelihoods.

Infrastructure in the Caribbean is already highly vulnerable to natural hazards, and important assets (including airports) are often low-lying. Further climate change impacts may affect the condition of infrastructure, increasing failures and maintenance costs. The high vulnerability to hurricanes and tropical storms in low-lying states could further increase with a growing population, putting growing numbers of assets at risk, exacerbating pervasive poverty/inequality and potentially leading to displacement of a greater proportion of the population, as was observed in the wake of Hurricane Mitch (Glantz and Jamieson 2000; McLeman and Hunter 2011). Ultimately, due to the small size of many Caribbean islands, more frequent natural disasters may cause severe setbacks to the overall economy. However, not only coastal areas are at high risk. In Central America and the Caribbean, the poor are often living on steep slopes or close to rivers; they are therefore especially exposed to landslides and floods. Such hydro-meteorological events may damage the poor quality (often informal) residential structures of vulnerable communities, which could in turn lead to higher mortality rates and population displacement. More generally, intensified non-climate stressors related to land use change and ecosystem degradation could impair the resilience and the ability to cope with the impacts of extreme hydro-meteorological events.

Climate extremes (e.g., drought, heat waves) in combination with long-term decreases in precipitation may reduce crop yields in Central America and Caribbean countries and affect food security and market prices. This is particularly relevant in the case of coffee crops, which are important for the livelihoods of workers and small farmers in Central America.

There are several studies projecting reduced runoff and groundwater recharge in a 4°C world (Table 3.15), which will reduce water availability. This may disproportionately affect the lives of women responsible for managing household water resources, as well as the health and wellbeing of vulnerable members of poor households (e.g., infants, the chronically ill, and the elderly). Ultimately, water stress could increase conflicts over land, affect food security, and provoke climate-induced migration. Additionally, Central America is heavily dependent on hydropower to generate electricity; it is expected that energy security could become an issue.

### *3.5.2.2 The Andes—Changing Water Resources Challenge the Rural and Urban Poor*

Climate change already affects and will further affect water resources in the Andes (Table 3.15). These resources are already scarce as a result of insufficient management and degradation of critical ecosystems (including the *páramo* and cloud forests). Increasing temperatures leading to higher evapotranspiration, changing precipitation patterns, and more extreme precipitation events all directly affect river runoff. Moreover, glacial melt and snow pack changes are important components of the regional hydrological balance. Increased glacial melt may increase water availability in the next few decades while reducing it thereafter. Both glacial melt and snowmelt affect the amount and seasonality of water flows. These changes threaten the water supply for hydropower, agriculture, and domestic use. This is particularly relevant because many large cities and populations are located at high altitudes or in arid regions in the lowlands where alternative sources of water are not abundant and where the urban poor are already suffering from limited access to water. Moreover, the regional energy mix strongly depends on hydropower; higher risks of power outages may impact household and community welfare. In addition, subsistence farming and cattle herding in the highlands, as well as large-scale agriculture in the coastal areas, depend on water coming from the mountains. While a decreasing water supply is an important risk to food security and poverty levels in general, women and children who are often in charge of agriculture in high-altitude communities are at particular risk of increasing poverty and water-scarcity-related conflicts. The same applies to indigenous people whose traditional water management systems are likely to be affected and whose livelihoods are already threatened. Other water-dependent activities, such as large-scale or artisanal mining, may be affected as well. These stresses could exacerbate the current urbanization trend, leading to further rural-urban migration and amplifying the risks to the urban poor.

Besides these more gradual changes, extreme hydrological events (such as an intensification of ENSO, extreme precipitation, high flows, and glacial lake outburst floods) increase the risk for natural disasters, erosion, and landslides. While such events may generally decrease GDP, the impact across different layers of the population is uneven, with the urban poor living on steep slopes typically at the highest risk.

#### *3.5.2.3 The Amazon—Risk of Tipping Point, Forest Degradation, and Biodiversity Loss Threatens Local Communities*

Despite an improved understanding of processes linking climate, vegetation, land-use change, and fire in the Amazon, the identification of the processes and the quantification of thresholds at which an irreversible approach toward a tipping point is triggered (i.e., a potential transition from forest to savannah) is still incomplete. Overall the most recent studies suggest that forest dieback is an unlikely, but possible, future for the Amazon region (Good et al. 2013). Should such die-back occur, the livelihoods of forest-dwelling and forest-fringe communities would be at particular risk, which could, in turn, spur additional migration of affected groups to cities, and could also open up forest regions to settlers, spurring additional deforestation.

Besides the risk of a tipping point, climate change is expected to contribute to forest degradation and biodiversity loss. There are variable rainfall patterns and significant differences in rainfall projections between the northern and southern zones of the Amazon. In a 4°C world, in the southern zone, winter annual precipitation is likely to decrease while evapotranspiration and aridity is expected to increase (see Section 3.3). This puts the southern part of the forest at increased fire risk.

Increasing fires will not only lead to large emissions of $CO_2$ but, in combination with deforestation, declining rainfall, and forest drying, may also draw the agricultural frontier northwards. This threatens the livelihoods of forest-dependent communities and could lead to land-use conflicts between existing communities and newly arriving farmers. In addition, timber harvest from concessions could be negatively affected. Moreover, increasing fires in the Amazon threaten rural and urban settlements and the resulting smoke/haze could aggravate respiratory disease for both forest dwellers and urban residents in central Brazil.

Negative effects of climate change on biodiversity resulting from habitat contractions and extinctions are very likely in a warmer than 2°C world. In combination with increasing forest degradation, changes in the range of certain species will affect resource availability for indigenous populations that are very reliant on native plants and animals. This could increase malnutrition among children and the elderly and undermine traditional knowledge of ecosystems, impacting the community social structure and the value placed on traditional knowledge. Altogether, these changes may push local communities to expand subsistence agriculture as an alternative livelihood strategy or to migrate to other forest areas, thereby amplifying forest degradation and threatening existing protected areas.

#### *3.5.2.4 Southern Cone—Risks to Export Commodities from Intensive Agriculture*

The Southern Cone countries are currently a major grain and livestock producing region for local and global markets (Chaherli and Nash 2013). The region has experienced significant climate shocks, mainly related to ENSO, which have resulted in floods or droughts at critical phases of the crop cycle. Moreover, despite small and uncertain increases in precipitation, the region faces increasing evapotranspiration rates under a 4°C world, (see Section 3.3). This highlights the high risks to agricultural production from climate change in a 4°C world; this is particularly true for rain-fed agriculture, which is prevalent in more than 98 percent of Brazil's agricultural area (FAOSTAT 2013; Oliveira et al. 2009).

The results of agricultural modeling studies differ in the severity of the climate change impact, but most agree that climate change will very likely decrease agricultural yields for important food crops in Latin America in the absence of adaptation measures and persistent $CO_2$ fertilization (ECLAC 2010; Fernandes et al. 2012; Nelson, Rosegrant, Koo et al. 2010) (see also Section 3.4.3, Climate Change Impacts on Agriculture). Moreover, while $CO_2$ fertilization may increases yields, there is some evidence of it decreasing protein contents in major grains (Müller et al. 2014; Myers et al. 2014). For sugarcane, there might be beneficial effects with yield increases (Table 3.15). Moreover, agro-ecozones in Brazil, including major grain belts, may move northward (to central Brazil) to already cleared lands in the Cerrado region; Assad et al. (2013) project displacement of poorly productive and degraded pasture with intensive multicrop grain cropping and intensified pastures.

The impacts on agriculture and livestock (Table 3.15) may lead to increasing food prices that could entail trade impacts and stresses on other regions' food production systems and may alter dietary patterns (especially of the poor). Alongside price risks, reduced nutrient contents (especially protein) could also raise the risk of malnutrition in children. Opportunities may arise from the reshuffling of agricultural zones as plantation forestry, horticultural crops, and biofuel production from sugarcane may be able to expand on lands that become unsuitable for grain crops. Reduced crop and livestock productivity can be moderated via adaptation measures and climate-smart technologies (e.g., improved varieties and breeds, irrigation, conservation agriculture, liming, and fertilizers to enhance crop rooting depth). These intensification and climate-smart innovations would, however, require a significant upgrading of knowledge and extensive field testing.

#### *3.5.2.5 Dry Regions (Mexican Dry Subtropics and North Eastern Brazil)—Increasing Drought Stress Threatening Rural Livelihoods and Health*

There has been significant development progress in these regions in recent decades, which has lifted a number of communities out of extreme poverty. The possibility of increasing droughts, however, threatens to force many of these populations back into extreme poverty.

The Central and Northern arid areas in Mexico and the semi-arid areas in Mexico and Northeast Brazil are already under water stress and are sensitive to inter-annual climate variability. For example, parts of northeast Brazil are situated within the so-called "drought polygon," an area characterized by a semi-arid climate that suffers from recurrent droughts (Krol and Bronstert 2007). Parts of this region in Brazil have been identified as having socio-climatic hotspots, given the naturally limited water availability, a relatively low human development index, a high population density (Torres and Lapola et al. 2012), and existing conflicts over water (Araújo and Knight 2005; Krol et al. 2006). Especially in a 4°C world, dry regions in Mexico and Brazil face strong increases in highly unusual heat extremes and aridity leading to more intense and longer drought events (Table 3.15). Northeast Brazil is particularly impacted by ENSO-related droughts; these may become more frequent in a 4°C world. In dryland Brazil, urban migration to rapidly growing coastal cities in the northeastern states is highly likely to be the result of the loss of agricultural income (Mendelsohn 2007).

In these dry regions, increasing drought events may lead to problems for urban water supply or widespread cattle deaths. In addition, small-hold family farmers in rural areas may experience lower productivity or even lose entire harvests, threatening their livelihoods. A decline in agricultural productivity may cause localized famines, especially among remote indigenous communities (particularly in Northern Mexico), and possibly result in long-term impacts on the household nutritional status.

Increases in irrigated agriculture, if not well integrated with long-term water resource planning and management, pose another risk as they will exacerbate issues of water availability and also concentrate wealth. A diminished drinking water supply in rural communities may also lead to an increasing reliance on water trucks that occasionally deliver contaminated water (resulting in illness and death). Moreover, the need to search for drinking water and the associated health problems associated with low-quality drinking water could decrease the work force and income in rural areas, leading to increased crime, social exclusion, and other problems related to rural-urban migration during drought events. Increasing water stress may also lead to further over-exploitation of aquifers in the Northern part of Mexico. This in turn would lead to the release of groundwater minerals, affecting groundwater quality, and, in coastal aquifers, lead to sea water intrusion. In general, hydropower and energy systems will be stressed across these dry regions. Direct damages from droughts and secondary impacts on the agriculture sector and related labor markets may result in negative GDP growth rates in the agriculture sector.

## 3.6 Synthesis Table—Latin America and the Caribbean

**Table 3.15:** Synthesis table of climate change impacts in LAC under different warming levels.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Heat Extremes** | **Highly Unusual Heat Extremes** | Absent | Around 10% of land area affected in DJF | Up to 30% of land area affected in DJF | 30–40% of land area affected in DJF | Around 65% of land area affected in DJF | Around 90% of land area affected in DJF |
| | **Unprecedented Heat Extremes** | Absent | Absent | Around 5% of land area affected in DJF | Around 15% of land area affected in DJF | Around 40% of land area affected in DJF | Around 70% of land area affected in DJF |
| **Regional Warming (austral summer temperatures)** | | | 0.8°C | | 1.5°C, warming limited along the Atlantic coast of Brazil, Uruguay, and Argentina with about 0.5–1.5°C. The central South-American region of Paraguay, northern Argentina, and southern Bolivia with more pronounced warming, up to 2.5°C* | | 5.5°C, warming limited along the Atlantic coast of Brazil, Uruguay, and Argentina with about 2–4°C. The central South-American region of Paraguay, northern Argentina, and southern Bolivia with more pronounced warming, up to 6°C* |
| **Precipitation** | | | | | Relatively small changes and disagreement among climate models. Peru, Ecuador, and Colombia on the Pacific coast with a small increase in annual mean precipitation of up to 10%. Reduction in winter precipitation over southeastern Amazon rainforest* | | Peru, Ecuador, and Colombia on the Pacific coast increase in annual mean precipitation of about 30%, most pronounced during the summer. The Caribbean, Patagonia (southern Argentina and Chile), Mexico, and central Brazil become drier (10–40%). Central America becomes drier in winter (up to 60%). The annual mean precipitation in southeastern Amazon rainforest is projected to drop by 20% mostly because of a strong decrease in winter precipitation (–50%)* |

**Table 3.15:** Continued.

| RISK/IMPACT | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|
| **Extreme Precipitation** | Robust increase in intensity of extreme precipitation events for South America[2] | | Annual extreme daily precipitation with 20–year return interval increases by 7% and the 20–year return value of maximum precipitation returns every 15 years*[3]<br>5%, 7%, and 3% increase in maximum 5–day precipitation in the Amazon, Central America, and Southern South America respectively*[4] | | Annual extreme daily precipitation with 20–year return interval increases by 11% and the 20–year return value of maximum precipitation returns every 12 years*[3]<br>9%, 7%, and 8% increase in maximum 5–day precipitation in the Amazon, Central America, and Southern South America respectively*[4] | Annual extreme daily precipitation with 20–year return interval increases by 25% and the 20–year return value of maximum precipitation returns every 6.5 years. Important areas are the Caribbean, Meso-America, Southern Argentina, and Chile as well as parts of Brazil and the Pacific coastline of Ecuador, Peru, and Colombia*[3]<br>16%, 8%, and 12% increase in maximum 5-day precipitation in the Amazon, Central America, and Southern South America respectively*[4] |
| **Drought** | Severe droughts in 2005 and 2010 in the Amazon[5]<br>Increase in drought conditions in Central America[6] | | 4-, 1- and 2-days longer droughts in the Amazon, Central America and Caribbean, and Southern South America respectively*[4] | 1%, 4% and 9% increase in days under drought conditions in Caribbean, Meso-America, and South America respectively*[7] | 8-, 2- and 2-days longer droughts in the Amazon, Central America and Caribbean, and Southern South America respectively*[4]<br>11.5%, 12%, and 12.5% increase in days under drought conditions in Caribbean, Meso-America, and South America respectively*[7]<br>Reduction by 5 to 9% in annual soil moisture content in Amazon and Central America*[8]<br>Increase in extreme droughts in the Amazon, Brazil, Central America, northern Mexico, and Southern Chile*[8] | 17-, 10- and 8-days longer droughts in the Amazon, Central America, and Caribbean and Southern South America respectively*[4]<br>22%, 25%, and 22% increase in days under drought conditions in Caribbean, Meso-America, and South America respectively*[7] |

| RISK/IMPACT | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|
| **Aridity** | 33% of land area hyper-arid, arid, or semi-arid | | | 36% of land area hyper-arid, arid, or semi-arid (increase of about 10%)* | | 41% of land area hyper-arid, arid, or semi-arid (increase of about 25%)* |
| **Sea-level Rise Above Present (1985–2005)** | | | Median estimate across the region 0.27–0.39 m, with highest sea-level rise on the Atlantic Coast and lowest on the tip of the American continent. Maximum 0.65 m sea-level rise in Recife* | | | Median estimate across the region 0.46–0.66 m, with highest sea-level rise on the Atlantic Coast and lowest on the tip of the American continent. Maximum 1.14 m sea-level-rise and 1.4 m in Rio de Janeiro and Barranquilla on the Atlantic Coast by 2100* |
| **El Niño Southern Oscillation (ENSO)** | ENSO has never been as variable as during the last few decades[9] | | | | | Doubling of frequency of extreme El Niño events*[10] |
| **Tropical Cyclones** | Tropical cyclone frequency increase in the North Atlantic[11] | | | Power Dissipation Index increasing by 100–150%*[12]<br>Increase of 40% in the frequency of the strongest Atlantic Tropical Cyclones*[13] | | Power Dissipation Index increasing by 125–275%*[12]<br>Increase of 80% in the frequency of the strongest category 4 and 5 Atlantic Tropical Cyclones*[14] |
| **Glaciers** – **Southern Andes** | Up to 22% loss of glacial volume[15,16]<br>Reduction in glacier length by 3.6–36% (Northern Patagonian Ice Field), 0.4–27% (Southern Patagonian Ice Field), and 2.5–38% (Cordillera Darwin Ice Field)[17]<br>31.7% loss of glacial area[15]<br>23–26.6 Gt/yr glacial mass loss rate over Patagonian Ice Fields[18]<br>1.88 Gt/yr annual calving loss in Northern Patagonian Ice Field[19] | | | 21–52% loss of glacial volume*[15] | 27–59% loss of glacial volume*[15, 16, 20] | 44–72% loss of glacier volume*[15, 20] |

**Table 3.15:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| | **Tropical Glaciers** | Up to 90% loss of glacial volume[15, 16]<br>79% loss of glacial area[15], 87% in Andes of Venezuela over 1952–2003, 11% in Andes of Colombia over 1950–1990s, 57% in Chimborazo over 1962–1997, 37% in Cotopaxi and 33% in Artinsana over 1979–2007, and 20–35% in Peruvian Andes over 1960–2000s[21]<br>6 Gt/yr glacial mass loss rates[22] | | | 78–94% loss of glacial volume*[15] | 66–97% loss of glacial volume*[15, 16, 20] | 91–100% loss of glacier volume*[15, 20] |
| **Water** | **Central America & Caribbean** | Up to 10% less runoff[23] | | | 13% decrease in total annual reservoir inflow in Rio Lempa*[24]<br>Around up to 15–45% reduction of annual discharge[39] | 10–30% decrease of mean annual runoff*[25]<br>5–20% decrease in river runoff[23]<br>20% decrease in discharge from Rio Grande*[26] | 24% decrease in total annual reservoir inflow in Rio Lempa*24<br>10% in groundwater recharge*[27]<br>15–45% reduction of annual discharge[39] |
| | **Andes** | Discharge in Cordillera Blanca decreasing annually and during the dry season[28] | Decreasing mean annual runoff for northeastern Chile[29] | | Wet season discharge in the Llanganuco catchment increases from 10–26% and dry season discharge decreases from 11–23%[30]<br>Reduced groundwater recharge for the central Andes region[31] | Wet season discharge in the Llanganuco catchment increases from 10–26% and dry season discharge decreases from 11–23%[30] | 21% streamflow decrease In the Limarí basin and increasing winter flows (28.8–108.4%), decreasing summer flows (–16.5 to –57.8%), and earlier center timing of mass of annual flows for different sub-basins of the Limarí basin[32]<br>Likely increase in flood frequency[33] |

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Water** | **Amazon** | Decreasing mean annual discharge and monthly minimum discharge for Tapajós in the southeastern Amazon, the Peruvian Amazon Rivers, and the upstream Madeira[34] | | | Low-flows become more pronounced over several Amazonian sub-basins[35]<br>Median high-flows increase by 5–25% in the western part of the Amazon basin[35]<br>Median low-flows decrease significantly, by 20% for the Japura and Negro river and 55% at the Río Branco[35] | Total annual runoff decreases in the southern half of the Amazon River[36]<br>Duration of inundation 0.5–1 month shorter in eastern Amazonia*[37]<br>Inundation area will increase with a 2–3 month longer inundation time in the western part of the Amazon basin*[37] | Low flows increase between 10–30% in the western part of the Amazon[35]<br>Low flows and high flows would increase each by 5% at Óbidos[35] |
| | **Northeast Brazil** | | | | Seasonality of river discharge remains stable but mean river discharge decreases[38]<br>No clear signal in relative change of annual discharge[39] | | Strong decreases and increases in mean groundwater discharge depending on the GCM[27] |
| | **Rio de la Plata** | Increase in river runoff of 10–30%[40] | | | Mean river flow from –20% to +18% for the Río Grande, a tributary of the Paraná[41] | Increase in mean relative runoff for the Rio de la Plata region of 20–50%[23] | Increase in frequency and duration of fluvial floods in the Uruguay and Paraná basin[42]<br>Decrease in the 20th century 100–year return period for floods for the Parana[43] |
| | **Southernmost South America** | Decrease in mean relative runoff up to 10%[23] | | | | Decrease in mean relative runoff by 10–30%[23, 39] | 15–45% reduction of annual discharge[39] |
| **Crop yield** | **Wheat** | | | Brazil: –23%[44]<br>Central America and Caribbean: –43%[44] | Brazil: up to –50%[44]<br>Central America and Caribbean: –56%[44]<br>LAC: 6.5–12%[45] and 0.3–2.3%[46] | Brazil: –41% to –52%[44]<br>Central America and Caribbean: –58% to –67%[44]<br>LAC: 0.9–12%[45] and –5.5 to 4%[46]<br>Chile*: up to –10%[45,47]<br>Argentina: –11%[48] | Argentina: –16%[48] |

**Table 3.15:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Crop yield** | **Maize** | | Panama: up to –0.5%[45,49] | México: –29%[44]<br>Panamá: 0.8%[45,49] | Ecuador and Brazil up to –64%[44]<br>México: up to –45%[44]<br>Panama: 1.5–2.4%[45,49]<br>LAC: –2.3 to +2.2%[45] and –0.4 to –2.8%[46]<br>Brazil: –15 to –30%[50] | Brazil: –30 to –45%[50]<br>Panama: 4.5%[45,49] | Argentina: –24%[48]<br>Ecuador: –54%[48] |
| | **Soybean** | | | Brazil: –45%[44] | Brazil: up to –70%[44]<br>Brazilian Amazon: –1.8%[45,51]<br>LAC: 19.1–19.5%[45] and –1.2 to 2.3%[46] | Brazil: –66% to –80%[44]<br>LAC: 18–19%[45] and –2.5 to 4%[46]<br>Argentina: –14%[48] | Argentina: –25%[48]<br>Brazilian Amazon: –44%[51] |
| | **Rice** | | | Central America and Caribbean: +3%[44] | Central America and Caribbean: –4%[44]<br>LAC: –1.2 to +13%[45] and –6.4 to 5%[46] | Central America and Caribbean: +1.5–4%[44]<br>LAC: 6.7–7[45] and –0.8 to –1.8%[46] | Ecuador: 37%[48] |
| | **Beans** | | | | Brazil: –15 to –30%[50] | Brazil: –30 to –45%[50] | Ecuador: –9%[48] |
| | **Coffee** | | | | | | Ecuador: –23%[48] |
| | **Cocoa** | | | | | | Ecuador: –21%[48] |
| | **Bananas** | | | | | | Ecuador: –41%[48] |
| | **Sugarcane** | | | Southern Brazil: 15%[45,52] | Southern Brazil: 59%[45,52] | | Ecuador: –36%[48] |
| **Livestock** | | | Livestock choice in Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay, and Venezuela:<br>Beef Cattle: –12.5 to 5.7%<br>Dairy cattle: –6.6 to 1.2%<br>Pigs: –1.6 to 0.2%<br>Sheep: –5 to 20.1%<br>Chicken: –2.9 to 1.4%[53] | Livestock choice in Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay, and Venezuela:<br>Beef Cattle: –1.6 to 5%<br>Dairy cattle: –6.7 to 2.5%<br>Pigs: –0.8 to 0.0%<br>Sheep: 0.0 to 7.0%<br>Chicken: –1.0 to 1.3%[53] | 7 to 16% decrease in beef cattle numbers in Paraguay[48]<br>Livestock choice in Argentina, Brazil, Chile, Colombia, Ecuador, Uruguay, and Venezuela:<br>Beef Cattle: –11.0 to 0.3%<br>Dairy cattle: –10 to 5%<br>Pigs: –0.9 to 0.1%<br>Sheep: 0.0 to 19%<br>Chicken: –1.5 to –0.3%[53] | 22 to 27% decrease in beef cattle numbers in Paraguay[48] | |

| RISK/IMPACT | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|
| **Biodiversity** | | | Extinction rates of species: 2–5% for mammals, 2–4% for birds, 1–7% for butterfly species in Mexico, and 38–66% for plant species in Cerrado[54] | Extinction rates of species: 2–8% for mammal, 3–5% for birds, 3–7% for butterfly species in Mexico, and 48–75% of plant species in Cerrado[54]<br>Changes in amphibian species ranges in the Atlantic Forest Biodiversity Hotspot[55]<br>Marsupial species ranges declining in Brazil[56]<br>85–95% of LAC amphibian species face net loss in range size*[57]<br>1 out of 26 biogeographic ecoregions in South America faces severe ecosystem change*[58]<br>Climatically suitable areas for cloud forest reduced by 54–76%[59]<br>44 of 51 birds species lose distribution area in Brazilian Atlantic forest[60]<br>Loss of habitat between 8.2% to 81.5% and change in species richness between –4.1% to –89.8% for plants in Amazon[61]<br>Majority of 430 amphibian species would face range contractions accompanied by an overall species loss in the Atlantic Forest Biodiversity Hotspot[62] | 68% loss of suitable area for cloud forest and extinction of 9 of 37 vertebrate species in Mexico[63]<br>78% reduction in geographic distribution of 110 Brazilian Cerrado plant species[64] | In most LAC ecoregions, amphibian species experience at least 30% turnover; in western South America and Central America at least 50%*[57]<br>Up to 21 out of 26 biogeographic ecoregions in South America faces severe ecosystem change*[58]<br>Loss of habitat between 11.6% to 98.7% and change in species richness between –25% to –100% for plants in Amazon[61] |

**Table 3.15:** Continued.

| RISK/IMPACT | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|
| **Amazon Dieback** | | | | Model agreement on above-ground live biomass loss: 14.3% for climate change only but increasing to 43.1–58.6% with different deforestation scenarios[65] | Carbon loss (kg C/m$^2$) by −1.8 to −0.6 in Eastern Amazonia, −1.2 to 0.6 in Northwestern Amazonia and −3.3 to −2.6 in Southern Amazonia*[66]<br>Carbon increase (kg C m$^2$) by 5.5–6.4 in Eastern Amazonia, 2.9–5.5 in Northwestern Amazonia and 2.1–4.3 in Southern Amazonia*[45,56]<br>Decrease of LAI by 12.6% and increase in land-atmosphere carbon flux of about 27.2% due to fire*[67] | 10–80% forest cover loss*[68]<br>–35% to +40% change of carbon without deforestation and –55% to –5% with 50% deforestation*[69]<br>10–80% forest cover loss*[70]<br>Carbon losses: [70] GtC (Vegetation carbon), 150 GtC (Soil carbon)*[71]<br>69% reduction in rainforest extent*[72]<br>Model agreement on above-ground live biomass loss: 25.5% for climate change only but increasing to 48.1–65.9% with different deforestation scenarios[65] |
| **Coral Reefs** | Strong bleaching event in 2005, less severe in 2010, in the Caribbean Sea, Guyana, Suriname, French Guiana, and north Pacific Ocean[73] | | 20–40% and up to 60% probability of annual bleaching events in Caribbean Sea and Guyana, Suriname, French Guiana, and north Pacific Ocean respectively[73]<br>Coral cover halved from initial state in Virgin Islands and Eastern Caribbean[74]<br>Onset of bleaching events starts 2046*[75] | <60% and >60% probability of annual bleaching events in Caribbean Sea and Guyana, Suriname, and French Guiana respectively[73]<br>60–80% and up to 100% probability of annual bleaching events in Caribbean Sea and Guyana, Suriname, and French Guiana respectively*[73]<br>Coral cover less than 3–5% in Virgin Islands and Eastern Caribbean[74]<br>Onset of bleaching events starts 2040*[75] | | >60% probability of annual bleaching events in all regions*[73] |

| RISK/IMPACT | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|
| **Marine Fisheries** | Species shifts toward higher latitudes[76] | | 35% decline in phytoplankton, zooplankton, and fish density[77] | Large increase in catch potential in the south (up to 100%), strong decrease in parts of the Caribbean Sea (up to 50%)[76] | | |
| **Health** | | | 5–13% increase in relative risk of diarrheal diseases in South America[78]<br>12–22% increase in Dengue incidence in Mexico[79] | Expansion of malarial areas mostly in Brazil[80]<br>No net changes in increased malaria length of transmission season except in southernmost Brazil and Uruguay*[81]<br>31–33% increase in Dengue incidence in Mexico[79] | 12–49 million people less exposed to risk of malaria for at least three months of the year*[82]<br>1–16 million people more exposed to risk of malaria for at least one month of the year*[82]<br>Increased malaria length of transmission season in southern Brazil, Uruguay, and parts of Mexico*[81]<br>Decreased malaria length of transmission season in parts of the Amazon basin in Brazil, Bolivia, and Paraguay*[81]<br>14–36% increase in relative risk of diarrheal diseases in South America*[78]<br>40% increase in Dengue fever incidence in Mexico*[79] | 19–169 million people less exposed to risk of malaria for at least three months of the year*[82]<br>5–42 million people less exposed to risk of malaria for at least one month of the year*[82]<br>Increased malaria length of transmission season in some highland areas of southern Brazil, Uruguay, Argentina, Bolivia, Peru, Ecuador, Colombia, and Mexico*[81]<br>Decreased malaria length of transmission season for tropical Latin America*[81] |

**Table 3.15:** Continued.

| RISK/IMPACT | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s[1]) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|
| **Energy** | 683,421 GWh/yr maximum hydropower energy potential in La Plata River Basin[83]<br>Energy demand for 1,802 cooling degree days in South America [84] | | | 688,452–861,214 GWh/yr maximum hydropower energy potential in La Plata River Basin[83]<br>0,63TWH (or 0.05%) and 0,3TWH (or 0.03%) increase in electricity production in South America and in the Caribbean respectively[85]<br>Decrease in hydropower capacity for the two main large reservoirs used for hydroelectricity generation in El Salvador: Cerron Grande and 15 Setiembre[*24] | 715,173–838,587 GWh/yr maximum hydropower energy potential in La Plata River Basin[83]<br>Decrease in hydropower capacity for the two main large reservoirs used for hydroelectricity generation in El Salvador: Cerron Grande and 15 Setiembre[*24]<br>Decrease in firm power by 3,15%[*86] | Decrease in firm power by 1.58%[*86]<br>Energy demand for 2,679 cooling degree days in South America[84] |

The impacts reported in several impact studies were classified into different warming levels (see Appendix for details)

## Endnotes

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) (and 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). Exceedance with a likely chance (>66 percent) generally occurs in the second half of the decade cited. Impacts are given for warming levels irrespective of the timeframe (i.e., if a study gives impacts for 2°C warming in 2100 then the impact is given in the 2°C column). If a study refers to a warming level by the end of the century, this is marked with an asterisk (*). Impacts given in the observations column do not necessarily form the baseline for future impacts. Impacts for different warming levels may originate from different studies and therefore may be based on different underlying assumptions; this means that the impacts are not always fully comparable (e.g., crop yields may decrease more under a 3°C than a 4°C scenario because underlying the impact at 3° warming is a study that features very strong precipitation decreases). Moreover, this report did not systematically review observed impacts. It highlights important observed impacts for current warming but does not conduct any formal process to attribute impacts to climate change.
2 Skansi et al. (2013).
3 Kharin et al. (2013); 20–year return value of maximum precipitation refers to 1986–2005.
4 Sillmann et al. (2013b).
5 Marengo et al. (2011); Zeng et al. (2008).
6 Dai (2012).
7 Prudhomme et al, (2013) increase in days under drought conditions refers to 1976–2005.
8 Dai (2012).
9 Li et al. (2013). This is a tree-ring-based reconstruction of ENSO strength over the last 700 years, but attribution to climate change is uncertain.
10 Cai et al. (2014).
11 IPCC AR5 WGI (2013). Frequency increase in the North Atlantic over the past 20–30 years.
12 Villarini et al. (2013). The Power Dissipation Index is a combination of frequency and intensity.
13 Knutson et al. (2013).
14 Bender et al. (2010); Knutson et al. (2013).
15 Marzeion et al. (2012). Past period for glacial volume loss and area loss refers to 1901–2000.
16 Giesen and Oerlemans (2013). For past: 6.1 percent (southern) and 7.3 percent (tropical) loss of glacial volume over 1980–2011 compared to 1980.
17 Lopez et al. (2010).
18 Ivins et al. (2011); Jacob et al. (2012) refers to 2000s.
19 Schaefer et al. (2013) refers to 1990–2011.
20 Radic et al. (2013).
21 Rabatel et al. (2013). Andes of Venezuela over 1952–2003; Andes of Colombia over 1950–1990s; Chimborazo over 1962–1997; in Cotopaxi and in Artinsana over 1979–2007; and Peruvian Andes over 1960–2000s.
22 Jacob et al. (2012) for past refer to 2000s.
23 Milly et al. (2005).
24 Maurer et al. (2009).
25 Hidalgo et al. (2013).
26 Nakaegawa et al. (2013).
27 Portmann et al. (2013).
28 Baraer et al. (2012).
29 Arnell and Gosling (2013).
30 Juen et al. (2007). No differentiation possible for changes in warming for >1.5°C in 2050 and >2°C in 2080.
31 Döll (2009).
32 Vicuña et al. (2010).
33 Hirabayashi et al. 2013).
34 Espinoza Villar et al. (2009).
35 Guimberteau et al. (2013).
36 Nakaegawa et al. (2013).
37 Langerwisch et al.(2013).
38 Döll and Schmied (2012).
39 Schewe et al. (2013).
40 García and Vargas (1998); Jaime and Menéndez (2002); Menéndez and Berbery (2005); Milly et al. (2005).
41 Nóbrega et al. (2011).
42 Camilloni et al. (2013).
43 Hirabayashi et al. (2013). There was little consistency across the 11 GCMs used.
44 Fernandes et al. (2012).
45 With $CO_2$ fertilization.
46 Nelson, Rosegrant, Koo et al. (2010).
47 Meza and Silva (2009).
48 ECLAC (2010).
49 Ruane et al. (2013).
50 Costa et al. (2009), including technological progress.
51 Lapola et al. (2011).
52 Marin et al. (2012), including technological progress.
53 Seo et al. (2010).

[54] Thomas et al. (2004). Mammal species (n = 96), bird species (n = 186), and butterfly species (n = 41) in Mexico all with dispersal; plant species in Cerrado (n = 163) without dispersal. The study was criticized by Harte et al. (2004) for overestimating potential extinction rates by using a common species-area exponent z for all species which may not be justified.
[55] Loyola et al. (2013).
[56] Loyola et al. (2012).
[57] Lawler et al. (2009).
[58] Gerten et al. (2013).
[59] Rojas-Soto et al. (2012).
[60] Souza et al. (2011).
[61] Feeley et al. (2012). Large range stems from different assumption about deforestation, land-use, and adaptation and migration potentials.
[62] Lemes et al. (2014).
[63] Ponce-Reyes et al. (2012).
[64] Simon et al. (2013).
[65] Poulter et al. (2010).
[66] Rammig et al. (2010).
[67] Cook et al. (2012).
[68] Zelazowski et al. (2011).
[69] Gumpenberger et al. (2010).
[70] Cox et al. (2004).
[71] Betts et al. (2004).
[72] Cook and Vizy (2008).
[73] Meissner et al. (2012).
[74] Buddemeier et al. (2011).
[75] Van Hooidonk et al. (2013).
[76] Cheung et al. (2010).
[77] Blanchard et al. (2012).
[78] Kolstad and Johansson (2011), compared to 1961–1990 levels.
[79] Colon-Gonzalez et al. (2013), compared to 2000.
[80] Beguin et al. (2011).
[81] Caminade et al. (2014).
[82] Van Lieshout et al. (2004).
[83] Popescu et al. (2014).
[84] Isaac and van Vuuren (2009).
[85] Hamududu and Killingtveit (2013), compared to 2005 levels.
[86] De Lucena et al. (2009), compared to 1971–2000.

# Chapter 4

# Middle East and North Africa

The Middle East and North Africa region is one of the most diverse in the world in economic terms, with per-capita annual GDP ranging from $1,000 in Yemen to more than $20,000 in the Arab Gulf States. As a consequence, adaptive capacity and vulnerability to climate risks varies enormously within the region. The region will be severely affected at both 2°C and 4°C warming, particularly because of the large increase in projected heat extremes, the substantial reduction in water availability and expected consequences for regional food security. In some countries, crop yields could decrease by up to 30 percent at 1.5–2°C and by almost 60 percent at 3–4°C in parts of the region. Deteriorating rural livelihoods may contribute to internal and international migration, adding further stresses on particularly urban infrastructure with associated health risks for poor migrants. Migration and climate-related pressure on resources might increase the risk of conflict.

## 4.1 Regional Summary

The population in Middle East and North Africa is projected to double by 2050, which together with projected climate impacts, puts the region under enormous pressure for water and other resources. The region is already highly dependent on food imports. Approximately 50 percent of regional wheat and barley consumption, 40 percent of rice consumption, and nearly 70 percent of maize consumption is met through imports. The region has coped with its inherent water scarcity through a variety of means: abstraction of groundwater, desalinization, and local community coping strategies. Despite its extreme water scarcity, the Gulf countries use more water per capita than the global average, with Arab residential water and energy markets among the most heavily subsidized in the world. The region is very diverse in terms of socio-economic and political conditions. Thus, adaptive capacity and vulnerability to climate risks varies enormously, especially between the Arab Gulf States and the other countries in the region.

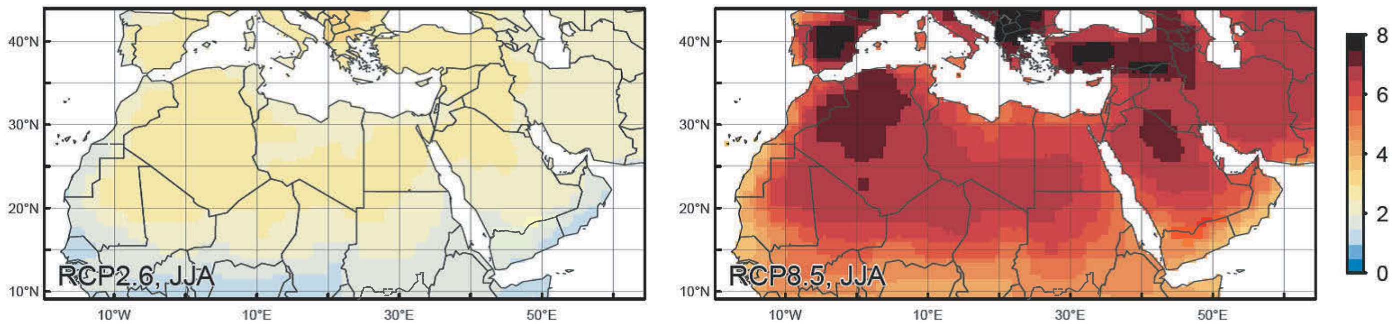
Middle East and Northern Africa heavily relies on agriculture as a source of food and income, not only in the historically important "fertile crescent" of the Euphrates and Tigris region, but also at the Mediterranean coast and the Nile, while at the same time being largely covered by drylands and deserts. Seventy percent of the region's agricultural production is currently rain-fed, which leaves the region highly vulnerable to temperature and precipitation changes, and the associated implications for food security, social security, and rural livelihoods. This, in combination with social changes and strong urbanization rates, indicates a very vulnerable future for the Middle East and North Africa, particularly for the urban and rural poor. All countries in the region face a severe and fast growing resource squeeze, especially relating to severe water and land scarcity. The region is very diverse in terms of socio-economic and political conditions. Thus, adaptive capacity and vulnerability to climate risks varies enormously, especially between the Arab Gulf States and the other countries.

### 4.1.1 Regional Patterns of Climate Change

#### *4.1.1.1 Temperatures and Heat Extremes*

Warming of about 0.2° per decade has been observed in the region from 1961–1990, and at even faster rate since then, which in line with an increase in frequency in temperature extremes. Geographically, the strongest warming is projected to take place close to the Mediterranean coast. Here, but also in inland Algeria, Libya and large parts of Egypt, warming by 3°C in a 2°C world is projected by the end of the century. In a 4°C world, mean

**Figure 4.1:** Multi-model mean temperature anomaly for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the months of June-July-August for the Middle East and North African region.




Temperature anomalies in degrees Celsius are averaged over the time period 2071–2099 relative to 1951–1980.

summer temperatures are expected to be up to 8°C warmer in parts of Algeria, Saudi Arabia and Iraq by the end of the century (see Figure 4.1).

By the end of the century, in a 2°C world, *highly unusual*[38] heat extremes will occur in about 30 percent of summer months almost everywhere in the MENA region. This implies that on average one of the summer months each year will exceed temperatures warmer than three standard deviations beyond the baseline average. *Unprecedented* heat extremes, however, will remain largely absent in a 2°C world, except for in some isolated coastal regions including the Mediterranean coasts of Egypt, and in Yemen, Djibouti and Oman. Here these events are projected to be relatively rare in a 2°C world, but are nevertheless expected to occur in 5–10 percent of summer months.

Whereas the increase in frequency of heat extremes is expected to level off by mid-century in a 2°C world, in a 4°C world it will continue increasing until the end of the century. in a 4°C world, 80 percent of summer months are projected to be hotter than 5-sigma (*unprecedented* heat extremes) by 2100, and about 65 percent are projected to be hotter than 5-sigma during the 2071–2099 period.

#### 4.1.1.2 Precipitation and Aridity

Future northward shifts of air moisture associated with a stronger North Atlantic Oscillation (NAO) anomaly are projected to reduce rainfall in North Africa, Maghreb, and Mashrek. In a 4°C world, countries along the Mediterranean shore, notably Morocco, Algeria, and Egypt, are projected to receive substantially less rain. However, a projected northward shift of the Inter-Tropical Convergence Zone (ITCZ) is expected to increase moisture delivery to the southern parts of the region (which are already under the influence of monsoon systems), in particular to the southern Arabian Peninsula (Yemen, Oman). Consequently, projected annual mean precipitation changes show a clear North-South dipole pattern, with regions north of 25°N becoming relatively drier and regions to the south becoming wetter. The absolute increase in precipitation in the southern regions, however, will be very small, because these regions (with the exception of Yemen) are already very dry today. Furthermore, the effect of an increase in precipitation on water availability should be counteracted by a simultaneous increase in temperature, resulting in a higher rate of evaporation. Lastly, an increase in precipitation in the southern part of the region may be associated with more intense and extreme precipitation events.

There is a close match between the pattern of change in the annual mean aridity index (AI) and projected precipitation changes. Changes in the aridity are primarily driven by changes in precipitation, with wetter conditions south of 25°N and in most southern parts of the Arabian Peninsula causing a drop in aridity, and drier conditions north of 25°N causing aridity there to increase. In the Mediterranean coastal region, the relative increase in aridity is more pronounced than would be expected from the drop in precipitation, because there is a substantial increase in evapotranspiration here due to enhanced warming.

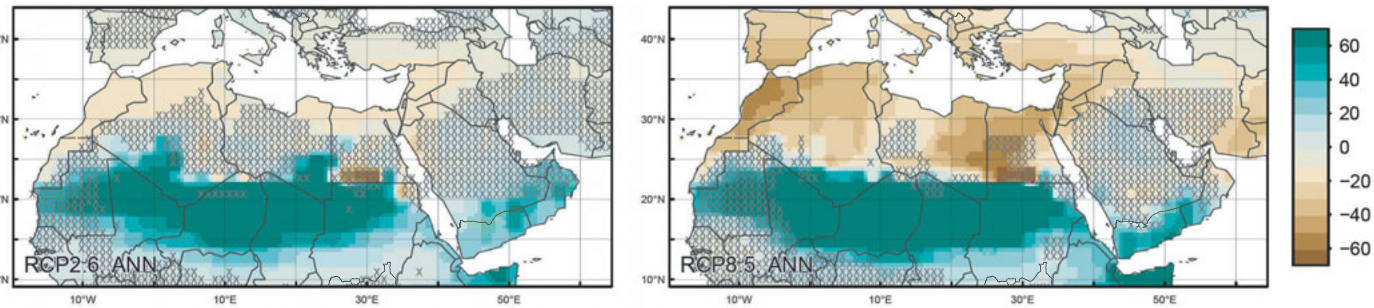
### 4.1.2 Regional Sea-Level Rise

In the Mediterranean area, tide gauges recorded below-average sea-level rise during the 20th century, with average rise of 1.1–1.3 mm per year (slower than the global average of 1.8 mm per year). There has been significant interdecadal variability, however, with a slow gradual rise from 1960–1990, and rapid (above-average) rise after 1990.

Analysis for the 21st century indicates slightly below-average rise in the Mediterranean basin mostly as a result of the gravitational

[38] In this report, *highly unusual* heat extremes refer to 3-sigma events and *unprecedented* heat extremes to 5-sigma events (see Appendix).

**Figure 4.2:** Multi-model mean of the percentage change in the aridity index in a 2°C world (left) and a 4°C world (right) for the Middle East and North Africa by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that a *negative* change corresponds to a shift to *more arid* conditions (see Appendix).[39]

influence of Greenland ice sheet. Tunis, on the Mediterranean Sea coast, is projected to experience a median sea-level rise of 0.56 m (with a maximum of 0.96 m) by the end of the century in a 4°C world. This is 8 cm less than in Muscat, on the Arabian Sea coast, where a median 0.64 m (low estimate: 0.44 m, high estimate: 1.04 m) sea-level rise is projected. On the Atlantic coast, a 0.58 m sea-level rise is projected for Tangier (low estimate: 0.39 m, high estimate: 0.98 m). In a 1.5°C world, median sea level rises of 0.34 m, 0.35 m and 0.39 m are projected for Tunis, Tangier, and Muscat.

## 4.1.3 Sector-based and Thematic Impacts

### *4.1.3.1 The Agriculture-Water-Food Security Nexus*

The Middle East and North Africa region is water scarce, with most of the land area receiving less than 300 mm of annual rainfall (200–300 mm represents the lower limit of rain-fed agriculture). Semi-arid belts along the coasts and mountains are the only water source areas and provide productive land for rain-fed agriculture. The annual availability of renewable water resources in most countries is below 1000 $m^3$ per capita (except for Iraq, Oman, Syria and Lebanon) and as low as 50 $m^3$ per capita for Kuwait. This water scarcity prevents countries from producing all required food domestically and makes the region dependent on food imports. From the current situation of critical water and arable land scarcity, both the 2°C and 4°C warming scenarios would put further pressure on water resources and agriculture.

- **Cropland:** Warmer and drier climate is projected to shift vegetation and agricultural zones northward (e.g., by 75 km for 2090–2099 relative to 2000–2009 in a 4°C world).
- **Length of growing period:** Lower rainfalls and higher temperatures will shorten growing periods for wheat in large parts of the region by about two weeks by mid-century (2031–2050). The wheat growing period in Tunisia is expected to be shortened by 10 days for 1.3°C warming, by 16 days for 2°C, by 20 days for 2.5°C and by 30 days for 4°C warming.
- **Crop yields:** Crop yields are expected to decline by 30 percent with 1.5–2°C warming and up to 60 percent with 3–4°C warming, with regional variation and without considering adaptation. Reductions in crop productivity of 1.5–24 percent are expected for the western Maghreb and 4–30 percent in parts of the Mashrek, by mid-century. Legumes and maize crops are expected to be worst affected in both areas as they are grown during the summer period.
- **Livestock:** Climate change will impact livestock production through various pathways, including changes in the quantity and quality of available feeds, changes in the length of the grazing season, additional heat stress, reduced drinking water, and changes in livestock diseases and disease vectors.

Uncertainty in projections arises from different approaches, different climate models, and the persistence of $CO_2$-effects because increasing atmospheric $CO_2$ concentration can potentially increase plant water-use efficiency (and thus crop productivity).

[39] Some individual grid cells have noticeably different values than their direct neighbors (e.g., on Turkey's Black Sea coast under RCP8.5). This is due to the fact that the aridity index is defined as a fraction of total annual precipitation divided by potential evapotranspiration (see Appendix). It therefore behaves in a strongly non-linear fashion and year-to-year fluctuations can be large. As the results are averaged over a relatively small number of model simulations, this can result in local jumps.

As a result of regional warming and changes in precipitation patterns, water availability is projected to decrease in most parts of the region throughout the 21st century. For example, in the eastern Anatolian mountains (headwaters of Euphrates and Tigris rivers) a runoff decrease of 25 percent to 55 percent is projected with 4°C warming.

Mountain areas in Morocco, Algeria, Lebanon, Syria, Iraq, Iran and Turkey play an important role in the water supply of the region, as they store a fraction of precipitation as snow. With projected reduction in snowfall and snow water storage, peak flows of melt water will shift towards earlier months, with negative impacts for downstream river systems and water availability in distant regions. For example, snowpack in the upper Nahr el Kalb basin in Lebanon was projected to shrink by 40 percent with 2°C warming, and 70 percent with 4°C warming. Hence, drought periods would occur 15–20 days earlier under a 2°C warming scenario, and more than a month earlier under a 4°C warming scenario.

#### 4.1.3.2 Desertification, Salinization, and Dust Storms

The importance of climate change for desertification varies depending on local conditions, and interactions between drivers can be multifaceted. An increase in temperatures and evapotranspiration, change of precipitation regime, and the intensification or change in frequency of extreme events can directly trigger or enhance the desertification processes. Being covered mostly by drylands, the region is frequently threatened by dust storms, causing damage and disruption to people, agriculture and the economy. While there are no direct projection studies on dust storms in the region, wind as a driving factor can be projected from climate models. However, there are no regional studies on changing wind patterns under climate change in the region as yet, and future trends have to be derived from global studies.

An increase in salinization under climate change holds for all water resources in the region. The densely populated coastal areas in the region are most affected by climate-change-induced salinization (seawater intrusion), which is accelerated by climate-induced sea level rise. River salinization, meanwhile, is documented in studies of the Euphrates and Tigris, the Jordan River, and the Nile.

The salinization process is complex, however, and climate change is but one important factor among others (including irrigation, water uptake and land subsidence). Climate change and, in particular, projected drier conditions in the region, are expected to compound these other drivers (e.g., as more irrigation is needed for agriculture).

#### 4.1.3.3 Human Health

The region is currently experiencing a resurgence of several vector-borne and viral diseases that had previously been in decline. Climate change may compound the challenge of managing these diseases, including such vector-board diseases as malaria, lymphatic filariasis, and leishmaniasis. In addition, outbreaks of cholera (which correlate with high temperatures and can follow extreme weather events that disrupt water supply) have in recent years caused deaths in Iraq, the Islamic Republic of Iran and the Republic of Yemen.

The Middle East and North Africa region is already characterized by very high summer temperatures, making the populations of the region highly susceptible to further temperature increases. In a 2°C world, the annual number of hot days with exceptionally high temperatures and high thermal discomfort is expected to increase in several capital cities, from 4 to 62 days in Amman (Jordan), from 8 to 90 days in Baghdad (Iraq) and from 1 to 71 days in Damascus (Syria). The greatest increase is expected in Riyadh (Saudi Arabia) where the number of hot days is projected to rise from 3 to 132 days per year. In a 4°C world, the average number of hot days is projected to exceed 115 days per year in all of these cities.

#### 4.1.3.4 Migration and Security

The literature review revealed a link between climate change and migration in the region. It is expected that migration options will be more limited in a warmer world. Internal migration will continue to be important, but traditional patterns of mobility might be disrupted. Many people will be forced to move, while others trapped in poverty will be forced to stay. This indicates that climate-induced migration should be addressed not only within the context of climate change but also within economic, cultural, technological, and political frameworks.

Climate change could act as a threat multiplier in the region by placing additional pressure on already scarce resources and reinforcing preexisting threats as political instability, poverty, and unemployment. This can create the conditions for social uprising and violent conflict. Establishing a direct link between climate change and conflicts is challenging due to contradictory conclusions and methods. The findings are in some cases based on a single extreme event; others use rainfall or temperature variability as proxies for long-term changes; and some examine short-term warming. Further research is needed to investigate and establish the link between climate change and conflict and to relate long-term climate change, instead of single climatologic hazards, to migration and to conflicts.

#### 4.1.3.5 Coastal Infrastructure and Tourism

Middle East and in North Africa countries are vulnerable to the impacts of sea-level rise. The population at risk in coastal cities numbered approximately 60 million in 2010; that number is expected to rise to 100 million by 2030. Separating out the socio-economic drivers of vulnerability from the effects of sea-level rise, a study of 136 coastal cities identified Alexandria, Benghazi, and Algiers as particularly vulnerable to a 0.2 m sea-level rise by 2050. The study projected that, in the event of the failure of flood defenses, the effects of sea-level rise would increase damages from $16.5 billion to $50.5 billion in Alexandria, from $1.2 billion to $2 billion in Benghazi, and from $0.3 billion to $0.4 billion in

Algiers. Annual losses would increase to $58 billion, $2.7 billion and $0.6 billion with 0.4 m of sea-level rise for these three cities respectively. A sea-level rise of one meter could impact 10 percent of Egypt's population, five percent of its urban area, and decrease the country's GDP by six percent. One study estimated that a sea-level rise of 0.30 m (projected for 2025 in this study) would flood 30 percent of metropolitan Alexandria, forcing about 545,000 people to abandon their homes and land, and leading to the loss of 70,500 jobs. With a sea-level rise of 0.5 m, projected for 2050, the same study calculated that about 1.5 million people would be displaced and about 195,500 jobs lost.

The impacts of climate change on tourism are unclear due to other non-climatic aspects of tourism, such as changes in travel costs, demand, and options for tourism destinations.

#### *4.1.3.6 Energy Systems*

Three types of climate-change-related stressors could potentially affect thermal power generation and hydropower generation: (1) Increased air temperatures could reduce thermal conversion efficiency; (2) changes in the water regime and water temperatures may decrease the available volume and decrease efficiency of water for cooling; and (3) extreme weather events could affect the production plants and the distribution systems. Regional studies published in English that quantify the impacts of climate change on thermoelectricity generation in the Middle East and in North Africa appear to be lacking. For North Africa, one study projects that hydropower production will decrease by almost 0.5 percent with 2°C warming compared to 2005 production levels due to changes in river runoff. In the same study the production is projected to decrease by 1.4 percent in the Middle East.

### 4.1.4 Overview of Regional Development Narratives

The development narratives build on the climate change impacts analyzed in this report (Table 4.10) and are presented in more detail in Section 4.5. The Middle East and North Africa region is one of the world's most climate vulnerable regions. With its high and growing import dependency, the region is particularly vulnerable to worldwide and domestic agricultural impacts and related spikes in food prices. While never mono-causal, such climate-related market signals may fuel the potential for social unrest and migration and have a lasting effect on poverty in the region. Both the rural poor and the urban poor would be hard hit by agricultural impacts, as poor farmers in rural areas are particularly vulnerable to hunger and malnutrition and the urban poor are hit hard by rising food prices.

While biophysical impacts vary only slightly across the region, there is also a clear division in vulnerabilities and socioeconomic impacts between the (oil-) rich Arab Gulf States and other countries in the region. The former have the financial means to afford adaptation options, such as desalination technology and food imports.

## 4.2 Introduction

In this report, the Middle East and North Africa (MENA) is composed of 20 countries from Morocco to Iran. For the projections on changes in temperature, precipitation, aridity, heat extremes, and sea-level rise, the MENA region stretches from 2°W to 63°E and from 10°N to 42°N. The countries in the region can be divided into four groups, which share geographical, historical, and/or economic similarities:

- the Maghreb in the western part of North Africa: Morocco, Algeria, Tunisia, and Libya.
- the Mashrek in the East: Egypt, Jordan, Lebanon, Iraq, and Syria.
- the Arab Gulf States, defined here as member states of the "Cooperation Council for the Arab States of the Gulf" (and not as the countries bordering the Persian Gulf): Iraq, Kuwait, Bahrain, Oman, Qatar, Saudi Arabia, and the United Arab Emirates.
- the least developed countries (LDC) with the lowest indicators of socioeconomic development following a definition from the United Nations: Yemen and Djibouti.

The region also includes the Islamic Republic of Iran, Israel, and the West Bank and Gaza.

MENA is one of the most diverse regions in the world from a socioeconomic point of view as illustrated by the wide spectrum of per-capita annual GDP. It ranges from $1,000 in Yemen to more than $20,000 in the Arab Gulf States. Qatar, Kuwait, the United Arab Emirates, Morocco, Egypt, and Yemen rank 4, 12, 27, 130, 132, and 151 in GDP per capita on a list of 189 countries (Table 4.1). Accordingly, adaptive capacity and vulnerability to climate change and other risks also vary greatly among MENA countries.

The main vulnerabilities of the MENA region related to climate change impacts are highlighted below.

There is **growing demand for water, food, and other agricultural products,** driven by a growing population but with strong sub-regional variances. While Qatar, Oman, the United Arab Emirates, Kuwait, and Bahrain rank number 1, 2, 3, 4, and 10 in population growth among 205 countries, with annual growth rates ranging between 3 and 9 percent, Morocco, Iran, Tunisia, Libya, and Lebanon rank only 99, 104, 115, 130, and 132 on that same list, with annual growth rates between 1.0 and 1.3 percent (World Bank 2013h). Population is projected to double by 2050 (Verner 2012).

#### Low-Economic Diversification

Agriculture employs more than 35 percent of the MENA population and contributes 13 percent to the region's GDP (the global average is 3.2 percent) (Verner 2012); if the agricultural value chain is accounted for, then this percentage more than doubles (Valdés and Foster 2010). Agriculture generally depends more strongly on natural resources and climate than other sectors. Accordingly, the


region's economy also strongly depends on water, as well as on climate conducive to food crop growth. As climatic conditions are projected to become increasingly unfavorable, natural resources—in particular land and water—will become overexploited and degraded. The fraction of total employment made up by agriculture ranges from 1.5 percent in Bahrain and three percent in Jordan to 32 percent in Egypt, 41 percent in Morocco, and 54 percent in Yemen (2013b). Another aspect of the region's low economic diversification is its strong dependence on gas and oil revenues, which make up 38 percent of total regional GDP (Arab Monetary Fund 2010). With decreasing availability of fossil fuels, export revenues and adaptive capacity may suffer.

### Dependence on Import

The region strongly depends on food and associated *virtual water* imports (water embedded in the trade of agricultural commodities—see Section 4.4.1, The Agriculture-Water-Food Security Nexus). About 50 percent of regional wheat and barley consumption, 40 percent of rice consumption, and nearly 70 percent of maize consumption is met through imports (Verner 2012), and the world's top nine wheat importers are MENA countries. High levels of per capita net food imports are due to severe domestic water (and land) constraints (i.e. low resource availability in combination with often low resource productivity). Import dependency results in a high vulnerability to fluctuating global food prices, which to some extent are also driven by climate impacts in food-exporting regions. On the other hand, food imports reduce the region's direct vulnerability to local climate risks. The Nomura Food Vulnerability Index[40] (Nomura Global Economics and Strategy 2010) ranks Morocco, Algeria, Lebanon, and Egypt as the 2nd, 3rd, 5th, and 6th most vulnerable among 80 countries listed.

### High Electricity and Water Consumption

Demand-side measures do not feature prominently, as illustrated by considerable over-consumption of various goods and services—in particular among the Arab Gulf States. The Gulf States hold world records in energy-intensity, per capita electricity consumption, greenhouse gas emissions, and domestic water demand. Despite its extreme water scarcity, the Arab region uses more water per capita than the global average, due in considerable part to very low resource use efficiencies of Arab residential water and energy markets as they are among the most heavily subsidized in the world. Electricity consumption per capita is twice as high as or higher than the world average in Bahrain, Israel, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (World Bank, 2013e), and water withdrawal per capita is nearly twice as high as the world average in Bahrain, Iraq, and Kuwait (FAO 2013).

[40] The index is composed of the indicators net food trade, household spending on food, and per capita GDP.

**Table 4.1:** Basic socioeconomic indicators of MENA countries.

| INDICATOR | POPULATION | URBAN POPULATION | URBAN POPULATION GROWTH | GDP PER CAPITA | AGRICULTURE, VALUE ADDED[1] | LIFE EXPECTANCY AT BIRTH[2] |
|---|---|---|---|---|---|---|
| UNIT | MILLION | % OF POPULATION | ANNUAL % | CURRENT $1000 | % OF GDP | YEARS |
| YEAR | 2011 | 2012 | 2012 | 2012 | 2009–2010 | 2011 |
| ID | SP.POP.TOTL | SP.URB.TOTL.IN.ZS | SP.URB.GROW | NY.GDP.PCAP.CD | NV.AGR.TOTL.ZS | SP.DYN.LE00.IN |
| **Arab Gulf States** | | | | | | |
| Bahrain | 1 | 89 | 2.0 | 22 | - | 76 |
| Kuwait | 3 | 98 | 4.0 | 51 | - | 74 |
| Oman | 3 | 74 | 9.5 | 23 | - | 76 |
| Qatar | 2 | 99 | 7.2 | 90 | - | 78 |
| Saudi Arabia | 28 | 82 | 2.1 | 25 | 2.4 | 75 |
| United Arab Emirates | 9 | 85 | 3.4 | 39 | 0.9 | 77 |
| **Least Developed Countries** | | | | | | |
| Djibouti | 1 | 77 | 1.6 | - | - | 61 |
| Yemen, Rep. | 23 | 33 | 4.1 | 1 | 7.7 | 63 |
| **Maghreb** | | | | | | |
| Algeria | 38 | 74 | 3.0 | 5 | 6.9 | 71 |
| Libya | 6 | 78 | 1.1 | 10[3] | | 75 |
| Morocco | 32 | 57 | 2.1 | 3 | 15.4 | 70 |
| Tunisia | 11 | 67 | 1.3 | 4 | 8.0 | 75 |
| **Mashrek** | | | | | | |
| Egypt | 79 | 44 | 2.0 | 3 | 14.0 | 71 |
| Iraq | 32 | 66 | 2.5 | 6 | - | 69 |
| Jordan | 6 | 83 | 2.5 | 5 | 3.4 | 74 |
| Lebanon | 4 | 87 | 1.1 | 10 | 5.6 | 80 |
| Syrian Arab Republic | 22 | 56 | 2.7 | 3 | 23.0 | 75 |
| **Other MENA Countries** | | | | | | |
| Iran, Islamic Rep. | 75 | 69 | 1.5 | 7 | - | 73 |
| Israel | 8 | 92 | 1.9 | 33 | - | 82 |
| West Bank and Gaza | 4 | 75 | 3.3 | - | - | 73 |
| **World** | **6,966** | **53** | **2.1** | **10** | **3.2** | **71** |

[1]Agriculture corresponds to ISIC divisions 1–5 and includes forestry, hunting, and fishing, as well as cultivation of crops and livestock production. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets or depletion and degradation of natural resources.
[2]Life expectancy at birth indicates the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life.
[3]in 2009.

Source: World Bank (2013b).

### Governance

Challenges and uncertainties associated with climate change, in combination with other pressures, require diverse, adaptable, and participatory governance structures (Folke 2003). Judging from commonly used indicators of democracy, corruption, and gender equity, the region may not be well prepared in this respect. According to the Economist's democracy index[41] of 167 countries, the MENA countries rank very poorly at positions 90 (Tunisia), 149 (United Arab Emirates), 150 (Bahrain), 158 (Iran), 163 (Saudi Arabia), and 164 (Syria) (The Economist 2012). UNDP's gender inequality index[42] (UNDP 2012), which lists 148 countries, ranks Qatar at position 117, Syria at 118, Iraq at 120, Egypt at 126, Saudi Arabia at 145, and Yemen at 148. The representation of women in Arab governments is nine percent, or just half of the global average (Verner 2012). According to the corruption perception index[43] (Transparency International 2012), which lists 174 countries, Syria, Yemen, Libya, and Iraq are ranked at positions 144, 156, 160, and 169 respectively. Regarding the economic governance of the region, large-scale and centralized supply-side measures are seen as solutions to the growing demand-supply gap, such as large-scale water transfers in Tunisia and Libya. There is less emphasis on diverse, distributed, decentralized, and small-scale solutions, which would increase the region's flexibility, diversity, and resilience to climate change (Folke 2003; Sowers et al. 2011).

### Low Investment in Research and Development

Innovation in supply-and-demand-side management and adaptation to climate change and other risks requires research and development. While globally countries spend on average 1.7 percent of GDP on research and development, the Arab region[44] ranks lowest of all the world's regions at 0.2 percent in 2007 (UNESCO 2010). Private investment in the region as a share of total investment is around 40–45 percent (lower than Africa, Latin America, and the Caribbean, where the share of total investment is around 75–80 percent) (Verner 2012).

[41] The index, on a 0 to 10 scale, is based on the ratings for 60 indicators grouped in five categories: electoral process and pluralism; civil liberties; the functioning of government; political participation; and political culture. Each category has a rating on a 0 to 10 scale, and the overall index of democracy is the simple average of the five category indexes.

[42] A composite measure reflecting inequality in achievements between women and men in three dimensions: reproductive health, empowerment, and the labor market. Data are those available to the Human Development Report Office as of October 15, 2012.

[43] The index ranks countries and territories based on how corrupt their public sector is perceived to be. A country or territory's score indicates the perceived level of public sector corruption on a scale of 0- to 100, where 0 indicates that a country is perceived as highly corrupt and 100 indicates it is perceived as not corrupt. A country's rank indicates its position relative to the other countries and territories included in the index.

[44] The Arab region in the UNESCO report is composed of Algeria, Djibouti, Egypt, Libyan Arab Jamahiriya, Mauritania, Morocco, Sudan, Tunisia, Bahrain, Iraq, Jordan, Kuwait, Lebanon, Oman, West Bank and Gaza, Qatar, Saudi Arabia, Syria, United Arab Emirates, and Yemen.

### Underemployment

High fertility rates in rural areas and technological changes are driving the movement of labor from the agricultural sector, leading to rural migration and urban population growth. Forty percent of the region's unemployed are young job seekers (UNESCWA 2007).

### Undernourishment and Malnutrition

The number of undernourished people in the region[45] in 2011–2013 reached 21 million in Western Asia (about 10 percent of the population) and 4 million in Northern Africa (about 3 percent of the population), higher than in 2008–2010 (FAO 2013); on the other hand, an estimated one quarter of the population is obese.[46]

All MENA countries face severe and fast-growing resource squeezes, in particular relating to extreme water and land scarcity; this leaves most of these countries unable to produce enough food for their population. The main focus of this chapter is therefore on agriculture and water resources.

The most recent IPCC Assessment report found that a reduction in precipitation by the end of the 21st century is likely over Northern Africa under the A1B and A2 scenarios, and that land temperatures over Africa are likely rising faster than the global average. There is high confidence that climate change will amplify existing stresses on water availability across the whole of Africa; acting together with non-climate drivers, this will exacerbate the vulnerability of agricultural systems, particularly in semi-arid regions (Niang et al. 2014). Water scarcity is expected to be a major challenge in West Asia, including the Arabian Peninsula and other MENA countries, due to increased water demand and lack of good management (medium confidence), although the impacts of climate change on food production and food security in West Asia will vary by region. Studies on the regional impacts of climate change are still inadequate, including for the Arab Gulf States and parts of the Mashrek (e.g. there is only limited information and knowledge gaps on the impacts on crops and farmland remain) (Hijioka et al. 2014).

## 4.3 Regional Patterns of Climate Change

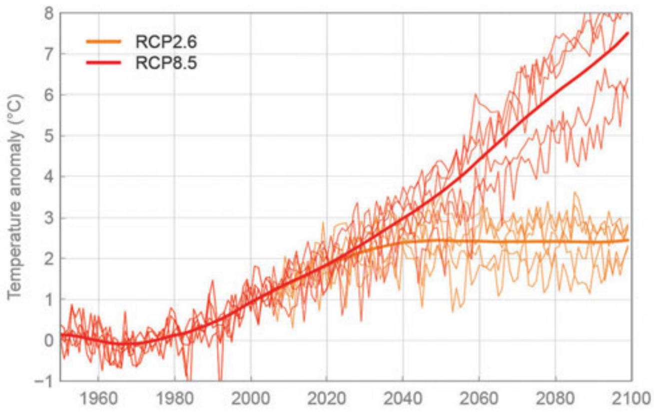
### 4.3.1 Projected Temperature Changes

The projected increase in temperatures during the boreal summer (June, July, August or JJA) over the Middle East and North African land area is shown in Figure 4.3 for both the 2°C and 4°C world.

[45] The FAO region Near East and North Africa: Algeria, Egypt, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Saudi Arabia, Sudan, Syria, Tunisia, United Arab Emirates, and Yemen.

[46] According to WHO. Data for adults aged 15 years and older from 16 countries in the region show the highest levels of overweight and obesity in Egypt, Bahrain, Jordan, Kuwait, Saudi Arabia, and United Arab Emirates. The prevalence of overweight and obesity in these countries ranges from 74–86 percent in women and 69–77 percent in men. A person with a BMI of 25 or more is considered by WHO to be overweight, while obesity is defined as having a BMI of 30 or more.

**Figure 4.3:** Temperature projections for the Middle East and North African land area compared to the baseline (1951–1980).



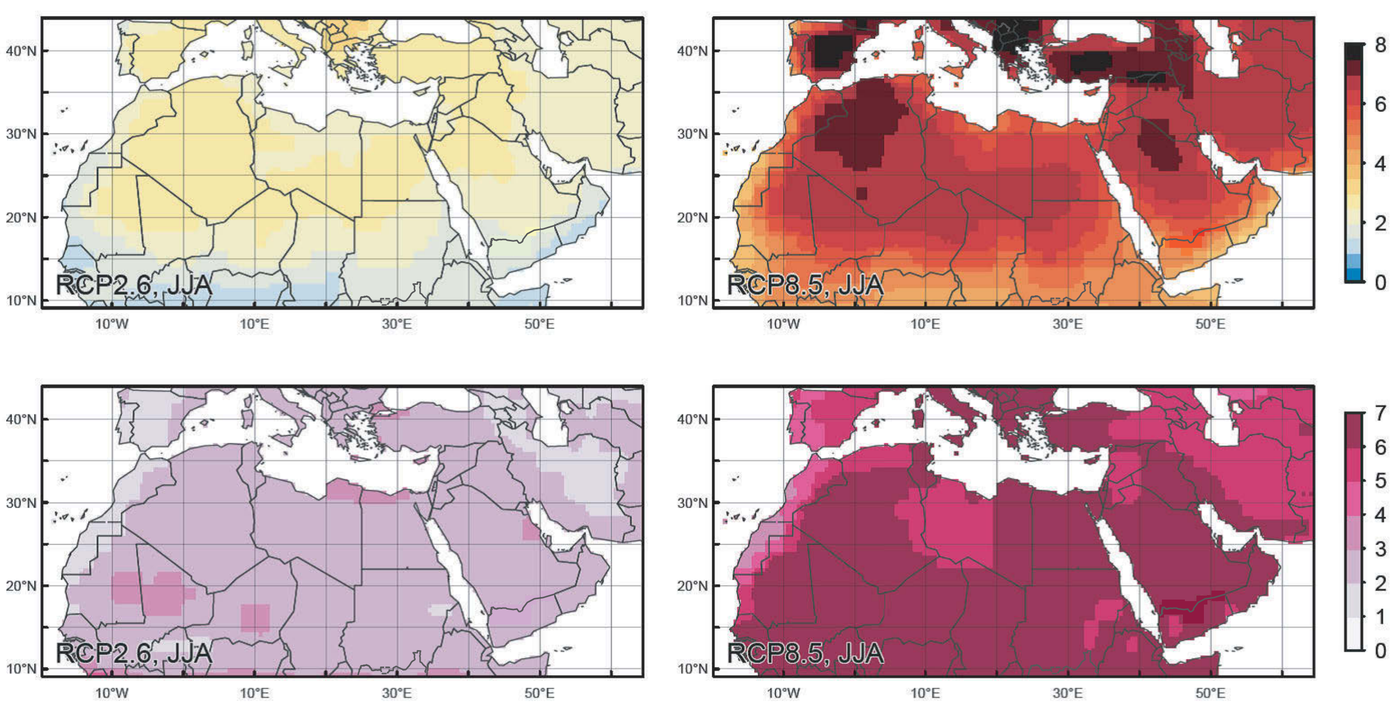

Temperature projections for the Middle East and North African land area compared to the baseline (1951–1980) for the multi-model mean (thick line) and individual models (thin lines) under RCP2.6 (2°C world) and RCP8.5 (4°C world) scenarios for the months of JJA. The multi-model mean has been smoothed to give the climatological trend.

The multi-model mean warming by 2100 is about 2.5°C in a 2°C world and about 7.5°C in a 4°C world, which is substantially more than the global mean land warming (see Figure 2.5 in World Bank 2013). Under the low-emissions scenario (i.e., a 2°C world), summer temperatures in MENA peak by 2040 at about 2.5°C above the 1951–1980 baseline and remain at this level until the end of the century. In a 4°C world, warming continues almost linearly beyond 2040, reaching about 7.5°C above the 1951–1980 baseline by 2100 (Figure 4.3).

Geographically, the strongest warming is projected to take place close to the Mediterranean coast (see Figure 4.4). Here, and also inland in Algeria, Libya, and large parts of Egypt, regions warm by 3°C in a 2°C world. In a 4°C world, mean summer temperatures in 2071–2099 are expected to be up to 8°C warmer in parts of Algeria. Warming over the Sahel region (i.e., below about 20°N in Figure 4.4) is more moderate (2°C in a 2°C world and 5°C in a 4°C world), which is likely related to an increase in precipitation (see Figure 4.7).

The lower panels of Figure 4.4 show the normalized warming (i.e., the warming expressed in terms of the local year-to-year natural variability—see Section 6.1, Methods for Temperature, Precipitation, Heat Wave, and Aridity Projections) over the Middle

**Figure 4.4:** Multi-model mean temperature anomaly for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the months of JJA for the Middle East and North African region.




Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–2099 relative to 1951–1980, and normalized by the local standard deviation (bottom row).

East and North African land area. The normalized warming is a useful diagnostic tool as it indicates how unusual the warming is compared to fluctuations experienced in the past in a particular region (Coumou and Robinson 2013; Hansen et al. 2012; Mora and Frazier et al. 2013). In a 4°C world, the probability density function of monthly temperatures (associated with the year-to-year variability of monthly temperatures) shifts by six standard deviations toward warmer conditions across all regions, from the Sahara to the Arabian Peninsula to the eastern Mediterranean coast. Such a large shift implies that summer temperatures here will move to a new climatic regime by the end of the 21st century. Such a dramatic change would be avoided in a 2°C world; even then, however, a substantial shift is expected (i.e., by about 2–3 standard deviations).

### 4.3.2 Heat Extremes

An increase in the number of extremely high temperatures since the 1960s has been detected, as would be expected for an increase in global mean temperatures over the same period (Seneviratne et al. 2012). An increase in the warm spell duration index (WSDI[47]) for heat waves has also been observed and is particularly pronounced over North Africa, the Eastern Mediterranean, and the Middle East (Donat et al. 2013; Donat, Peterson et al. 2013; Hoerling et al. 2012; Kuglitsch et al. 2010).

As expected from the large shifts in normalized warming, the number of threshold-exceeding extremes is expected to strongly increase across the Middle East and North African region under projected future warming (Figure 4.5 and Figure 4.6). In a 2°C world, by the end of the century about 30 percent of summer months will be hotter than 3-sigma (see Section 6.1, Methods for Temperature, Precipitation, Heat Wave, and Aridity Projections) almost everywhere in this region. This implies that every year on average one of the summer months (June, July, or August) is expected to exceed temperatures by more than three standard deviations beyond the 1951–1980 mean. This value is substantially higher than the global mean projections (20 percent of summer months) (see Figure 2.7 in World Bank 2013). The Mediterranean and Middle East are particularly prone to an increase in extreme temperatures and heat waves, because temperature extremes in these regions are expected to be amplified by a reduction in soil moisture, resulting from decreasing precipitation (Lorenz et al. 2010; Orlowsky and Seneviratne 2011; Vautard et al. 2013). Summer months warmer than 5-sigma, however, will remain largely absent, except for some isolated coastal regions (including the Mediterranean coasts of Egypt and over Yemen, Djibouti, and Oman). Here 5-sigma events will still be relatively rare in a 2°C world but are nevertheless detectable and expected to occur between 5–10 percent of summer months.

[47] The Warm spell duration index (WSDI) is one of the 27 indices developed and recommended by the WMO CCl/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (Zhang et al. 2011b). It is defined as the longest annual spell of at least six consecutive days with maximum temperatures exceeding the local 90th percentile relative to a reference period (in days).

**Figure 4.5:** 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 scenarios RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) over the Middle East and North Africa.

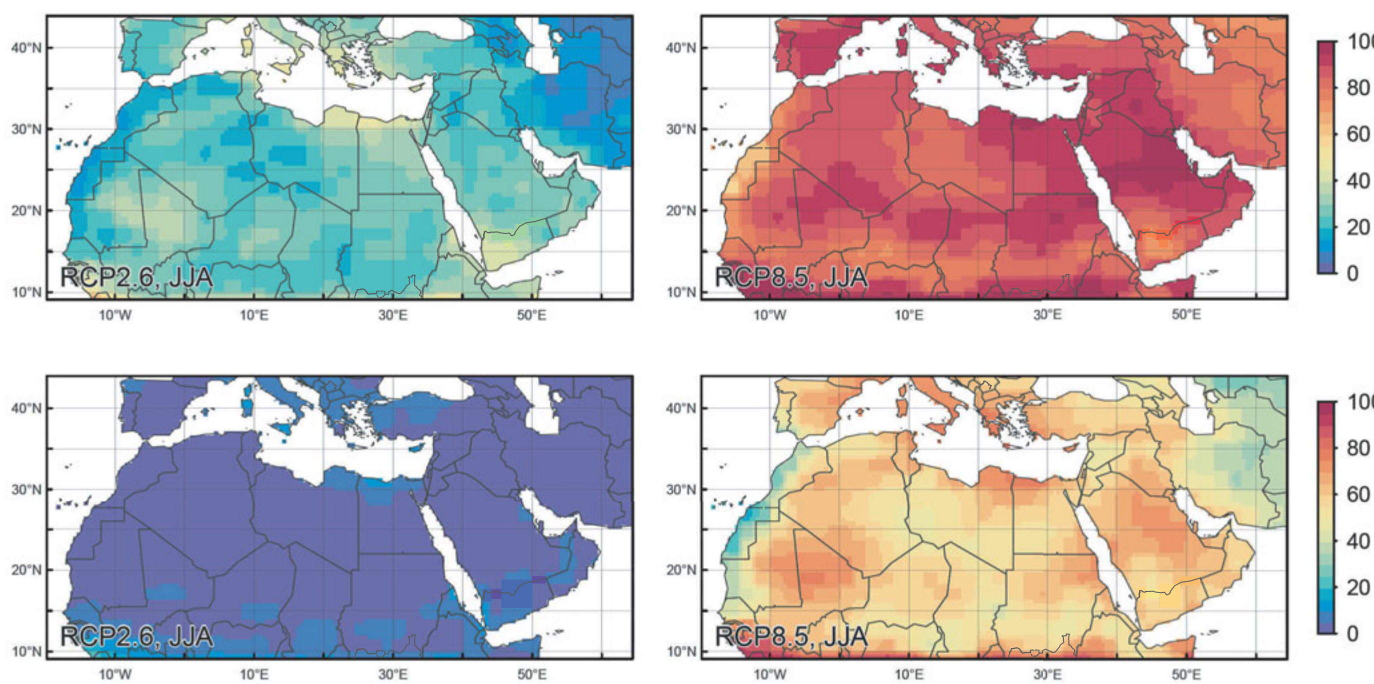


**Figure 4.6:** Multi-model mean (thick line) and individual models (thin lines) of the percentage of Middle East and North African land area warmer than 3-sigma (top) and 5-sigma (bottom) during boreal summer months (JJA) for scenarios RCP2.6 (2°C world) and RCP8.5 (4°C world).

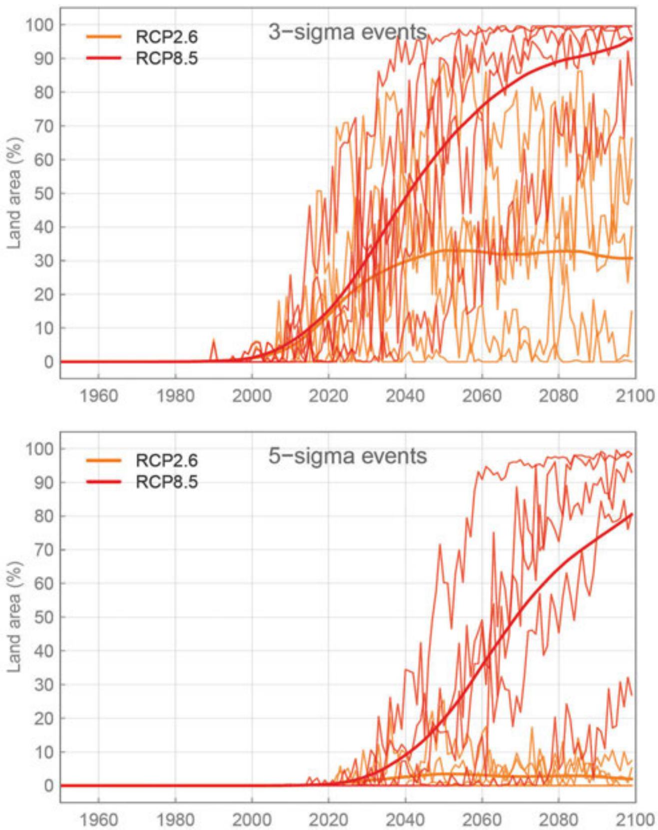



**Table 4.2:** Mean WSDI (Warm Spell Duration Index) for capital cities in the MENA region for different levels of global warming based on regional climate model projections by Lelieveld et al. (2013).

| | | | WARMING LEVEL [°C] | | | |
|---|---|---|---|---|---|---|
| | PERIOD OF OBSERVATION | OBSERVED | 1.5 | 2.0 | 3.0 | 4.0 |
| Abadan | 1951—2000 | 6 | 43 | 82 | 99 | 134 |
| Amman | 1959–2004 | 4 | 31 | 62 | 84 | 115 |
| Ankara | 1926–2003 | 7 | 44 | 67 | 111 | 128 |
| Athens | 1951–2001 | 1 | 40 | 61 | 121 | 166 |
| Baghdad | 1950–2000 | 8 | 47 | 90 | 113 | 162 |
| Beirut | – | – | 47 | 93 | 126 | 187 |
| Belgrade | 1951–2010 | 9 | 39 | 39 | 76 | 113 |
| Cairo | – | – | 32 | 53 | 80 | 94 |
| Damascus | 1965–1993 | 1 | 36 | 71 | 98 | 129 |
| Istanbul | 1960–2010 | 0 | 26 | 41 | 78 | 113 |
| Jerusalem | 1964–2004 | 7 | 26 | 46 | 73 | 102 |
| Kuwait | – | – | 45 | 87 | 123 | 167 |
| Nicosia | 1975–2001 | 6 | 25 | 58 | 81 | 162 |
| Riyadh | 1970–2004 | 3 | 81 | 132 | 157 | 202 |
| Sofia | 1960–2010 | 1 | 40 | 49 | 88 | 136 |
| Tehran | 1956–1999 | 5 | 48 | 92 | 122 | 159 |
| Tirana | 1951–2000 | 6 | 49 | 71 | 125 | 168 |
| Tripoli | 1956–1999 | 3 | 13 | 22 | 33 | 59 |

The observational record is taken from Klok and Tank (2009). The annual WSDI is averaged over the observational period as well as over 20-year periods from the A1B scenario over the 21st century that correspond to a mean warming of the given temperature level. The 4.0°C warming level is averaged over the 2079–2099 interval from the A2 scenario.

The increase in frequency of heat extremes is projected to plateau by mid-century in a 2°C world. In a 4°C world, however, heat extremes are projected to become ever more frequent up to and beyond the end of the century (see Figure 4.5). This is similar to the timing of the mean summer warming (see Figure 4.3). The multi-model mean projection indicates that in a 4°C world 80 percent of summer months will be hotter than 5-sigma by 2100 (Figure 4.6), with about 65 percent of summer months reaching this level during the 2071–2099 period (Figure 4.5). Figure 4.6 also clearly shows that there is substantial inter-model spread, with the area of land experiencing 5-sigma events by 2100 ranging from 30 percent to almost 100 percent in different models. The inter-model spread for projected mean summer temperatures is much more limited (see Figure 4.3) compared to that of the projected frequency of 3- and 5-sigma events (see Figure 4.6). It is possible that the large spread in the projected frequency of heat extremes is primarily due to the difference in simulated inter-annual variability in surface temperatures in the models for this particular region. Further research would be needed to confirm this. Only in some isolated coastal areas (The Egyptian Red Sea coast and the Mediterranean coasts of Egypt, Libya, and Tunisia) is the frequency higher than the regional mean during the 2071–2099 period (i.e., close to 80 percent of summer months). The large shift in normalized temperatures to warmer conditions (i.e., by about six standard deviations in a 4°C world, see Figure 4.4) will cause almost all summer months to be warmer than 3-sigma (i.e., more than 90 percent of summer months for the 2071–2099 period in a 4°C world).

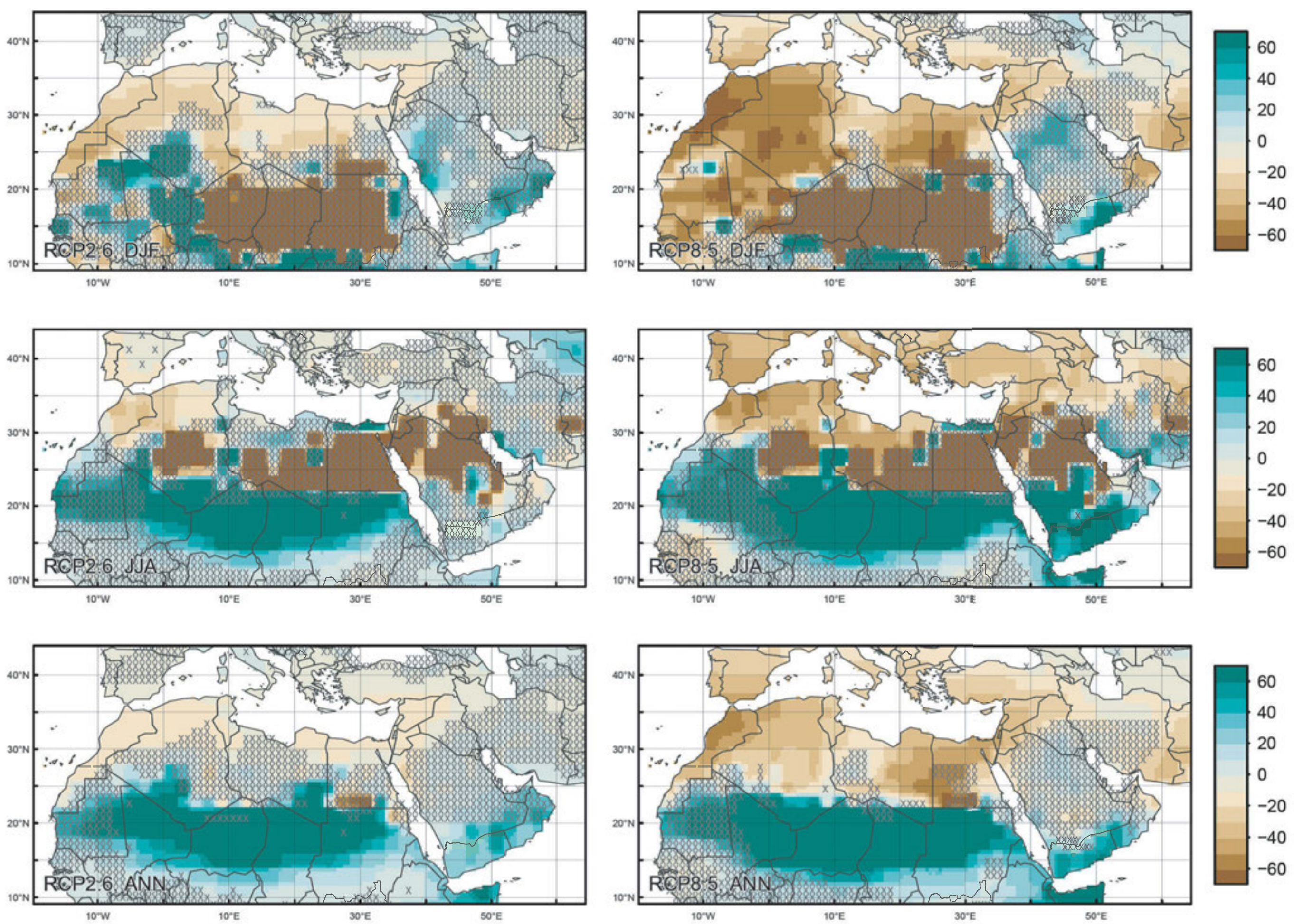
These projections in heat extremes are consistent with published analyses based upon the full CMIP5 dataset of climate projections. These studies indicate that over the Mediterranean, the Sahara, and the Arabian Peninsula, the minimum nighttime temperature and the maximum daytime temperature increase by about 2°C under RCP2.6 and by 6°C under RCP8.5 by 2081–2100 compared to 1981–2000 (Sillmann et al. 2013a; b); this is very similar to the seasonal changes shown in Figure 4.3. In addition, the increase in the percentage of 3-sigma and 5-sigma monthly heat extremes as shown in Figure 4.5 is consistent with the results of Coumou and Robinson (2013), who analyzed all climate models in the CMIP5 dataset. Although an above-global average increase in Mediterranean summer temperatures is robust over a wide range of regional and global climate models, it might be partly overestimated due to systematic warming bias (Boberg and Christensen 2012).

Using a high resolution regional climate model, Lelieveld et al. (2013) projected a substantial increase in the warm-spell duration index (WSDI) for several capital cities in the region (Table 4.2). The mean WSDI over the observational period lies between zero and about one week; it is projected to exceed four months for most capital cities in the region in a 4°C world and even six months for Beirut and Riyadh. The mean WSDI would be limited to between 1–2 months for most capital cities and would rarely exceed three months in a 2°C world. The increase in future heat wave risk as indicated by the increase in the WSDI represents a serious risk for a variety of sectors, including health and tourism.

### 4.3.3 Projected Precipitation Changes

Annual precipitation is projected to decrease north of ~25°N and to increase south of that latitude. It is important to note that the projections shown in Figure 4.7 are given as relative changes (percentage changes compared to the 1951–1980 average); thus, especially over already dry regions, large relative changes do not necessarily reflect large absolute changes. The Sahel and the southern part of the Arabian Peninsula bordering the Indian Ocean (Yemen, Oman) are projected to become wetter in both a

**Figure 4.7:** Multi-model mean of the percentage change in winter (DJF, top), summer (JJA, middle) and annual (bottom) precipitation for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the Middle East and North Africa by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that projections are given as relative changes; thus, over dry regions like the Sahel/Sahara, large relative changes reflect only small absolute changes.

2°C and 4°C world, primarily during the summer months (JJA). The IPCC AR5 reports similar seasonal precipitation changes for the Sahel, but the wetting region is substantially smaller (limited to the southeast only) and model disagreement is larger. Thus, the projected JJA wetting of the Sahel as shown here should be treated with caution due to the limited number of models used. During the winter months (DJF), the eastern part of the Sahel region in fact becomes drier. Wetting of the southern Arabian Peninsula is part of a larger and well-documented pattern of wetter conditions over the Horn of Africa expected under future climate change (Giannini et al. 2008; World Bank 2013). Rainfall in this region is associated with tropical convection, which is projected to strengthen under future warming. Future wetting in this region is also supported by paleo-climate data, and it is likely to intensify inter-annual rainfall variability (Wolff et al. 2011).

In a 2°C world, the relative wetting of regions south of 25°N is pronounced (~50 percent more rain), whereas the relative drying to the North is small (with the Mediterranean coasts receiving about 10–20 percent less rain annually). In fact, the climate models used here disagree on the direction of change over substantial areas, notably between 25°N and 30°N. This is true for both seasons. However, the larger set of CMIP5 models used for the IPCC AR5 project robust drying of the Mediterranean coastal regions.

In a 4°C world, the magnitude of change in the models used becomes much more pronounced in the region north of 25°N and the models converge toward drier conditions. Only over Saudi Arabia, the Islamic Republic of Iran, and parts of Libya do the projected relative changes in annual-mean precipitation remain small, and models show disagreement on the direction of change. Clearly, in a 4°C world, countries along the Mediterranean shore (notably Morocco, Algeria, Egypt, and Turkey) will receive substantially less rain annually (up to 50 percent less precipitation). In this region relative changes in seasonal precipitation are similar to changes in the annual mean, indicating that the drying happens year-round.

### 4.3.4 Extreme Precipitation and Droughts

The observational record for North Africa, the Middle East, and the Arabian Peninsula indicates an overall reduction in extreme precipitation events since the 1960s, despite a local positive trend over the Atlas mountains since the 1980s (Donat and Peterson et al. 2013). At the same time, an increase in meteorological drought has been reported since the 1960s, consistent with an overall regional drying trend (Donat and Peterson et al. 2013; Sousa et al. 2011).

Despite a global trend toward more extreme precipitation events over the 21st century, Kharin et al. (2013) conducted an analysis using CMIP5 models under the RCP8.5 scenario and reported no significant change or even a slight decrease in heavy precipitation across most of North Africa and the Middle East. It is not clear, however, to what extent these models are able to reproduce rare climatological phenomena like the Active Red Sea Trough (ARST) that is associated in the observational record with extreme heavy precipitation events in the Middle East (de Vries et al. 2013).

While the projected changes in extreme precipitation events are below the global average for Saudi-Arabia and Iran, the southern tip of the Arabian Peninsula (notably Oman and Yemen) is projected to experience a substantial intensification of extreme precipitation events over the 21st century under the RCP8.5 scenario (Kharin et al. 2013; Sillmann et al. 2013b). This is consistent with the robust projection for increasing annual precipitation over the Horn of Africa.

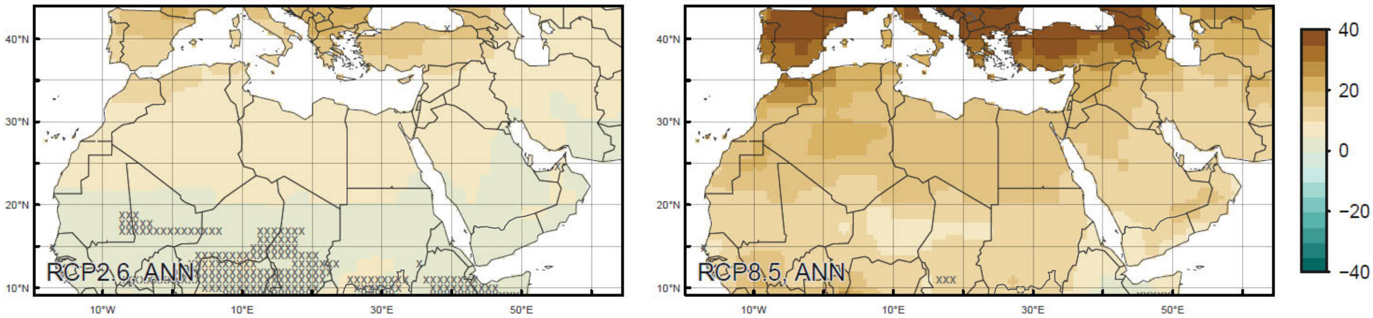
The North African countries (and notably Morocco, Algeria, and Tunisia), as well as the countries of the Middle East, are consistently projected to become global hotspots for drought by the end of the 21st century under the RCP8.5 (Dai 2012; Orlowsky and Seneviratne 2013; Prudhomme et al. 2013; Sillmann et al. 2013b). Dai (2012) projects severe drought conditions for Morocco and the Middle East under the RCP4.5 scenario, which is found to strongly intensify under RCP8.5 (Prudhomme et al. 2013). Based on the comprehensive ISI-MIP modeling framework, Prudhomme et al. (2013) report an increase of more than 50 percent in the number of drought days around the Mediterranean by the end of 21st century (2070–2099) under the RCP8.5 scenario relative to the 1976–2005 period. For the same region, Orlowsky and Seneviratne (2013) project an average of more than six months per year with at least moderate drought conditions in the 2080–2100 period under the RCP8.5 scenario, compared to less than one month per year under RCP2.6. Although projections of future droughts not only suffer from large model uncertainties—and also largely depend on the methodology and baseline periods chosen (Trenberth et al. 2014)—the projections for an increase in extreme drought conditions around the Mediterranean, Northern Africa, and the Middle East are consistent across a variety of studies (IPCC 2012). Drought projections for the Mediterranean are strongly dependent on the emissions scenario used, and are much less pronounced under RCP2.6 (Orlowsky and Seneviratne 2013; Prudhomme et al. 2013).

In the Islamic Republic of Iran, a weaker intensification of future droughts is expected compared to projections for Northern Africa and the Middle East (Dai 2012; Orlowsky and Seneviratne 2013; Prudhomme et al. 2013); uncertainty in this region, however, is large (Hemming et al. 2010) and these projections might not be statistically robust (Sillmann et al. 2013b). For the Arabian Peninsula, a possible reduction in future droughts, or at least no further intensification in the already-extreme drought conditions, is projected by Dai (2012).

### 4.3.5 Aridity

The availability of water for both people and ecosystems is a function of supply and demand. The long-term balance between supply and demand fundamentally determines whether ecosystems and agricultural systems are able to thrive in a certain area. This section assesses projected changes in the aridity index (AI), an

**Figure 4.8:** Multi-model mean of the percentage change in the annual-mean (ANN) of monthly potential evapotranspiration for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the Middle East and North African region by 2071–99 relative to 1951–80.



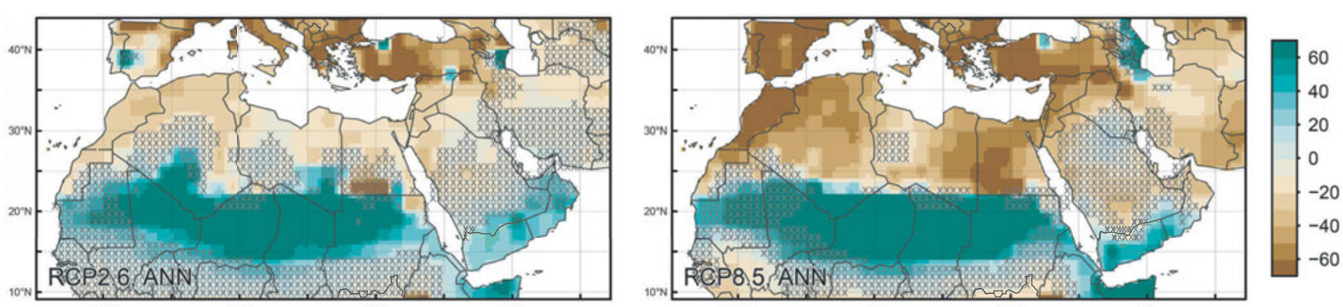

Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change.

indicator designed to identify regions with a structural precipitation deficit (Zomer et al. 2008). AI is calculated as the total annual precipitation divided by the annual potential evapotranspiration—a standardized measure of water demand (see Section 6.1.3, Aridity Index and Potential Evaporation). Although several meteorological variables affect potential evapotranspiration, including radiation and near-surface wind speed, it is to a large extent governed by changes in temperature. A smaller AI value indicates a larger water deficit (i.e. more arid conditions), with areas classified as hyper-arid, arid, semi-arid, and sub-humid as specified in Table 6.1).

Annual-mean monthly potential evapotranspiration is projected to increase throughout the region with robust model agreement. The magnitude of the relative changes forms rather uniform geographical patterns (Figure 4.8). There is a small increase under RCP2.6, typically of only 10 percent although somewhat more in regions directly surrounding the Mediterranean Sea. In a 4°C world, a more substantial increase is observed, again especially in countries bordering the Mediterranean Sea.

There is a close match between the pattern of change in the annual mean AI value (Figure 4.9) and projected precipitation changes (Figure 4.7). This indicates that changes in AI are primarily driven by changes in precipitation causing an increase in AI (wetter conditions) south of 25°N (i.e., the Sahel and the most southern part of the Arabian Peninsula) and a decrease in AI (drier conditions) north of 25°N. The relative increase in AI values in the southern region is similar to the relative increase in annual mean precipitation (about 50 percent wetter conditions), as the change in potential evapotranspiration is small. Note that this relative increase in AI south of 25°N is imposed on an already very low AI value, which results in AI values still classified as arid.

**Figure 4.9:** Multi-model mean of the percentage change in the aridity index under RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the Middle East and North Africa by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that a negative change corresponds to a shift to more arid conditions.[48]

[48] Some individual grid cells have noticeably different values than their direct neighbors (e.g. on Turkey's Black Sea coast under RCP8.5). This is due to the fact that the aridity index is defined as a fraction of total annual precipitation divided by potential evapotranspiration (see Appendix). It therefore behaves in a strongly non-linear fashion and year-to-year fluctuations can be large. As the results are averaged over a relatively small number of model simulations, this can result in local jumps.

In the Mediterranean coastal region, the percentage decrease in AI is more pronounced than that for precipitation because there is a substantial increase in evapotranspiration here due to enhanced warming. In other words, the opposing trends of more evapotranspiration and less annual-mean precipitation mean that this region is expected to see a shift to much more arid conditions. In fact, this is linked to a feedback between precipitation and evaporation via temperature. In regions where the soil dries out because of a decline in precipitation, less heat can be converted into latent heat and thus more heat is present to warm surface temperatures (Coumou and Rahmstorf 2012; Schär et al. 2004). Higher surface temperatures then lead to enhanced potential evapotranspiration. Thus, a decline in precipitation can make local conditions more arid in two ways: directly via a reduction in the supply of water, and indirectly via an increase in surface temperatures which further enhances evapotranspiration (Trenberth 2011). This results in a reduction of up to 30 percent in AI (increased aridity) over the African and eastern shores of the Mediterranean in a 2°C world; in a 4°C world, essentially all coastal regions will see a reduction in AI of about 50 percent. Trends in AI over the Arabian Peninsula are weaker and models disagree on the direction of change due to the uncertainty in precipitation changes.

The shift in AI in Figure 4.9 translates into a shift of categorization of areas into specific aridity classes. The total hyper-arid area is projected to grow by about five percent in a 4°C world, something which would mostly be avoided in a 2°C world (see Table 4.3). Less than half of this increase in hyper-aridity can be explained by a reduction in arid, semi-arid, and sub-humid areas, indicating that humid regions (i.e., AI > 0.65) have shifted into the arid classification.

### 4.3.6 Regional Sea-level Rise

Sea-level rise projections for MENA present a particular challenge due to the semi-enclosed nature of both the Mediterranean and Red Sea basins. They are connected to the broader Atlantic and Indian Oceans, respectively, through relatively narrow straits which are not well represented in the coarse resolution of GCMs (Marcos and Tsimplis 2008). For that reason, this report notes that the steric-dynamical[49] section of the analysis of the new CMIP5 ensemble is explorative.

In the Mediterranean area, tide gauges recorded below-average sea-level rise during the 20th century, with an average rise of 1.1–1.3 mm per year (Tsimplis and Baker 2000); this is lower than the global average of 1.8 mm per year (Meehl et al. 2007). There has been significant inter-decadal variability, with reduced rise between 1960 and 1990 and rapid (above-average) rise after 1990. In the 2009/2010 and 2010/2011 winters, sea levels rose 10 cm above the seasonal average. Atmospheric influence is thought to be the primary driver, where pressure and wind variations associated with the North Atlantic Oscillation control water flow through the Gibraltar Strait (Gomis et al. 2006; Landerer and Volkov 2013; Tsimplis et al. 2013). Compared to the well-studied Mediterranean basin, tide gauge records in the Red Sea and Arabian Sea are much sparser—limited to a few, non-continuous records.[50] Available evidence from the neighboring Northern Indian Ocean, also including satellite altimetry and modeling, suggests past rates of rise consistent with the global mean (Han et al. 2010; Unnikrishnan and Shankar 2007).

This report's analysis of the 21st century projections indicates slightly below-average rise in the Mediterranean basin (Figure 4.10 and Figure 4.11 top panel), mostly as a result of the gravitational influence of the Greenland ice sheet (Figure 4.11 bottom panel). In our GCM ensemble, this is compensated by the above-average steric-dynamic contribution in this area (but lower than in the neighboring Atlantic Ocean) (Figure 4.11 middle panel). The combined gravity- and steric-dynamic pattern induces a stronger rise in the Arabian Sea compared to the Mediterranean (see Figure 4.10 and Figure 4.11). Consistent with this finding, Tunis is projected to experience 0.56 m (0.38–0.96 m) sea-level rise by the end of the century (2081–2100) compared to 1986–2005 in a 4°C world (see Figure 4.12 and Table 4.4). This is eight cm less than in Muscat, where 0.64 m is projected (0.44–1.04 m). On the Atlantic coast, 0.58 m (0.39–0.98 m) sea-level rise is projected for Tangier. Across all the locations present in the figures, the projected high-end rates of sea-level rise range from 6.4 mm per year (Alexandria) to 7.8 mm per year (Tangier) in a 1.5°C world and from 20 mm per year (Tunis) to 21.4 mm per year (Alexandria) in a 4°C world (Table 4.5). This is comparable with global mean projections (up to 7.2 mm per year in a 1.5°C world and 21.9 mm per year in a 4°C world by the end of the century).

Note that this report excludes the steric-dynamic component of three models (MIROC-ESM, HadGEM-ES, CSIRO-Mk3-6-0) with obvious deficiencies in this area (e.g., projecting more than one meter deviation from the global mean or from the neighboring oceans, or simulating a reversed sea-level gradient across Gibraltar). The remaining 5 models simulate a present-day sea-level difference of

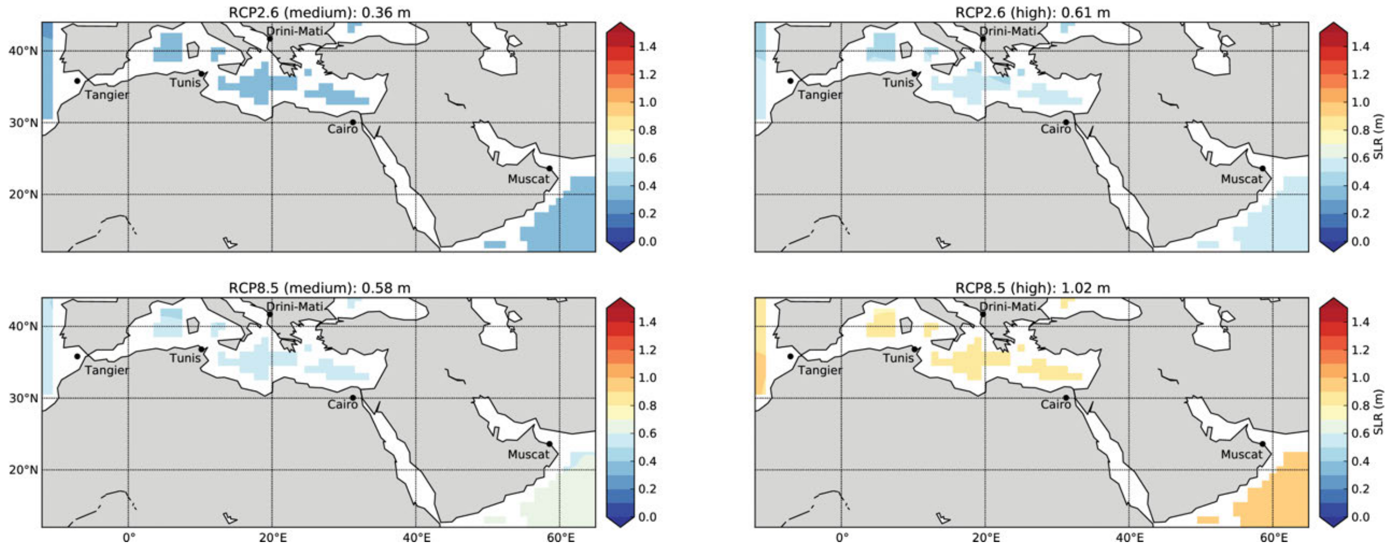
**Table 4.3:** Multi-model mean of the percentage of land area in the Middle East and North African region which is classified as hyper arid, arid, semi-arid and sub-humid for 1951–1980 and 2071–2099 for both the low (2°C world, RCP2.6) and high (4°C world, RCP8.5) emissions scenarios.

| | 1951–1980 | 2071–2099 (RCP2.6) | 2071–2099 (RCP8.5) |
|---|---|---|---|
| Hyper Arid | 68.9 | 70.7 | 74.2 |
| Arid | 13.2 | 13.0 | 12.4 |
| Semi-Arid | 7.1 | 7.0 | 6.3 |
| Sub-Humid | 1.8 | 1.7 | 1.4 |

[49] Related to changes in ocean density and circulation.

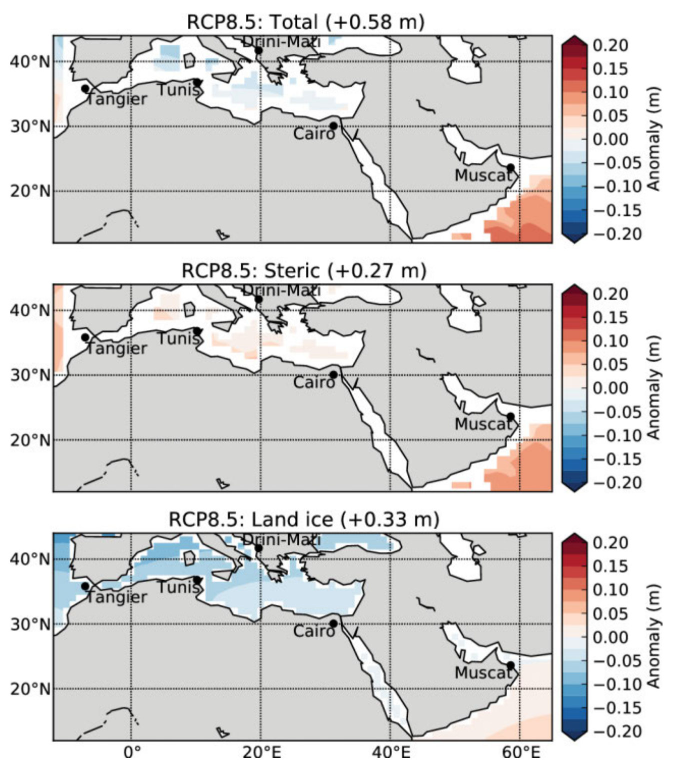
[50] Tide gauge records can be found at http://www.psmsl.org/data/obtaining/map.html.

**Figure 4.10:** Patterns of regional sea-level rise (m).




Median (left column) and upper range (right column) of projected regional sea-level rise for the RCP2.6 scenario (1.5°C world, top row) and the RCP8.5 scenario (4°C world, bottom row) for the period 2081–2100 relative to the reference period 1986–2005. Associated global mean rise is indicated in the panel titles.

**Figure 4.11:** Regional sea-level rise anomaly pattern and its contributions to the median RCP8.5 scenario (4°C world).




Total sea-level rise (top), steric-dynamic (middle), and land-ice (bottom) contributions to sea-level rise are shown as anomalies with respect to the global mean sea-level rise. Global mean contributions to be added on top of the spatial anomalies are indicated in the panel titles.

**Table 4.4:** Sea-level rise between 1986–2005 and 2080–2099 in selected MENA locations (m).

| | RCP2.6 (1.5°C WORLD) | RCP8.5 (4°C WORLD) |
|---|---|---|
| Tangier | 0.35 (0.21, 0.57) | 0.58 (0.39, 0.98) |
| Tunis | 0.34 (0.20, 0.57) | 0.56 (0.38, 0.96) |
| Alexandria | 0.35 (0.21, 0.57) | 0.58 (0.40, 1.00) |
| Muscat | 0.39 (0.22, 0.64) | 0.64 (0.44, 1.04) |

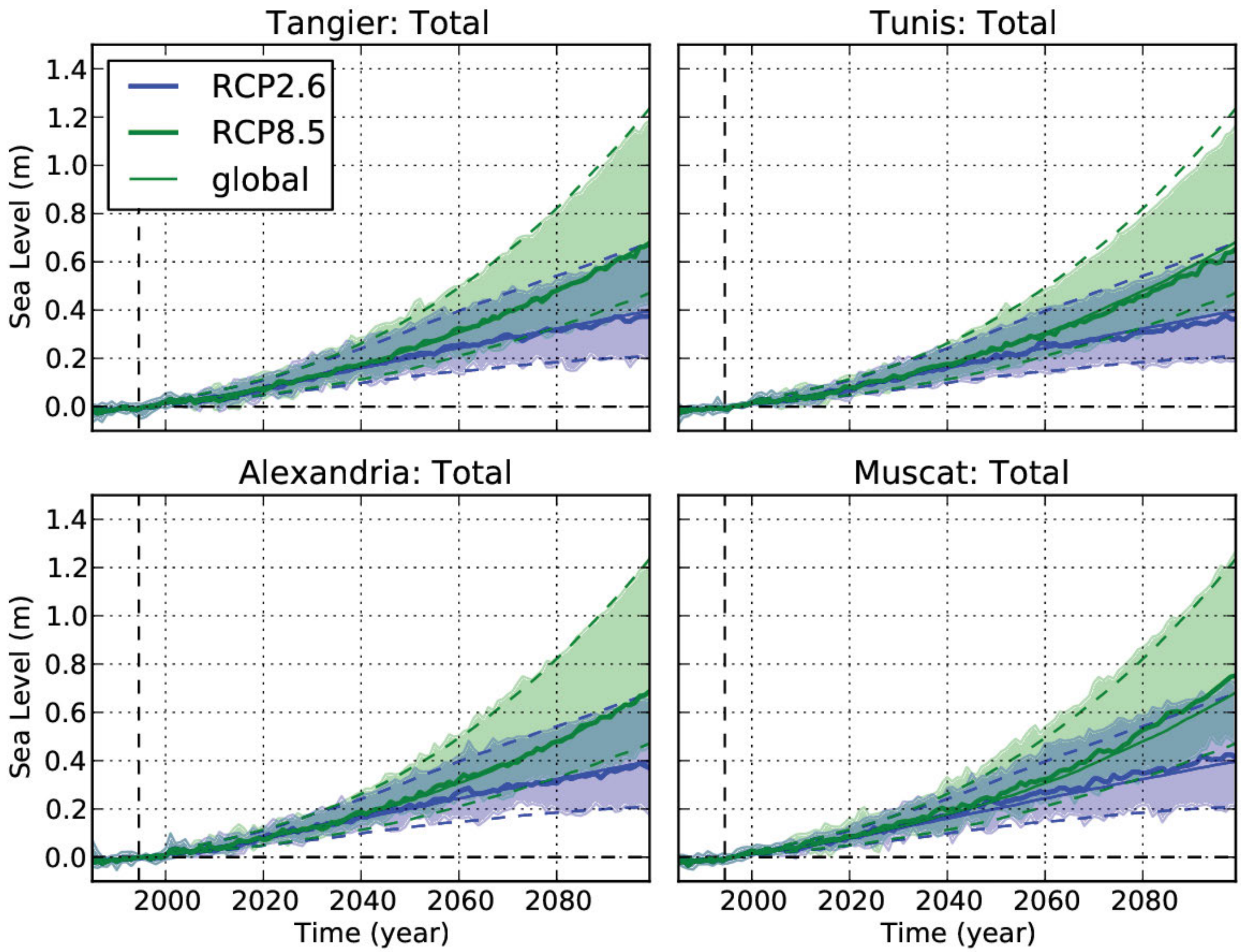
Numbers in parentheses indicate low and high bounds (see Section 6.2, Sea-Level Rise Projections for an explanation of the 1.5° world).

**Table 4.5:** Rate of sea-level rise in MENA between 2080–2100 (mm per year).

| | RCP2.6 (1.5°C WORLD) | RCP8.5 (4°C WORLD) |
|---|---|---|
| Tangier | 3.3 (1.8, 7.8) | 10.2 (6.8, 21.0) |
| Tunis | 3.5 (1.2, 6.6) | 10.1 (6.4, 20.0) |
| Alexandria | 3.4 (1.2, 6.4) | 10.9 (6.9, 21.4) |
| Muscat | 4.2 (1.5, 6.9) | 12.0 (8.9, 20.6) |

Numbers in parentheses indicate low and high bounds (see Section 6.2, Sea-Level Rise Projections for an explanation of the 1.5° world).

**Figure 4.12:** Sea-level projections for Tangier, Tunis, and Alexandria.



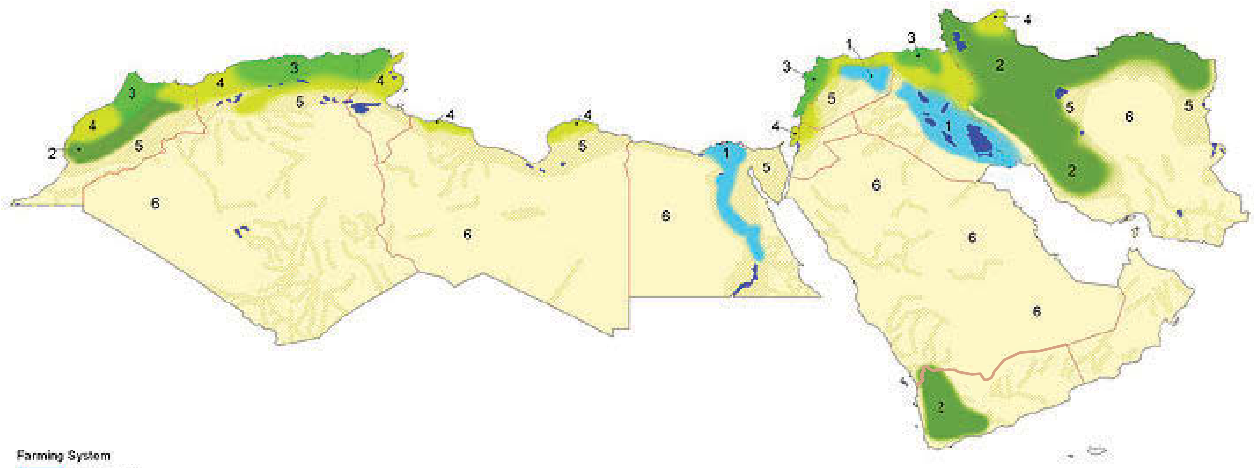

Time series for sea-level rise for the two scenarios RCP2.6 (1.5°C world, blue) and RCP8.5 (4°C world, green). Median estimates are given as full thick lines and the lower and upper bound given as shading. Full thin lines are global median sea-level rise with dashed lines as lower and upper bounds. Vertical and horizontal black lines indicate the reference period and reference (zero) level.

11–30 cm between the neighboring Atlantic Ocean and Mediterranean Sea; this is consistent with observations (Rio et al. 2014). The difference between the Mediterranean and nearby Atlantic sea-level rise depends on processes at the Strait of Gibraltar which are poorly represented in GCMs (Marcos and Tsimplis 2008) and which are just beginning to be investigated with regional climate models (Artale et al. 2010; Gualdi et al. 2013; Somot et al. 2008). Any addition of mass in the Atlantic, such as from melting ice sheets, would be immediately transferred through the Strait of Gibraltar; this may not be the case for steric-dynamic changes (including atmospheric influences).

On top of these projections, decadal and shorter-term variability will continue to occur (Calafat et al. 2012; Landerer and Volkov 2013). Sea-level extremes are generally lower in the Mediterranean basin than along the neighboring Atlantic coasts, except for a few hotspots (such as in the Gulf of Gabes) due to the presence of large tides (Marcos et al. 2009). Available evidence from past observations and modeling indicate that sea-level extremes will change in line with mean sea levels (Marcos et al. 2009).

As mentioned in the introduction, this analysis only considers absolute sea-level changes; it omits vertical land movements despite their relevance for local planning and adaptation. Alexandria is a well-known example where sediment compaction in the Nile delta provokes land subsidence (Syvitski et al. 2009), thereby enhancing the effect of climate-induced sea-level rise. Alexandria is ranked top among the cities with projected increased loss of local GDP as a result of damages from sea-level rise by 2050 (Hallegatte et

**Figure 4.13:** Major farming systems in the MENA region.




Notes:
Projection = Geographic (Lat/Long)

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The designations employed and the presentation of the material in the maps do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal or constitutional status of any country, territory or sea area, or concerning the delimitation of frontiers.

The major farming systems have been identified based on the available natural resource base (water, land, grazing areas, slope, farm size, tenure, and organization) and the dominant pattern of farm activities and household livelihoods, broadly grouped and mapped. Note that besides the systems displayed there are small but important irrigated areas which might not be visible in the figure. Source: Dixon et al. (2001b).

al. 2013). Post-glacial rebound and tectonic movements may also provoke land subsidence or uplift in the Mediterranean area. There is a sustained effort to detect these processes with a combination of tide gauges, satellite altimetry measurement, GPS stations, and modeling (Lambeck and Purcell 2005; Ostanciaux et al. 2012; Wöppelmann and Marcos 2012), as well as via archaeological information (Anzidei et al. 2011).

## 4.4 Regional Impacts

### 4.4.1 The Agriculture-Water-Food Security Nexus

#### *4.4.1.1 Water Scarcity and Climatic Limitations to Agricultural Production*

Most of the land area of the MENA region receives less than 300 mm annual rainfall (and 200–300 mm per year roughly represents the lower limit for rain-fed agriculture). Semi-arid belts along the coasts and mountains are the only water sources and provide productive land for rain-fed agriculture (Immerzeel et al. 2011). The availability of renewable water resources is generally below 1000 $m^3$ per capita per year (except for Iraq, the Islamic Republic of Iran, and Lebanon), and as low as 50 $m^3$ per capita for most countries on the Arab peninsula (Selvaraju 2013; Sowers et al. 2011; Verner 2012). Accordingly, withdrawal-to-availability ratios exceed the critical threshold of 40 percent in all MENA countries except Lebanon; they exceed 100 percent in Jordan, Yemen, Libya, and most of the Arab peninsula countries (FAO-AQUASTAT 2012), leading to groundwater resource depletion.

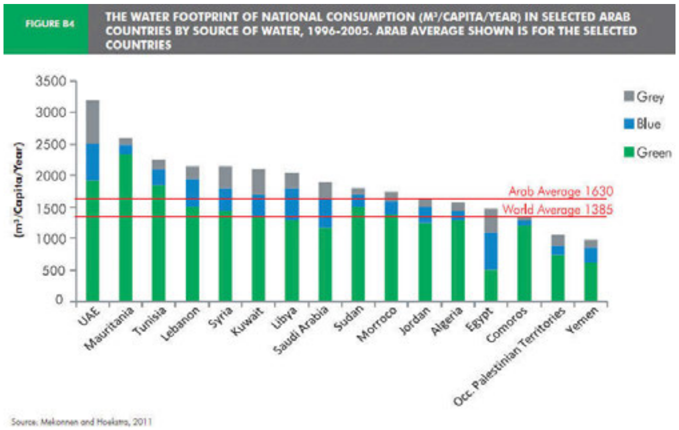
This water scarcity prevents MENA countries from producing all required food domestically and makes the region depending on food imports. From the current situation of critical water and arable land scarcity, 2°C and 4°C warming scenarios will result in further increased pressures on water resources and agriculture.

Egypt, Syria, and Iraq depend strongly for their water supply and food security on precipitation in upstream countries situated in different climatic zones. Egypt depends primarily on Ethiopia (via the Nile), and Syria and Iraq depend to a large extent on Turkey (via the Euphrates and Tigris rivers). These two major river basins support most of the irrigated farmland in the MENA region (Figure 4.13).

Despite conditions of extreme water scarcity, MENA uses more water per capita than the global average (see Figure 4.14) due in large part to very low resource-use efficiencies, with Arab residential water and energy markets being among the most heavily subsidized in the world.

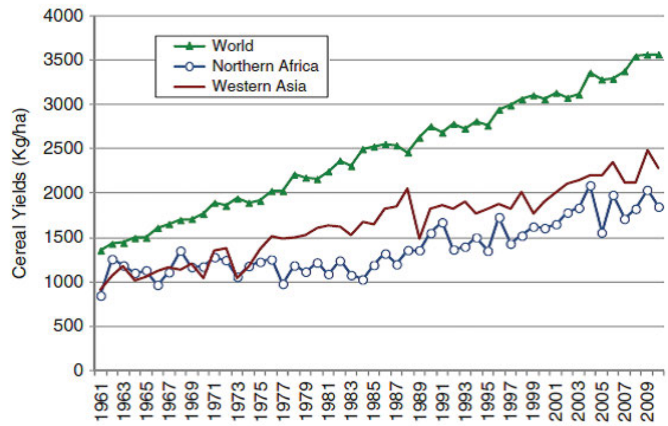
The growing water scarcity prevents MENA countries from producing all their required food domestically. The region as a whole exceeded its capacity for domestic food production in the 1970s (Allan 2001). The growing deficit has had to be met by food

**Figure 4.14:** Water footprints in m³ per capita and year.




Source: Mekonnen and Hoekstra (2011) as cited in Saab (2012).

**Figure 4.15:** Average cereal yields (kilograms per hectare) from 1961–2010 for Northern Africa and Western Asia as compared to the world average.




Source: FAOSTAT data in Selvaraju (2013).

imports, with associated imports of *virtual water* (i.e., water that has been used in the production of food abroad).

Across much of MENA, the conditions for rain-fed agriculture are marginal in terms of absolute water availability and the fact that the months of highest temperatures coincide with lowest precipitation. Despite this, around 70 percent of cropland area is rain-fed, with even higher percentages in most Maghreb and Mashrek countries. Wheat, barley, and some rice and sorghum are the main crops (Selvaraju 2013). Between 60–90 percent of all water used in MENA countries goes into agriculture (Selvaraju 2013). The Arab Gulf States depend exclusively on groundwater for irrigation, while the rest of the region (with the exception of Egypt) depends almost equally on surface water and groundwater (Siebert et al. 2010).

Irrigated agriculture is generally more productive per hectare than rain-fed agriculture and, as a result, makes up more than 50 percent of total agricultural production in the region. The productivity of rain-fed agriculture depends on stable and continuous rainfall. Rainfall is more variable in the MENA region than almost anywhere else (Bucknall 2007); in combination with often inefficient systems of production, this causes cereal yields to consistently remain below world averages (see Figure 4.15) (Selvaraju 2013).

As a result of low agricultural productivity and other factors (e.g., supply chain losses, lack of access to food, and low income levels), about 25 million people in the MENA region are currently undernourished—four million in Northern Africa (2.7 percent of the total population)[51] and 21 million in Western Asia (10 percent of the total population)[52] (FAO 2012a, 2013). Besides sub-Saharan Africa, the MENA region is the only region where the number of undernourished has increased since the 1990s (UNDP RBAS 2009).

While there are opportunities for intensification, agricultural production in the MENA region will remain severely water-limited. This is due to three key reasons: (1) that rain-fed agriculture often takes place under marginal precipitation conditions, so that the projected reduction in precipitation, in combination with increasing temperatures, will cause conditions to pass the threshold whereby irrigation would be required to maintain cropping systems; (2) that blue water resources are already fully or even overexploited (with competition from other sectors rapidly growing) such that, in the future, water allocations for irrigation cannot be increased or may even need to be reduced; and (3) that increasing precipitation variability and extremes will reduce the reliability of the crop water supply.

#### *4.4.1.2 Climate Risks to the Water Sector*

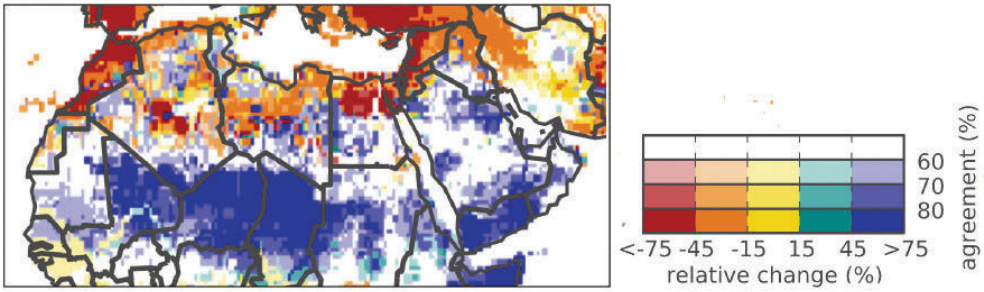
According to the IPCC WGII report, there is high agreement that climate change will reduce renewable surface water and groundwater resources considerably in most dry subtropical regions, aggravating competition for water within and among sectors. Reductions in water availability will generally be greater than the underlying reductions in precipitation, due to increases in potential evapotranspiration from warmer temperatures and non-linearity in the hydrological system (e.g. as precipitation is transformed into river runoff or groundwater recharge).

This analysis distinguishes between green water (plant-available water in soils, directly resulting from precipitation) and blue water (water in rivers and lakes, groundwater, and other water bodies), because these two types of water have different uses and

[51] With highest shares in Morocco (5.5 percent). The region includes Algeria, Egypt, Libya, Morocco, and Tunisia.

[52] With highest shares in Iraq (26 percent) and Yemen (32 percent). The region includes Iraq, Jordan, Kuwait, Lebanon, Saudi Arabia, Syria, Turkey, United Arab Emirates, and Yemen.

**Figure 4.16:** Relative change in annual water discharge in the Middle East and North Africa region in a 4°C world.




Relative to the 1986–2006 period based on an ISI-MIP model intercomparison using climate projections by CMIP5 GCMs as an input for global hydrology models (GHMs)21 (based on Schewe et al. 2013). Colors indicate the multi-model mean change, whereas the saturation indicates the agreement in sign of change over the ensemble of GCM—GHM combinations.

opportunity costs and respond differently to climate change. Blue water is used for irrigation and direct human consumption; green water supports rain-fed agriculture as well as other land-based ecosystems. Reductions in green water availability closely follow reductions in precipitation. Reductions in blue water availability are generally greater than the underlying reduction in precipitation.

As a result of global warming, especially changes in precipitation patterns, water availability will decrease in most parts of the MENA region throughout the 21st century (García-Ruiz et al. 2011) with decreases possibly exceeding 15 percent in a 2°C world and 45 percent in a 4°C world in parts of the region (Schewe et al. 2013). The exception is the southernmost areas Figure 4.16 shows changes in discharge (i.e., blue water availability) in the 21st century as a result of a multi-model inter-comparison with five global climate models and nine global hydrological models under the RCP8.5 scenario (Schewe et al. 2013).

The trend toward decreasing average water availability will be compounded by higher variability and more extremes, such as droughts and flooding, leading to a loss of reliability and increasing uncertainty in water management (García-Ruiz et al. 2011; Törnros and Menzel 2014). Examples of previous severe flooding events include those in Algiers in 2001, Morocco in 2002, and Tunis in 2003.

While decreasing annual average precipitation in combination with higher temperatures is likely to cause a reduction in surface runoff and groundwater recharge (aggravating current trends in groundwater overexploitation and depletion), the effects of increasing extremes (with higher rainfall per event) are not so straightforward. Liu (2011) found that in some arid regions the higher intensity of extreme precipitation events may increase the fraction of precipitation that enters the soil and becomes plant-available soil moisture and contributes to groundwater recharge. In other regions, the fraction of runoff and loss of water to unproductive evaporation, in contrast to productive plant transpiration, may increase.

In a Lebanon-based study, Shaban (2008) found that over the past four decades there has been a significant decrease (in the order of 25 percent) in those water resources, including most rivers and groundwater reservoirs, that are subject to climate change and other direct human pressures. The decrease was somewhat smaller (about 15 percent) for those water resources only subject to climatic trends (e.g., snow cover and precipitation). Lebanon's total water resources are projected to decrease by 6–8 percent for an increase in average annual temperature of 1°C, and by 12–16 percent for an increase of 2°C, using the HadCm3 and PRECIS global and regional climate models (Republic of Lebanon 2011).

## Surface Water

In a study of the tributaries of the Jordan River, Samuels et al. (2010) projected a reduction in mean daily runoff of 17 percent for the period 2036–2060 (relative to 1980–2004), using the A1B scenario and the ECHAM 5 global/RegCM regional climate model and the HYMKE watershed model. For the Zarqa basin in Jordan, Abdulla et al. (2008) projected changes in surface runoff ranging from –23.6 to +36.6 percent, and changes in groundwater recharge from –57.5 to +89.8 percent, in response to stylized combinations of temperature increases of 0–3.5°C and precipitation changes of between –20 and +20 percent, using the BASINS-HSPF model. It is important to note that the positive changes for precipitation (and subsequently runoff and recharge) are very hypothetical, given the strong agreement of global climate models projecting a decrease in precipitation.

For the eastern Anatolian mountains (the headwaters of the Euphrates and Tigris rivers), snow water storage is expected to decrease (see Box 4.1: Snow Water Storage) and, accordingly, a runoff decrease of 25–55 percent is projected between 1961–1990 and 2071–2099, using different SRES scenarios (A1FI, A2 and B1), different GCMs (ECHAM5, CCSM3 and HadCM3), and the RegCM3 regional climate model (Bozkurt and Sen 2013).

For Morocco, the 2nd National Communications (Kingdom of Morocco 2010) projected a decrease in river discharge of

## Box 4.1: Snow Water Storage

Mountainous areas notably in Morocco, Algeria, Lebanon, Syria, Iraq, the Islamic Republic of Iran, and Turkey, play an important role in the water supply of the MENA region. Under climate change, however, mountainous areas are expected not only to experience a reduction in total precipitation but also a reduction in the fraction of precipitation falling as snow, thereby affecting snow cover and snow water storage.

Changes in melt-water regimes are expected to result in a shift in peak river flows toward the earlier months of the year, with negative impacts for downstream riparian systems in terms of water availability and seasonal shortages during the hot and dry summer months. In the 2nd National Communications of the Republic of Lebanon (2011), the upper Nahr el Kalb basin was analyzed under a stylized warming of 2°C and 4°C. Snowpack volume was projected to shrink from a total of 1,200 million $m^3$ to 700 million $m^3$ under 4°C warming and 350 million $m^3$ under 2°C warming. Drought periods would thereby be expected to occur 15–20 days earlier (for 2°C warming) and more than a month earlier (for 4°C warming), according to the report. For the Euphrates and Tigris basins, snow water equivalent (the amount of water stored in the highland snowpack) has been projected to decrease by 55 percent in the B1 scenario and 87 percent in the A1F1 scenario by 2071–2099, relative to 1961–1990 using the CCSM3 global climate model (Bozkurt and Sen 2013).

15–55 percent by 2080 (relative to 1961–1990) for different scenarios and river basins, with an average decrease under the B2 scenario of 21 percent, and a decrease of 34 percent under the A2 scenario, using the WatBal model.

#### Ground Water

Groundwater in many water-scarce regions serves as a buffer for variable surface water availability. The buffering function of groundwater can only be maintained in the long term if there is a balance between recharge and withdrawal. In most MENA countries, however, groundwater is severely over-extracted (beyond the recharge rate). With falling groundwater levels, extraction becomes ever more energy intensive and expensive, eventually forcing the abandonment of wells. Climate change is expected to accelerate the loss of groundwater buffer capacity as decreasing rainfall decreases groundwater recharge in a non-linear way.

For the West Bank and Gaza, Mizyed (2008) projected a decrease in recharge between 7.1 and 50.9 percent for stylized warming scenarios from 2°C to 6°C in combination, with a decrease in precipitation of 0–16 percent, using a GIS-based spatial analysis.

For Algeria, the 2nd National Communication report (Republique Algerienne Democratique et Populaire 2010) projected a decrease in groundwater resources of 10–15 percent by 2050 relative to 1961–1990 under an IS92a scenario and using the GR2M model.

For Saudi Arabia, increases in reference evapotranspiration are expected to reduce groundwater recharge by 2–12 percent of total annual recharge in 2070–2100 relative to 1960–1990 using the regional climate model PRECIS and SRES A2 (Kingdom of Saudi Arabia 2011).

### *4.4.1.3 Climate Risks to the Agricultural Sector and Food Security*

The potential impacts of climate change on agriculture are various. In water-limited regions, the length of the growing period is generally reduced if precipitation decreases while temperature and evaporative demand simultaneously increase. Higher rainfall variability with more intense and more frequent droughts, and possibly also floods, can cause more frequent crop failures. With increasing temperatures, several crops will exceed their temperature tolerance levels. All of these effects contribute to an overall reduction in crop yields.

Increasing atmospheric $CO_2$ concentration, on the other hand, can decrease crop water demand and increase crop productivity. It is important to note that the following studies do not account for adaptation, such as crop breeding, improved agricultural management practices, and additional irrigation. Adaptation measures have great potential given the very low level of agricultural productivity across the MENA region.

#### Length of the Growing Period and Crop Yields

Lower rainfalls and higher temperatures are expected to shorten the growing season for wheat in the MENA region by about two weeks by mid-century (Ferrise et al. 2013), as projected under the A1B scenario to 2031–2050, using the AORCM model. For Tunisia, Mougou et al. (2010) projected a shortening of the wheat growing period by 10 days for 1.3°C, by 16 days for 2°C, by 20 days for 2.5°C and by 30 days for 4°C warming, and a reduction in yields of 10 percent for a 10 percent decrease in precipitation, 30 percent for a temperature increase of 1.5°C, and 50 percent for a combination of both scenarios, using the DSSAT crop model.

Most agricultural activities in the MENA region take place in the semi-arid climate zone, either close to the coast or in the highlands (Figure 4.13), where rainfall and green water availability are predicted to decline most strongly (see Section 4.3.3). The resulting increases in irrigation water demand will be difficult to meet due to a simultaneously increasing blue water scarcity. Due to increasing water scarcity, in combination with higher temperatures which are expected to deviate more and more from the temperature optima of several crops (and possibly even exceed their heat tolerance levels), agricultural productivity is expected to drop in the MENA region.

In a study by Drine (2011), North African crop yields were projected to decrease by 0.8–12.8 percent under conditions of 20 percent less precipitation, or by 1.6–26.6 percent under conditions of 2°C warming, using a logarithmic regression model. For Algeria and Morocco, yield reductions of 36 percent and 39 percent (26 percent and 30 percent including the $CO_2$ fertilization) respectively are projected for 2080 (relative to 2003) for a B2 scenario (Schilling et al. 2012). For the southwestern Mediterranean (Tunisia, Algeria, and Morocco), Giannakopoulos et al. (2009) projected yield reductions for a variety of crops of between 1.5 and 23.9 percent; for the southeastern Mediterranean (Jordan, Egypt, and Libya), yield changes of between +3.7 and –30.1 percent were projected for the period 2030–2060 relative to 1961–1990. This study used the A2 and B2 scenarios, the HadCM3 climate model, and the CROPSYST crop model.

In a study of Jordan's Yarmuk basin, Al-Bakri et al. (2011) projected changes in wheat yields by mid-century ranging from –0.5 to +1.5 tons per hectare and changes in barley yields ranging from about –0.05 to –0.5 tons per hectare, starting from current values of about 1 ton per hectare. These ranges were calculated for different stylized temperature (+1°C to +4°C) and precipitation (–20 to +20 percent) scenarios, using the DSSAT crop model. The scenarios that include precipitation increases are very hypothetical, given the strong agreement of global climate models regarding a projected decrease in precipitation.

For Syria, a study by Verner and Breisinger (2013) used the DSSAT crop model to project reductions in rain-fed wheat yields of between 23 and 57 percent for 2041–60, relative to 1991–2010, under the A1B scenario.

Egypt's 2nd National Communications report (EEAA 2010) projected a reduction in productivity under climate change of 11–20 percent by 2050 for wheat, rice, maize, and barley, and an increase in irrigation water demand by 2050 of about five percent across all SRES scenarios.

For Tunisia, a study by Lhomme et al. (2009) found increases as well as decreases in yields for 2071–2100 relative to 1961–1990, depending on the location within the country and the sowing rules applied, using the ARPEGE climate model for the A1B scenario.

### Meta-Analysis of the Impacts of Climate Change on Crop Yields

A meta-analysis of the impacts of climate change on crop yields for the MENA region was conducted based on one single dataset that consists of data from 16 different studies analyzed (see Section 6.3, Meta-analysis of Crop Yield Changes with Climate Change, for details on data processing and methodology). The aim of the meta-analysis was to summarize the range of projected crop yield changes in the literature and to assess consensus for the MENA region. The dataset was used to address three main questions: (1) what are the likely impacts of incremental degrees of warming on yields?; (2) what is the impact when also considering adaptation measures and the effects of $CO_2$ fertilization (see Box 2.4: The $CO_2$ Fertilization Effect) on change in crop yields?; and (3) to what extent can adaptation measures and/or the effects of $CO_2$ fertilization counteract the negative effects of increased temperature? Due to the lack of data, both the influence of adaptation measures and $CO_2$ fertilization on crop yields could only be assessed below a temperature increase of 2°C.

**Table 4.6:** Summary of crop yield responses to climate change, adaptation measures, and $CO_2$ fertilization.

| | SLOPE | r2 | t-STAT | p-VALUE |
|---|---|---|---|---|
| Full dataset | –0.08 | 0.16 | –5.5 | <0.001*** |
| Full dataset (below 2°C) | –0.06 | 0.028 | –1.86 | 0.065 |
| $CO_2$ fertilization | 0 | 0 | –0.04 | 0.96 |
| Adaptation measures | 0.11 | 0.33 | 1.22 | 0.3 |
| Without adaptation measures or the effects of $CO_2$ fertilization | –0.08 | 0.16 | –3.54 | 0.007** |

Results of a general linear model applied to all studies with reported values for changes in yield and changes in temperature, to studies considering the effect of $CO_2$ fertilization, to studies not considering the effect of $CO_2$ fertilization, and to studies not considering the effects of adaptation measures. Significance levels: *P<0.05, **P<0.01, ***P<0.001.

Overall, there exists a significant correlation between crop yield decreases and temperature increases (see Figure 4.17 and Table 4.6) regardless of crop type or whether the effects of $CO_2$ fertilization or adaptation measures are taken into account. If only studies with temperature increases below 2°C are included, then the correlation is no longer significant (see Table 4.6). This suggests that below a 2°C threshold the effects of adaptation measures and $CO_2$ fertilization may compensate for the adverse effects of climate change.

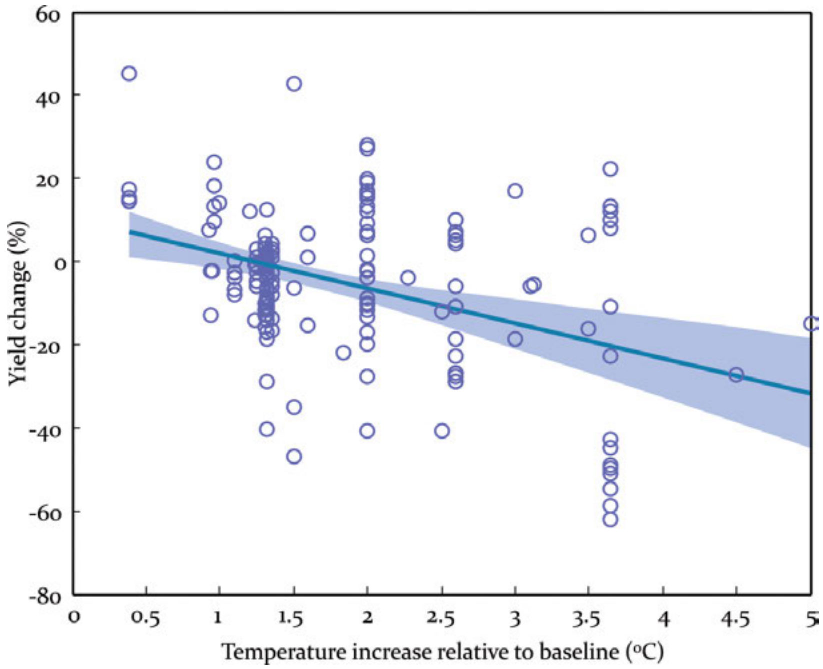
If the effects of $CO_2$ fertilization are considered, no significant relationship between crop yield change and temperature increase is revealed (Figure 4.17 and Table 4.6). The beneficial effects of $CO_2$ fertilization are highly uncertain and there is considerable doubt that the full benefits can be obtained (Ainsworth et al. 2008) (see Box 2.4). The relationship between the change in temperature and crop yield response, in a scenario under which the effects of adaptation measures are taken into account, is positive but not significant (Figure 4.18 and Table 4.6).

Previous meta-analyses (Easterling et al. 2007; World Bank 2013) showed that above this temperature threshold the negative effects of climate change on crop yields are dominant, with crop yields considerably declining regardless of the positive effects of adaptation measures and $CO_2$ fertilization. This could not be tested here due to lack of data. The relationship between the change in crop yield and temperature increase is significantly negative in scenarios that do not consider adaptation measures or $CO_2$ fertilization.

### Cropland

According to Evans (2008), a warmer and drier climate is projected to shift vegetation and agricultural zones northward (e.g. by 75 km) for 2090–2099 relative to 2000–2009 for the A2 scenario at the 0.9

**Figure 4.17:** Meta-analysis of the impact of temperature increase on crop yields.




Best-fit line over the full dataset for the MENA region (blue line) and 95 percent confidence interval of regressions consistent with the data based on 500 bootstrap samples (blue shade). The influence of temperature increase on crop yield change is significant.

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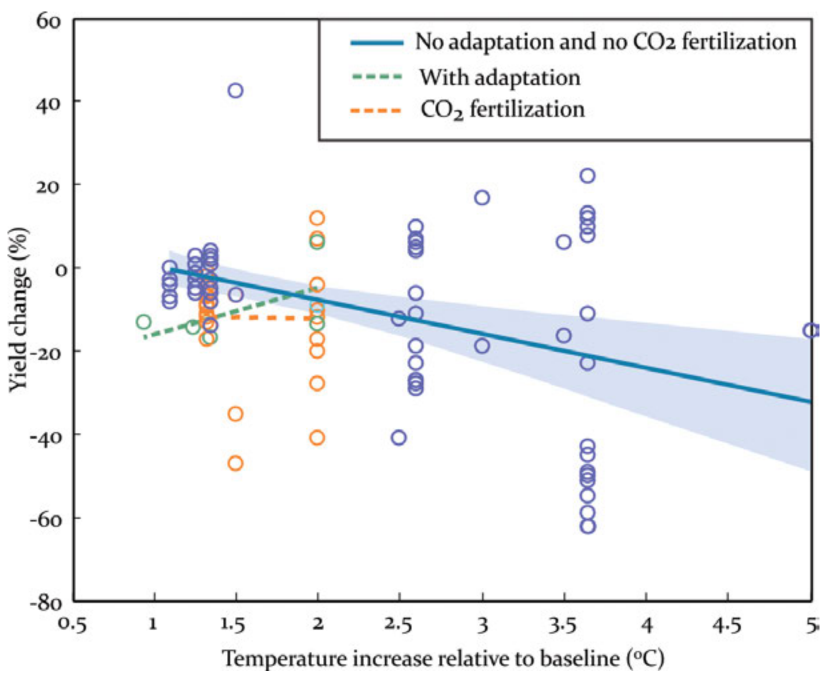
**Figure 4.18:** Meta-analysis of the impact of temperature increases on crop yields excluding adaptation and $CO_2$ fertilization.




Best-fit lines for MENA studies considering neither the effect of adaptation measures nor of $CO_2$ fertilization (blue line) and 95 percent confidence intervals of regressions consistent with the data based on 500 bootstrap samples (blue shade), for studies considering the effects of adaptation measures (green line) and studies considering the effects of $CO_2$ fertilization (orange line). The solid line depicts a significant relationship and dotted lines non-significant relationships.

significance level. In Lebanon, shifts in agro-climatological zones may push special crops, including cherry and olive plantations, to higher elevations (Republic of Lebanon 2011). Ferrise et al. (2013) also projected a shift northward for olive plantations.

Large fractions of currently marginal rain-fed cropland are expected to be abandoned or transformed into grazing land; current grazing land, meanwhile, may become unsuitable for any agricultural activity (Evans 2008). Increasing aridity reduces the available soil moisture, exacerbating the effects of ongoing land degradation. Evans (2008) projected the area viable for rain-fed agriculture in the Middle East to decrease by more than 8,500 $km^2$ by mid-century, and by more than 170,000 $km^2$ by late-century (at the 0.9 significance level), when using the 200 mm isohyet as the limit for rain-fed agriculture, below which only seasonal grazing is practiced. The study used the A2 scenario and an ensemble of 18 GCMs which project a temperature increase of 1.4°C in the first half, and an additional 2.5°C warming in the second half of the century, as well as a decrease in precipitation of 8.4 percent in the first half and another 17 percent in the second half of the century.

#### Livestock

Livestock is an important component of rural livelihoods and food security in the MENA region. Climate change will impact livestock production through various pathways, including changes in the quantity and quality of available feeds and the length of grazing season, additional heat stress, loss of drinking water availability, and changes in livestock diseases and disease vectors (Thornton et al. 2009). These climate-related pressures may be amplified by, or may amplify the effects of other pressures (e.g. rangeland degradation, fragmentation of grazing land, changes in land tenure, and lack of market access).

The vulnerability of livestock production systems to droughts was recently on display in northeastern Syria, where herders lost almost 85 percent of their livestock as a result of recurring droughts from 2005–2010 (Selvaraju 2013). The precarious situation of the rural population in this region caused large waves of migration to the cities.

### *4.4.1.4 Synthesis*

The MENA region, also known as the "cradle of agriculture" or "cradle of civilization," is one of the world's most vulnerable regions to climate change in combination with other pressures. From the current situation of critical water and land scarcity, both the 2°C and 4°C warming scenarios will result in further increased pressures on water resources and agriculture, so that by the end of the century climate risks are projected to be much more severe. Other pressures, including increasing demand for food and water and further resource degradation, if following current trends, will multiply the impacts of climate change.

Impacts on water resources will have severe consequences for the agricultural sector, which is the largest user of water in the region. There is a close relationship between climate risks for the water sector and the agricultural sector, with feedbacks from agricultural water use (e.g., increasing water demand, more irrigation, and pollution of rivers) potentially compromising other water uses (the water-agriculture nexus).

The MENA region is very likely to experience a decrease in crop productivity unless effective adaptation measures are taken and global $CO_2$ emissions are reduced. The impacts of climate change on agricultural production and food security, which are expected to grow throughout the 21st century, will be aggravated by water and land resource degradation and also by indirect climate change effects (occurring in major food exporting regions) through higher food prices on world markets. If groundwater buffers fail due to prolonged droughts leading to long-term decreases in recharge, as recently observed in northeastern Syria, agricultural land use and livelihoods will have to be abandoned.

MENA countries have at their disposal a wide range of adaptation options for reducing their overall vulnerability. Demand management and increased resource use efficiencies can provide many opportunities for adapting to increased water scarcity. Diversification of the MENA countries' economies also holds a large potential for increasing resilience to climate and other risks. The MENA countries are blessed with rich renewable energy resources, in particular solar and wind, providing them with climate change adaptation and mitigation options (and combinations of them, for example, via solar desalination). Knowledge and technology transfer and investments across the region from more to less advanced countries can help to overcome the resource predicament and contribute to prosperity and stability.

While biophysical impacts vary only slightly across the region, vulnerability and socioeconomic impacts show a clear division between the (oil) rich Arab Gulf countries and the rest of the region. While the former have the financial means for adaptation (e.g., desalination technology, increasing food imports), the latter are much more vulnerable to climate risks. Vulnerability also varies a lot within countries, with poor and rural populations at particular risk (e.g., due to their dependency on agriculture).

## 4.4.2 Desertification, Salinization, and Dust Storms

### *4.4.2.1 Desertification*

Large parts of the MNA region are covered with drylands, either dry-subhumid, semi-arid, arid or hyper-arid. These harsh environments support, in addition to their limited water resources, fragile ecosystems. The concept of desertification is vague, and many definitions exist to describe the phenomenon (Verstraete et al. 2009). Most reports and studies on this topic refer to the UN Convention to Combat Desertification (UNCCD 1994), which defines desertification as land degradation affecting drylands (Adeel et al. 2005; Boko et al. 2007; Reynolds and Stafford Smith

**Figure 4.19:** The far-reaching impacts and downward spiral of desertification.


Source: (UNCCD Secretariat 2013).

2002; Reynolds et al. 2007; Safriel 2009). This process includes a change in soil properties, vegetation, or/and climate (D'Odorico et al. 2013).

Desertification transforms a dryland ecosystem into a new ecosystem with a lower level of service provision (Safriel and Adeel 2005). This causes various stresses. Loss of vegetation cover, soil erosion, dust storms, salinization, and a decrease in soil productivity are some common threats in a downward spiral that lead to a decrease in agricultural yields, loss of biodiversity, poverty, reduced human wellbeing, and migration (Bayram and Öztürk 2014; Boko et al. 2007; D'Odorico et al. 2013; Safriel and Adeel 2005, 2008) (see Figure 4.19).

The processes and drivers which trigger and control this ecosystem change are often labeled as either the "desert paradigm" or the "desert syndrome." The Millennium Ecosystem Assessment (2005) described this phenomenon as the "long-term failure to balance demand for and supply of ecosystem services in drylands." Population growth, poverty, marginalization, and environmental degradation are coupled in socioecological feedback loops that drive the system into a downward spiral of desertification (D'Odorico et al. 2013; Easdale and Domptail 2014; Reynolds and Stafford Smith 2002; Safriel and Adeel 2005; Stafford Smith 2008; Verstraete et al. 2009). Finally, the fragile balance between the dryland ecosystem and the people living in it, which has been established over generations, is destabilized. A new equilibrium state is established in the degraded land in a process that is all but irreversible (Safriel and Adeel 2005; Seely et al. 2006).

## Desertification and Climate Change

The role of climate change in desertification can be multifaceted, and it varies depending on local conditions and the interactions among drivers. An increase in temperatures and evapotranspiration rates, a change in the precipitation regime, and an intensification or change in frequencies of extreme events can all directly trigger or enhance desertification processes (Aguirre-Salado et al. 2012; Belaroui et al. 2013; Scheiter and Higgins 2009; Schilling et al. 2012; Verstraete et al. 2009). Furthermore, these climatic alterations can indirectly push the dryland ecosystem towards desertification—for example, via a shift in biomes, an increase in bush fires, or the lowering of groundwater tables (Geist and Lambin 2004).

No study has attributed recent climate change as the single driver of desertification. As a result, it is difficult to quantify the role of climate change relative to other drivers (Evans and Geerken 2004; Herrmann and Hutchinson 2005; Wessels et al. 2007). It is clear, however, that climate change can modify the natural conditions of biomes in many ways and that it generally makes the ecosystems more vulnerable to desertification processes (Evans and Geerken 2004; Verstraete et al. 2009; Xu et al. 2011).

The desertification process can also affect the climate. At the regional scale, the decline of plant cover reduces evapotranspiration and increases mean temperatures. This leads to a decrease in humidity within the regional climate system, which in turn may reduce the mean annual precipitation and/or cause greater variability in precipitation patterns (Abiodun et al. 2007; D'Odorico and Bhattachan 2012; Foley et al. 2003; Mahmood et al. 2013). At the global scale, desertification is a driver of climate change through the loss of carbon sequestration capacity in dryland ecosystems and an increase in land-surface albedo (Adeel et al. 2005; Aguirre-Salado et al. 2012). Recent studies show, however, that the effect of $CO_2$ fertilization on drylands (see Box 4.2) can potentially reverse the feedback loop and transform desert into grassland.

There are attribution studies on desertification or national reports explaining the causes of desertification for all the MENA countries. All of these studies attribute desertification at least in part to malpractices in land management.

Some studies identify climate change as an additional driver of desertification. In most cases, the observed driver was a change in rainfall pattern, with either a negative trend or higher variability. For example, Conca et al. (2010) analyzed changes in humidity in the United Arab Emirates, and concluded that a reduction in humidity linked to climate change during the last decade could be responsible for an increase in desertification in the hyper-arid areas. For many of the studies, however, it is not clear whether the increase in aridity is within the normal climatic variation or connected to recent climate change.

## Box 4.2: The $CO_2$ Fertilization Effect on Drylands

Recent studies show a major influence of the $CO_2$ fertilization effect on vegetation cover/growth in dryland ecosystems. Field studies found that the $CO_2$ effect already influences African dryland ecosystems, notably savannahs (Donohue et al. 2013; Kgope et al. 2009). The increasing atmospheric $CO_2$ concentration affects the photosynthetic pathway of C3 plants (trees) and C4 plants (grasses) by improving the plants' water use efficiency. This forces transitions in ecosystems characterized by higher biomass and/or woody-plant dominance.

For grassland ecosystems, like savannahs, the $CO_2$ fertilization effect leads to an increase in woody species which profit more from the additional $CO_2$ in the atmosphere than C4 plants (Bond and Midgley 2012). However, C4 plants also profit from the $CO_2$ fertilization effect, and Higgins and Scheiter (2012) project a substantial re-greening of deserts on the African continent even under decreasing precipitation.

### Projected Desertification

Although human influences related to land management have been identified as direct drivers of desertification, climate change is expected to alter the underlying natural conditions under which desertification may occur. Projections need to incorporate the natural and human aspects of desertification (Verstraete et al. 2009). To date, however, there is no regional study of future land degradation that assesses both climate change and social dynamics as drivers of desertification. As land degradation of drylands is likely to occur under certain climate change conditions, projections of these climate parameters and their potential impact on ecosystems may be used as indicators to assess impending desertification.

Gao and Giorgi (2008) projected the climate in the Mediterranean region (including North Africa and the Western Mashrek) for the period 2071–2100 with the regional climate model RegCM, driven by the global model HadAM3H under the SRES scenarios A2 and B2. From the results, they derived three different measures of aridity from precipitation and temperatures. As a first measure they used the changes in climatic conditions according to the Köppen-Geiger classification under both emissions scenarios (Köppen 1936) and found that subtropical summer-dry climates turn into dry arid or dry semi-arid climates. The Budyko-dryness index (Budyko 1958) and the UNEP dryness index (UNEP 1992) support this change and they show a strong increase of aridity in the whole region. The authors concluded that North Africa and western Mashrek are especially at risk of both increased water stress on natural ecosystems and desertification.

Scheiter and Higgins (2009) projected a reduction in desert ecosystem area over Africa because of the $CO_2$ fertilization effect. They used the adaptive dynamic global vegetation model aDGVM, which can also account for the influence of bush fires on vegetation. The model was driven using projected atmospheric $CO_2$ concentrations under the SRES scenario A1B, and temperature and rainfall projections were derived from the climate model ECHAM5. At the baseline year of 2008, 32.8 percent of Africa´s land surface was covered with deserts. By 2100, desert cover is projected to decline to 27.1 percent including bush fires, and to 26.9 percent without taking bush fires into account. The authors explained that the projected reduction in desert ecosystem area is due to the $CO_2$ fertilization effect and an increase in the potential growing season for grasses and trees under elevated temperatures. In a similar study of Africa, Higgins and Scheiter (2012) once again used the aDGVM and ECHAM5 models under the SRES A1B scenario. They projected a reduction in desert area from 28 percent in 1850 to 23 percent in 2100, whereby desert biomes shift to grassland mainly due to the positive effects of increased $CO_2$ concentrations on plant growth and biomass.

### *4.4.2.2 Salinization*

While saline and sodic soils can be found naturally in many parts of the MENA region, this report refers to the soil degradation processes of salinization and sodification. Salinization is a form of soil degradation whereby water-soluble salts accumulate in the soil (Jones et al. 2013; JRC 2009). A special form of salinity is sodicity, whereby sodium is accumulated in the soil (D'Odorico et al. 2013). Salinization is typically connected to the desertification process. High levels of salinity in soils affect plant growth through an increase in osmotic pressure (making it more difficult for plants to draw water from the soil) as well as through the toxic effects of salts. These processes make salinization a threat to both agriculture and natural ecosystems (Sowers et al. 2011; Vengosh 2014).

The most common causes of salinization are non-groundwater-associated salinity (whereby dissolved salts from rocks are introduced to the soil via rain), groundwater-associated salinity (groundwater infusing the salt into the soils), and irrigation-associated salinity (D'Odorico et al. 2013). Climatic conditions in particular influence the latter two mechanisms. A decrease in precipitation and an increase in temperatures lead to a higher demand for irrigation, which causes salinization when drainage is not adequate. The intensification of irrigation may also lead to an increase in freshwater withdrawal from the groundwater, triggering salinization of aquifers and also aggravating soil salinization (D'Odorico et al. 2013; Vengosh 2014).

The increase in salinization with further intrusion due to sea-level rise under climate change holds not only for groundwater but also for other water resources in the region. (Sowers et al.

2011). River runoff and aquifer replenishment rates typically decrease under drier conditions, causing an increase in the salt-concentration of the remaining water. The higher salinity in the river also affects other water resources (e.g., lakes and groundwater aquifers), leading to a general increase in salinity, including soil salinity (Vengosh 2014). In the MENA region, river salinization can be observed in the Euphrates and the Tigris rivers (Odemis et al. 2010), in the Jordan River (Farber et al. 2004), and in the Nile (Elewa and El-Nahry 2008; El-Nahry and Doluschitz 2010).

In coastal areas, the intensive extraction of groundwater leads to seawater intrusion into the aquifers, causing severe salinization. This process is accelerated by climate-change-induced sea-level rise (Carneiro et al. 2009; Niang et al. 2010). The Nile Delta (see Box 4.3), an area that is home to more than 35 million people and that provides 63 percent of the agricultural production of Egypt, is especially vulnerable to salinization under changing climate conditions (Bohannon 2010; El-Nahry and Doluschitz 2010; Hereher 2010). According to Mabrouk et al. (2013), salinization is very likely to rapidly worsen under climate change; the authors call for an integrated three-dimensional groundwater modeling of the Nile Delta in order to fully understand the implications of sea-level rise and salinization.

#### 4.4.2.3 Dust Storms

Dust storms are a typical phenomenon in arid regions without full vegetation cover (Squires 2002). Covered mostly by drylands, the MENA region is frequently threatened by dust storms that cause widespread damage to people, to agriculture, and to the overall economy (Akbari 2011; Kumar 2013; UN 2013; UNCCD Secretariat 2013; Verner 2012).

The extent of dust storms varies widely, depending on the meteorological conditions, the land surface, and the size of the particles transported. In the MENA region, dust storms reach large scales in terms of mass lifting, spatial extent (i.e., 100–1000 km), and duration (i.e., from several hours to several days) (Ghoneim 2009; Kocha et al. 2012; Miller et al. 2008; Pey et al. 2013). The wall of dust and sand can reach concentrations of 6000 µg particles per $m^3$ (Goudie 2009), causing traffic accidents, disruptions of flight traffic, destruction of telecommunications and mechanical systems, and damage to crops. In addition, dust storms influence the performance of solar photovoltaic power plants, directly by depositing dust on the panels and indirectly by reducing radiation. In Egypt, for example, Elminir et al. (2006) found a 12–52 percent reduction in transmittance, depending on the amount of dust and tilt angle, and a 17 percent per month reduction in output power. Mani and Pillai (2010) reviewed several impact studies and reported reductions in photovoltaic performance by 17–32 percent in Saudi Arabia and Kuwait.

Agricultural productivity is also affected in the long term by soil loss, as dust storms in particular remove light, nutrient-rich particles and organic matter (Akbari 2011; Elasha 2010; Notaro et al. 2013). In addition to economic losses, there are severe health impacts for people from breathing dust particles and from the airborne microorganisms that are transported in dust clouds (Goudie 2009; Griffin 2007; Kanatani and Ito 2010; de Longueville et al. 2013).

Fine atmospheric dust, as an aerosol, can also affect the local climate, as it influences cloud formation and precipitation even in remote regions (Creamean et al. 2013; Jung et al. 2013). Dust storms not only influence local climate, but the frequency and magnitude of dust storms is also affected by climate change and desertification in different ways. Decreasing vegetation cover not only increases the sources of dust, due to an increase in bare soils (Bayram and Öztürk 2014; Mulitza et al. 2010; Pierre et al. 2012), but may also affect wind speeds by decreasing the surface roughness (Cowie et al. 2013; Pierre et al. 2012).

There are no studies linking projected climate change and changes in dust storm occurrence in the MENA region (Goudie 2009). The frequency and strength of dust storms depend on both the availability of dust (and therefore regional vegetation cover) and wind patterns. The vegetation coverage is directly linked to desertification, which is a highly uncertain process under future climate conditions and depends on both natural and human factors. Wind is a climatic factor and changes in wind patterns can be projected from climate models. However, there are currently no regional studies on changing wind patterns under climate change in the MENA region; as a result, future trends have to be derived from global studies.

#### 4.4.2.4 Synthesis

Desertification, salinization, and dust storms are closely related in the MENA region. In an arid environment in which irrigation accelerates the salinization of soils and results in a degraded desert environment, dust storms carry away the soils, putting pressure on agriculture and further driving the desertification process. This narrative is referred to in the literature as the desertification paradigm; it is oversimplified, but the core message is clear—none of these processes stands alone. In many aspects, salinization is an important driver of desertification (JRC 2009), but land use and land cover changes (e.g., land clearing and replacing natural vegetation with annual crops) can also reinforce or even trigger the salinization process (Vengosh 2014).

In general, desertification, salinization, and dust storms are well understood and described in the literature. There are still large gaps, however, when it comes to the multifaceted role of climate change (Verstraete et al. 2008, 2009) and the role of $CO_2$ fertilization (Donohue et al. 2013; Higgins and Scheiter 2012). This may be one reason for the lack of quantitative projections on desertification that account for biophysical (including climate change), socioeconomic, and anthropogenic drivers (including population growth and land use change). Numerous studies on the observed impacts of desertification in the

MENA region do however demonstrate a strong need for integrated modeling approaches to assess desertification under global climate change. As the MENA region is already prone to desertification, and with climate change bringing increasingly arid conditions, sensitivity to desertification is likely to increase. A reduction in precipitation, an increase in extreme events (e.g., drought and flash floods), and an increase in temperature and evapotranspiration will reinforce desertification in the region (WMO 2007).

### 4.4.3 Human Health

People in the MENA region face a variety of health risks, many of which are exacerbated by the hot and arid conditions and relative water scarcity that generally characterize the region. For example, trachoma (an infectious disease affecting the eyelids) tends to occur in dry areas with poor sanitation; it is endemic in Morocco, Algeria, Libya, Egypt, Iraq, the Islamic Republic of Iran, Oman, and Yemen (Smith et al. 2013). The MENA region is also experiencing a resurgence of several vector-borne and viral diseases that had previously been in decline (Lelieveld et al. 2012). Climate change may compound the challenge of managing these diseases.

#### 4.4.3.1 Vector-Borne Diseases

Malaria is rarely endemic in North Africa, and the measures in place to control the disease are considered effective. The disease is also present in the Middle East, with cases reported in the Islamic Republic of Iran, Iraq, and Saudi Arabia, but in most countries endemicity is relatively low and localized. Malaria is, however, prevalent in Djibouti and Yemen (WHO 2013*a*); (WHO and EMRO 2009).

While the relationship between climate change and malaria remains somewhat in dispute, evidence indicates that changes in climatic factors can affect the incidence of the disease in the MENA region. Malaria distribution and seasonal occurrence have been linked to temperature, elevation, humidity, and low rainfall in the Islamic Republic of Iran (Salehi et al. 2008). Environmental changes indirectly associated with climate change could also favor the disease vectors of malaria such as the *Anopheles sergentii* mosquito. This mosquito is known as the "oasis vector" due to its prevalence in oases across the Sahara and its ability to cope with extreme climatic conditions. Lotfy (2013) suggested that the underground water reservoirs in the Western Desert being constructed by the Egyptian government to mitigate water stress could aid the emergence of *Anopheles sergentii* in new areas. In the World Health Organization Eastern Mediterranean region B (EMR-B),[53] the additional population exposed to risk of malaria for at least one month of the year by the 2080s is 20 million under the B2 scenario, 34 million under B1, 62 million under A2, and 39 million under the A1F1 scenario (van Lieshout et al. 2004).

Lymphatic filariasis, commonly known as elephantiasis, is a disease of the lymphatic system caused by parasitic worms transmitted by mosquitoes. Like malaria and other mosquito-borne diseases, the prevalence of lymphatic filariasis could be affected by climate change (via the effects of changes in temperature, rainfall, and humidity on mosquito breeding and survival rates). While it is currently present in North Africa only in Egypt's Nile Delta, Slater and Michael (2012) project with a 75–100 percent probability that the range of the disease could extend to include much of coastal North Africa by 2050 under both the SRES B2 and A2 scenarios.

Leishmaniasis, a skin disease carried by sandflies endemic to the MENA region, is also affected by climatic factors (Ben-Ahmed et al. 2009; Toumi et al. 2012); it is also affected by environmental factors such as dam construction (Riyad et al. 2013). The disease, which occurs in several forms, can result in morbidity, disfigurement, and mortality (McDowell et al. 2011)—and is considered a major public health problem in the region (Postigo 2010). Outbreaks are reportedly becoming more frequent in Tunisia, Algeria, and Morocco, where the range of the disease has expanded due to a variety of environmental (e.g., agricultural projects) and human factors (e.g., migration of nonimmune populations) (Riyad et al. 2013).

A serious and potentially fatal form of the disease is visceral leishmaniasis. A study conducted in the northwest part of the Islamic Republic of Iran reported a strong association between rising temperatures and growing populations of carrier sandflies (Oshaghi et al. 2009). A study from Tunisia showed that large numbers of Mediterranean visceral leishmaniasis (MVL) cases tend to be preceded two years earlier by a particularly rainy season (Ben-Ahmed et al. 2009). Increased rates of MVL transmission in the canine reservoir following the rainy season could explain the delayed increase in the incidence of human cases.

Schistosomiasis, or bilharzia, is transmitted by snails and is found in North Africa, the Islamic Republic of Iran, Iraq, Saudi Arabia, and Yemen. Schistosomiasis is expected to be affected by temperature changes, although in a non-linear way (Mangal et al. 2008). Mangal et al (2008) found that the burden of infection within infected people increases by more than tenfold as mean ambient temperatures rise to 30°C; mean temperatures above 30°C could cause the mortality of snail hosts, however, potentially limiting further transmission. This means that increased temperatures could result in increased morbidity and mortality for infected people rather than an increased prevalence of infection.

#### 4.4.3.2 Food and Water-Borne Diseases

The prevalence of food-borne diseases such as salmonella and *Escherichia coli*, and water-borne diseases such as cholera, dysentery, and typhoid fever, is expected to be affected by changing

[53] This region includes Bahrain, the Islamic Republic of Iran, Jordan, Kuwait, Lebanon, Libya, Oman, Qatar, Saudi Arabia, Syria, Tunisia, and the United Arab Emirates. Note that it excludes Djibouti, Egypt, Iraq, Morocco, and Yemen. Malaria endemicity in Djibouti, Iraq, and Yemen is currently relatively high.

temperature and rainfall patterns. Outbreaks of cholera, for example, have followed seasonal patterns in the last three decades, with the effect being stronger at latitudes further away from the Equator (Emch et al. 2008). Cholera outbreaks correlate with high temperatures and can follow extreme weather events that disrupt water supplies (e.g., drought and flooding). In recent years, cholera has caused deaths in Iraq, the Islamic Republic of Iran, and Yemen (WHO 2013*b*).

The incidence of diarrheal disease among children is high in parts of the MENA region where warm weather, inadequate access to drinking water, poor sanitation, and poverty collide (Kolahi et al. 2010). Kolstad and Johansson (2011) projected increased rates of diarrheal diseases as a result of climatic changes in the A1B scenario. The relative risk of diarrheal disease (compared to a 1961–1990 baseline) is expected to increase in North Africa by 6–14 percent for the period 2010–39, and by 16–38 percent for the period 2070–99, and by 6–15 percent in the Middle East for the period 2010–2039, and 17–41 percent for the period 2070–2099.

#### 4.4.3.3 Impacts of Extreme Heat Events

The MENA region is already characterized by very high summer temperatures, making the populations of the region highly susceptible to further temperature increases (Habib et al. 2010; Lelieveld et al. 2012). Giannakopoulos et al. (2013) assessed changes in levels of thermal discomfort as indicated by the humidex, an index used to express the temperature perceived by people. The number of days characterized by high thermal discomfort (humidex > 38°C) in the base period of 1961–1990 is approximately 100 days in North Africa and the eastern and southern parts of the Arabian Peninsula. For 2040–2069 under the SRES A1B warming scenario, this is projected to increase by approximately 35 days in North Africa and by 70 days in the Arabian Peninsula.

High temperatures can cause several medical conditions, including heat stress, heat exhaustion, and heat stroke, with the elderly, young children, and people with existing medical conditions most vulnerable to heat-related mortality. Novikov et al. (2012) reported that the number of emergency hospital admissions in Tel Aviv increases by 1.47 percent per 1°C increase in ambient temperature. Regression modeling has further found extreme high temperatures to be linked to increased mortality rates in Tel Aviv (Leone et al. 2013; Peretz et al. 2012), Tunis (Leone et al. 2013), and Beirut (El-Zein et al. 2004). Peretz et al. (2012) reported an increase in mortality of 3.72 percent for every one unit increase in the human thermal discomfort index (that involves temperature and relative humidity as both additive and multiplicative factors) above a discomfort threshold of 29.3.

There are also indications that extreme heat events may have an indirect effect on health by worsening air pollution, which can aggravate respiratory illnesses (Markandya and Chiabai 2009). Together with increased temperatures, elevated concentrations of sulfur dioxide and particulate matter have been associated with increased hospital admissions in the Israeli cities of Tel Aviv and Haifa (Novikov et al. 2012; Portnov et al. 2011).

Increased rates of heat stress under climate change can affect labor productivity. Kjellstrom et al. (2009) noted that, in densely populated cities of the world that already experience very high maximum temperatures and are projected to experience the greatest increases under climate change (including some densely populated cites in the MENA region), heavy outdoor work (e.g., in agriculture and construction) will become more challenging and may take a heavier toll on the health of workers.

According to the Climate Vulnerability Monitor produced by the Spanish nonprofit organization DARA, the proportion of the workforce expected to be particularly affected between 2010 and 2030 by reduced productivity under the A2 scenario ranges between 10–20 percent in North Africa, as well as in Israel, Jordan, Lebanon, Syria, the Islamic Republic of Iran, and Iraq. For the countries of the Arabian Peninsula, the proportion is projected to be higher—ranging from 15–40 percent (DARA 2012).

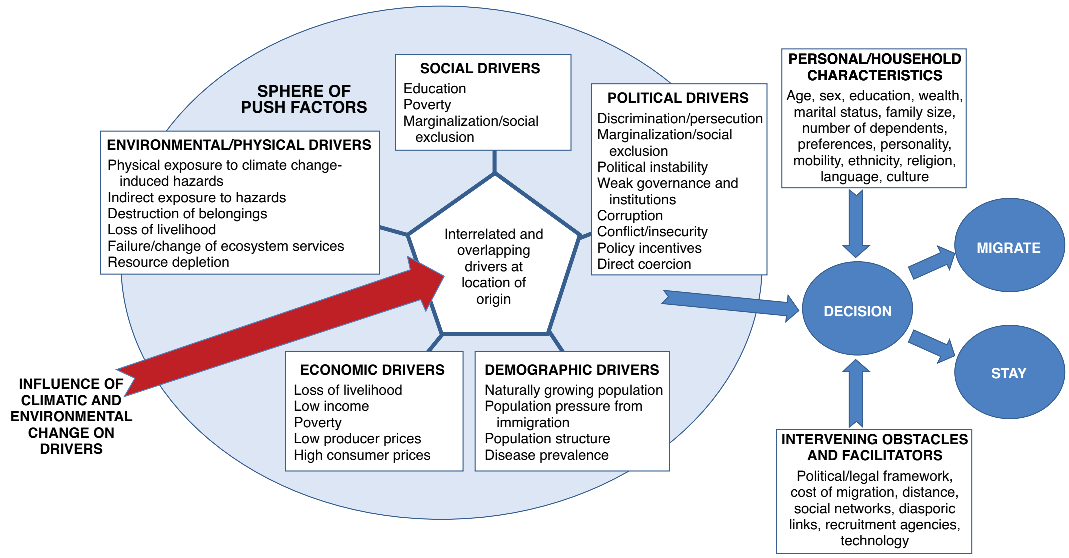
#### 4.4.3.4 Synthesis

Several studies exist that investigate how various climatic changes affect transmission of vector-borne disease. These studies tend to be location-specific, however, which might prevent generalization at a broader scale. Emch et al. (2008) show a relatively strong observed correlation between cholera outbreaks, elevated temperatures, and contaminated water supply; this appears to point to a substantial risk to the MENA region under climate change. A strong correlation is also apparent between extreme heat and increased mortality rates, although further research on future patterns of heat-related illness, as well as on the indirect effects of extreme heat, is needed. Likewise, there is evidence in the literature to suggest that the region will face greater health burdens associated with air pollution; this, however, refers to the effect of anthropogenic emissions on atmospheric composition and does not include the effect of climatic change on air pollution. As pointed out by Lieleveld et al. (2013), further work linking projections of atmospheric composition to climate simulations is required.

### 4.4.4 Migration and Security

Mobility as an integral part of people's livelihoods allows for diversification and the securing of income (Gemenne 2011). Migration, in the form of pastoral nomadism, has long been a part of traditional lifestyles in MENA and the Sahelian adjacent territories in the south (Brücker et al. 2012; Fritz 2010). Nomads and their livestock have for thousands of years been cyclically migrating to places where they could find sufficient fodder and water (Nijeri Njiru 2012). Moreover, migration has always been a human response to climatic hazards. Migration, in the context of climate change, happens as soon as the physical, economic, social, or political security of a population decreases and no other

**Figure 4.20:** Push factors as interrelated drivers for migration and determinants for decision making.




Source: Adapted from Foresight (2011), p. 33.

resources can be mobilized to adapt to the new conditions. Some scholars therefore consider migration as a last resort (Laczko and Piguet 2014; Warner et al. 2010, 2008), while others debate whether migration should be considered a successful adaptation strategy or a failure to adapt (Bardsley and Hugo 2010; Fritz 2010; Gemenne 2013; Luecke 2011; Tacoli 2009).

The goal of a migratory movement is to reach a higher level of physical, economic, social, or political security, which can bring new opportunities and resilience (Black, Bennett et al. 2011; Scheffran et al. 2011). An improvement in living conditions is not always achieved, however, due to new physical, economic, and social vulnerabilities encountered en-route or at the point of destination (Warner et al. 2010).

Conceptual studies on migration as a response to climate change and the relationship of climate and violent conflict are abundant. Practical studies, especially those providing numbers, are however scarce (Gemenne 2011). The EACH-FOR studies, a series of local qualitative household surveys investigating the motivation to migrate in Egypt, Morocco, and the Western Sahara (Afifi 2009; Gila et al. 2009; Hamza et al. 2009) appear to be among the only comprehensive studies on migration and climate change. Wodon et al. (2013) also conducted household interviews in five Arab countries on migration, climate change, and related topics. Other studies are mostly based on documentary research[54] and do not provide original findings.

The research challenges include a general lack of disaggregated data on drivers of migration and conflict as well as very divergent projections for the future. Even though the occurrence of migration and conflict spatially overlaps with vulnerability to climate change, this does not necessarily indicate a topical correlation. Moreover, environmental migrants, environmental refugees, climate migrants, and climate refugees (as they are referred to in the literature) are not officially recognized as refugees[55] by the United Nations High Commissioner for Refugees (UNHCR). This is a possible explanation for why there is little available data on climate-change-related migration.

### 4.4.4.1 Climate Change and Migration in the MENA Region

Due to the interrelation of several factors and their common contribution to decisions for and against migration, it is difficult to say whether migrants are driven by climate changes or are economically, socially, or politically motivated (Brücker et al. 2012). Tacoli (2011) identified demography as a further dimension (see Figure 4.20).

It is also difficult to extrapolate future migration patterns from current patterns, because these may change with increasing temperature levels and changing socioeconomic conditions, and are also dependent on future population growth. Projecting the nature and magnitude of migration, especially at the local and regional levels, is also fraught with uncertainty. Gemenne (2011) predicted that

[54] The use of sources and documents from the personal, private or public domain, such as personal papers, commercial records, state archives, legislation or speeches, in order to categorize, investigate and interpret information relating to a topical field. This technique of data collection is commonly used in social sciences.

[55] Conditions anchored in the 1951 Geneva Convention text exclusively comprise persecution for reasons of race, religion, nationality, membership of a particular social group or political opinion (UNHCR 2010).

migration options will be limited in a warmer world, that internal migration will prevail, and that traditional patterns of mobility (e.g., nomadism, temporary or circular labor migration) might be disrupted. Many people will be forced to move, but others will be forced to stay because they lack the financial resources or social networks facilitating mobility. This indicates that climate-induced migration should be addressed not only within the framework of climate change, but also within other economic, cultural, technological or political conditions that might foster or limit migration (Gemenne 2011).

Migrants from the MENA countries move internally within their countries or across borders to neighboring countries. The internal migration dynamic within the MENA region is rather short-distance (Afifi 2009; Wodon et al. 2013). From past observations it is well known that migrants in Tunisia, Algeria, and Morocco who were left homeless after sudden climatic hazards have a high propensity to return to their homes after a disaster (Gubert and Nordman 2010). Slow-onset hazards that may drive migration include increasing water scarcity, drought, desertification, and soil degradation (see Section 4.4.2, Desertification, Salinization, and Dust Storms). Icduygu and Sert (2011) found that rural populations in particular migrate to nearby or larger cities once food self-sufficiency and livelihoods are threatened. Jónsson (2010), however, found that drought does not necessarily lead to migration.

Contrary to the situation during the 1950s and 1960s, when labor migration from the Maghreb to Europe was prevalent (Wodon et al. 2014), today the MENA countries are a region of internal migration. Urbanization is currently the predominant form of migration (Brücker et al. 2012), and it adds additional pressure to urban infrastructure. In Algeria, for example, migrants are shown to move from rural areas to mid-sized towns rather than to large urban areas (Gubert and Nordman 2010). This movement is partly due to slow-onset environmental degradation, including water scarcity, soil erosion, and desertification which threatens agricultural livelihoods in rural Algeria (Wodon et al. 2014). However, unlike for many of its neighbors, climate change is not predicted to drastically increase migration in Algeria (Wodon et al. 2014) since the country's agricultural sector makes up only a small fraction of GDP (and relatively few people are employed in this sector). As Algeria imports 45 percent of its food, however, it is exposed to increasing global food prices, which may eventually lead to migration if demand can no longer be satisfied (Brown and Crawford 2009; Wodon et al. 2014).

As of 2009, a large share of the Nile Delta and Nile valley populations had migrated from the fertile rural areas to Cairo. This movement was mostly driven by unemployment and poverty, which was in turn caused by land degradation and water scarcity (Afifi, 2009). Due to high population growth, the yearly water quota from the Nile is reported to be insufficient for the increasing population that is still using outdated and inefficient irrigation methods (Afifi, 2009).The steady reduction in water availability per capita in Egypt will further drive migration in the country. For 2030, the annual water availability per capita is estimated to be only 468 $m^3$, whereas in the 1990s it was 1000 $m^3$ per capita (Wodon et al. 2014). Other major migratory patterns that have been identified in Egypt include migration from south to north, and migration from throughout the country to the Suez Canal zone (Wodon et al. 2014).

There are several studies that examine the effect of sea-level rise in Egypt and the potential impact on migration. Kumetat (2012) found that a one meter sea-level rise could drive up to six million migrants from the Nile delta region. The statement for this estimate is limited, however, because a reference year is not given.

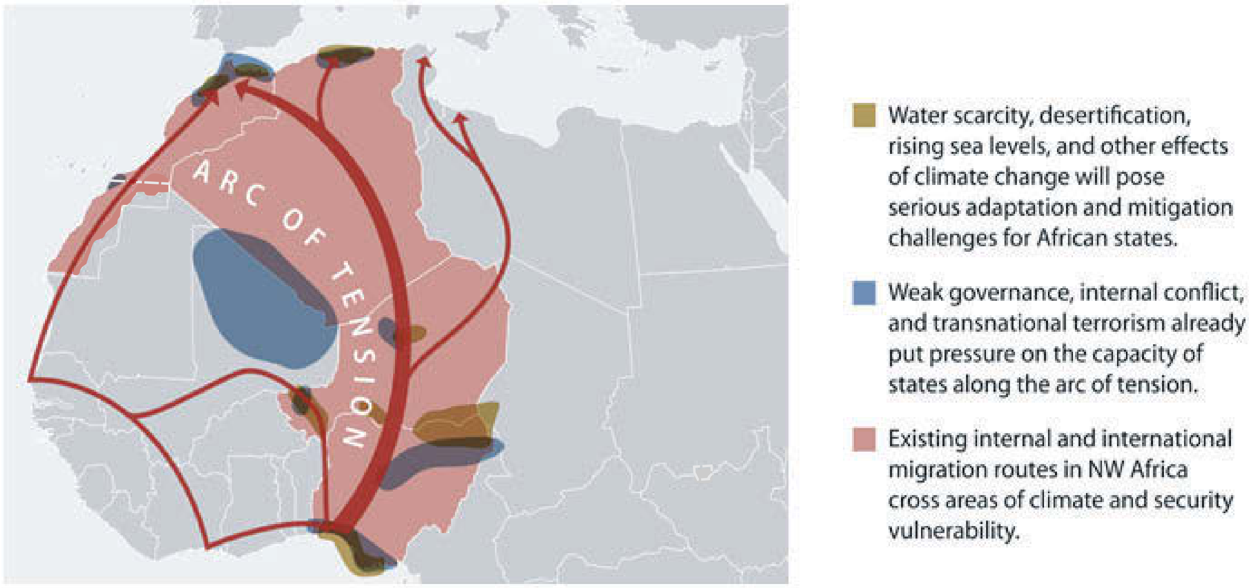
For Morocco, internal migration exceeds international migration; similar to Egypt and Algeria, rural areas are being abandoned in favor of cities. The principal destinations of Moroccan migrants are cities on the Atlantic coast, which grew rapidly between 2000 and 2010 (Wodon et al. 2014). Rural livelihoods in Morocco are more prone to climate change, especially due to a high share of employment in agriculture. This means that, in the future, the urbanization trend will likely continue. Water stress is already a severe problem in the country, but it will become worse due to high population growth (Hamza et al. 2009); this will further influence migratory movements.

Water availability is also a serious problem in Syria, especially for the rural population. The country experienced a drought in 2007–2008 which affected about 1.3 million Syrians (Wodon et al. 2014). As a result of the drought, 800,000 people, among them small-scale farmers and herders, are believed to have lost their livelihoods. As a consequence, about 40,000–60,000 households migrated to urban areas (DREF 2009), putting enormous pressures on local urban infrastructure (Wodon et al. 2014).

Yemen has experienced strong internal migration flows to its fast-growing urban centers (Wodon et al. 2014). Water shortages as a result of decreasing rainfall and resource depletion are problematic in Yemen, and average per capita water availability is low. This has serious implications, including for an agricultural sector that contributes 15 percent to the country's GDP and employs over half of the population (Wodon et al. 2014; World Bank 2013g). Because Yemen's population is already exposed and vulnerable to water shortages, climate change could have a large future impact on migration (Joseph and Wodon 2013).

According to Grant et al. (2014) in a study on the causes of migration, migrants in Morocco and Egypt were motivated more frequently by socioeconomic opportunities and freedom, whereas for example Algerians, and Yemenis were motivated to migrate as a result of inhospitable climatic conditions and frequent crop failures. Besides agriculture, climate change will probably have impacts on other sectors and economic branches, including energy production, coastal infrastructure, manufacturing, and tourism (Gubert and Nordman 2010). These impacts will also contribute to loss of livelihoods and constitute push factors for migration.

**Figure 4.21:** The "Arc of Tension."




According to Werz and Conley (2012), p.18. Migratory routes from Nigeria and Niger to the densely populated coastal areas of Morocco and Algeria are areas that are prone to climate-change-induced hazards and suffer from weak governance and frequent conflicts.

As identified by Wodon et al. (2013) and by Werz and Conley (2012), the MENA countries are also a popular destination and transit region for migrants coming from Sahelian and Sub-Saharan African countries. This Sub-Saharan in-migration and transit migration constitutes an additional population burden for the Maghreb countries, which are themselves weakened by climate change and weak governance (see Figure 4.21).

### 4.4.4.2 Climate Change, Conflict, and the Security of Nations

The identification of climate change as a direct cause of conflict and insecurity is challenging. To date, research has been able to present some evidence of a statistical correlation; the underlying causal relationship between climatic change, the occurrence of conflicts, and insecurity has not however as yet been explicitly explained (Gemenne et al. 2014). For this reason, this report focuses on the studies that establish relationships between climatic changes and conflicts.

A framework by Scheffran et al. (2011) summarizes the climate-society interaction. Climate change puts pressure on natural resources, which in return can have adverse impacts for human security. Elements which make up human security include access to water, food, energy, transportation, health, and livelihoods, as well as education, lifestyle, and community. Where these aspects of human security are no longer guaranteed, possible consequences include societal instability (both violent and non-violent conflicts).

There is common consensus among the research community that climate change functions as a "threat multiplier" (Center for Naval Analysis 2007), amplifying such preexisting threats as political instability, high levels of poverty, unemployment, and other factors. This implies that conflict-proneness and sensitivity to climate change through adaptation failure derive from institutional fragility and poor governance (Smith and Vivekananda 2012). Gemenne et al. (2014) suggest extending the focus in this research field, so that not only risks and threats, but also factors of peace and cooperation, capabilities, and the power of institutions, are taken into account.

Sterzel et al. (2013) showed the relationship between the vulnerability profiles of small dryland farms (composed of environmental scarcities, resource overuse, and poverty-related factors) and the occurrence of violent conflicts. They stated that it is the extent of resource overuse that determines conflict proneness under conditions of intermediate resource availability; they found that poverty is the crucial factor when resource availability is either very poor or rather good (Sterzel et al. 2013). Competition over scarce resources, such as land and water, may constitute a considerable threat to security, and may even foster conflicts, especially when freeriding[56] occurs (Brown and Crawford 2009;

[56] Taking advantage of a commonly shared resource by intensifying individual use beyond one's own fair share, while other resource users respect a fair allocation. This may lead to overexploitation of the collective resource.

Osman-Elasha 2010). In Yemen, water scarcity has led to conflicts over water wells (Hoffman and Werz 2013).

Water scarcity in the MENA region will increasingly constitute a problem for the population—and, in particular, for those engaged in agriculture. The problem will be exacerbated in the Maghreb region by natural population growth in combination with in-migration, and, in the Mashrek region (e.g. in Iraq), by weak institutions together with poor resource management (Maas and Fritzsche 2012; Sowers et al. 2011; Wodon et al. 2014). These findings are consistent with a study on Sub-Saharan Africa by Burke et al. (2009), who found the variation in precipitation and temperature affecting the agricultural performance to be the major mechanism linking global warming and conflict in Africa; they concluded that global warming increases the risk of civil war.

Studies from the peace research community disagree. Drought, in particular, is thought to be unlikely to cause civil war (Theisen et al. 2011), even though the authors admit that climate events may cause poverty (which in turn can lead to conflict). Additionally, a multivariate regression analysis revealed that countries that experience climatic disasters are less likely to experience civil war (Slettebak 2012).

Studies linking climate change to conflict are somewhat contradictory. From an econometric perspective, and based on historical data, Bergholt and Lujala (2012) argue that while certain types of climate-related disasters may be serious threats for the economy of the affected countries, this still does not necessarily increase the risk of armed conflict. By reanalyzing the data of Burke et al. (2009), Buhaug (2010) attempted to show that weather or climate patterns do not increase the risk of civil war in Sub-Saharan Africa. This study was criticized by Hsiang and Meng (2014), however, for incorrect and insufficient statistical testing. Another recent study by Hsiang et al. (2013) extended the analysis of temperature influence to types of violence (e.g. violent crime, domestic crime, and murder). The authors found that even small changes from the mean climate toward warmer temperatures or more extreme rainfall increases the frequency of interpersonal violence by four percent and the frequency of intergroup conflict by 14 percent in median estimates. This study was criticized among the scientific community for not being comprehensive enough and ignoring important controversial findings from previous studies (e.g., Buhaug 2014). Most recently, Selby and Hoffmann (2014) reversed the mainstream thought on water scarcity, state failures, and under-development and introduced a model of environment-conflict relations focusing on resource abundance, globally embedded processes of state-building, and development. They suggested that violent conflict can also emerge from water abundance accompanied by inefficient management and state-directed processes of economic development as well as from internal colonization. However, this model is only applied to investigate links between water issues and conflict and does not take into account other kinds of climatic issues.

In brief, the scientific discourse shows that this emerging field of scientific inquiry has not yet succeeded in establishing a consensus on primary causes, mechanisms, links, and interventions between climate change and conflicts and insecurity (Gemenne et al. 2014). Adger et al. (2014) concluded that it is not yet possible to make confident statements about the present or for the future as to how changes in climate may affect armed conflict. This is due to the absence of commonly supported theories and a lack of evidence about causality. In the following section, the Arab Spring serves as case study to illustrate the possible implications of climate change on national security in the MENA region.

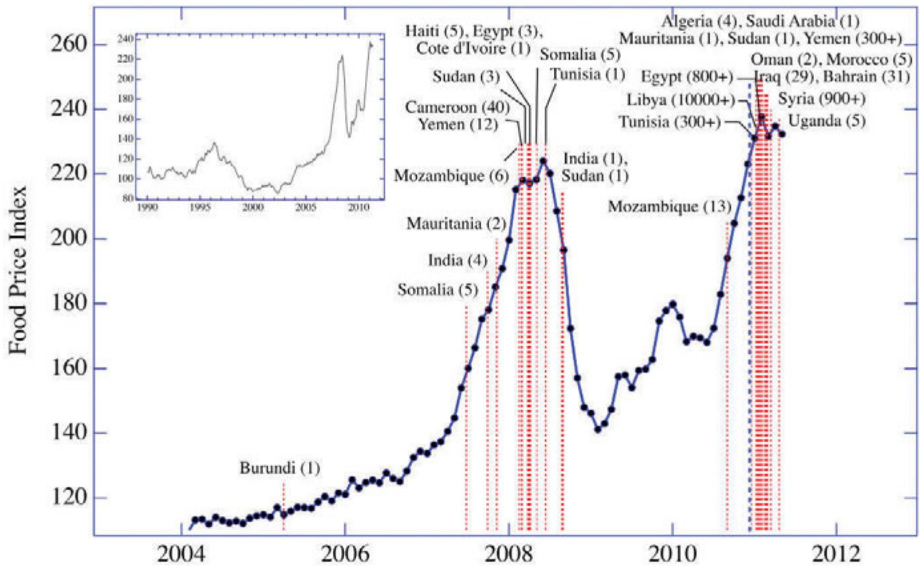
#### *4.4.4.3 A Possible Link between Climate Change and the Arab Spring?*

Finding a possible link between climate change and the Arab spring, with its series of violent events, seems far-fetched. Indeed, a more global view has to be taken in order to make the causal links between climate patterns and the Arab Spring visible. Original empirical evidence is provided by Lagi et al. (2011) and Sternberg (2011, 2012), who attribute the outbreak of violence in Egypt not only to political instability, unemployment, and poverty but also to a food crisis induced by extreme climatic conditions and market mechanisms. Lagi et al. (2011) found this link by analyzing the timing of protests and global food price peaks (see Figure 4.22). Sternberg (2012) quantified the drought in China's eastern wheat belt in late 2010 and early 2011, and displayed China's and Egypt's reaction to this drought and to the world price for wheat. Both Lagi et al. (2011) and Sternberg (2012) argue that these rather-indirect causes of the Arab Spring have received only little attention. Both provide studies with original empirical evidence, in contrast to research produced by several policy-related institutions, which is often based on documentary review (Femia and Werrell 2013; e.g. Johnstone and Mazo 2011, 2013).

Egypt has high population growth rates (World Bank 2013h). Being a largely arid country, Egypt is not able to meet domestic food demand without importing wheat on a large scale. This dependency on wheat imports exposes the country to commodity price fluctuations and variability in commodity supplies on the world market. Generally, food expenditures in Egypt are at about 38 percent of income (Sternberg 2012). It is important to note that Egypt's unemployment and poverty rates are relatively high, with unemployment at nine percent as of 2010 (World Bank 2013i) and 15.5 percent of the population living on less than \$2 per day (as of 2008—World Bank 2013j). Bread subsidies help to stabilize the social order in Egypt, with the government spending three percent of the country's GDP on wheat subsidies (Sternberg 2013).

Drought conditions in eastern China in late 2010 and early 2011 lead to a reduction in the winter wheat harvest (Lagi et al. 2011). Sternberg (2012) estimates the shortfall at 10 million tons of wheat, or approximately 10 percent of annual wheat production. Earlier in the same year, Russia and Ukraine also experienced drought

**Figure 4.22:** Food prices and conflict.




Time dependence of the FAO Food Price Index (Jan. 2004–May 2011). Red dashed lines mark the beginning dates of "food riots" and protests in the MENA region. Numbers in () show overall death tolls. The blue dashed line marks the day (12/13/2010) when Lagi et al. (2011) warned the U.S. government of the link between food prices, social unrest, and political instability. Inset: FAO Food Price Index 1990–2011. Source: Lagi et al. (2011), p. 3.

conditions; meanwhile, heavy rainfall in Canada and Australia led to poor wheat harvests (Sternberg 2012) and decreases in wheat production.[57] In 2011, this drop in supply lead to an increase in the world market price for wheat, a commodity for which 18 percent of the total global harvest is slated for export (Sternberg 2012).

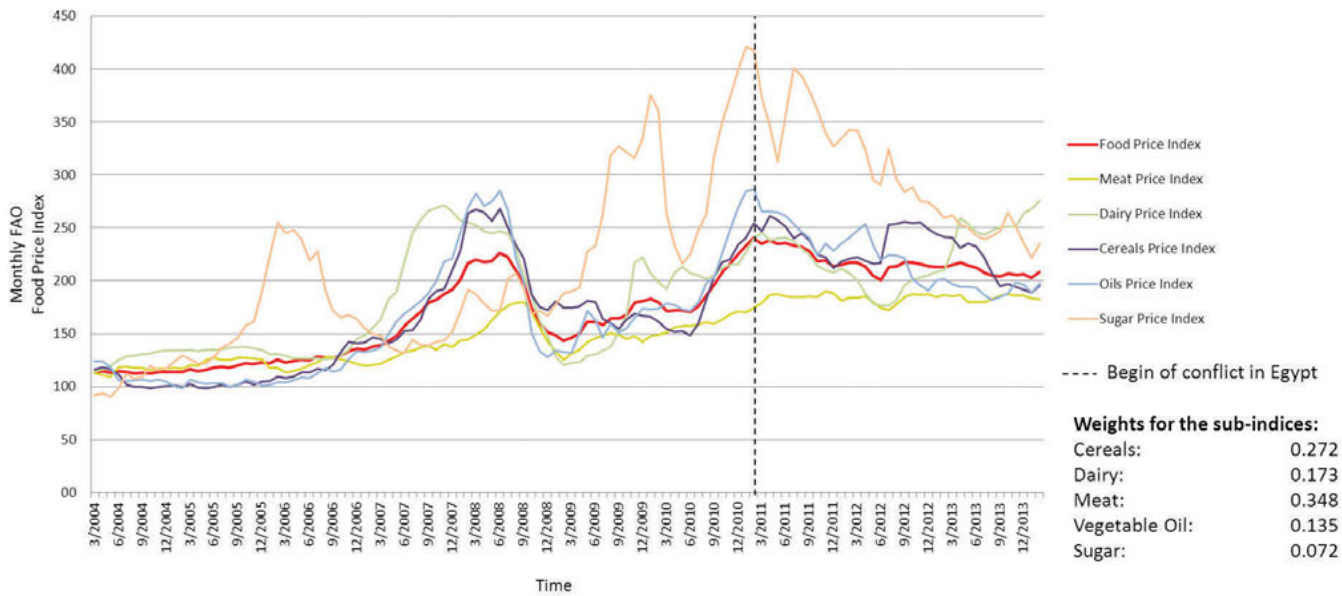
China, a country with a high population growth rate, saw the need to secure its domestic wheat demand. While China's wheat production was reduced by only 0.5 percent, the country's wheat consumption increased by 1.68 percent (Sternberg 2013). Consequently, China made a large-scale wheat purchase from the world market. Russia levied an export ban on wheat due to its domestic shortage, decreasing imports to Egypt by five percent (Sternberg 2012). Johnstone and Mazo (2013) report that Egypt received only 1.6 million tons of wheat from Russia in the second half of 2010 as compared to 2.8 million tons in the same period in the previous year. These reductions in global supply lead to further increases in commodity prices.

The climatic events (droughts and floods), together with global market forces, were contributing factors to high wheat prices in Egypt and affected the price of bread. As Egypt had not yet fully recovered from its 2008 food price crisis (Johnstone and Mazo 2013), and as food became unaffordable for the population again in 2011, social conflicts developed (Sternberg 2013). While partly the result of economic and political instability, conflicts were also due to discontent with the food supply situation as, at the time, 50 percent of the population relied on ration cards and the country's bread subsidy system was fraught with corruption (Johnstone and Mazo 2013). Johnstone and Mazo (2013) report similar linkages between food prices and social unrest in Algeria, with a correlation between unemployment and high food prices for sugar, oil, and other staples.

In high income countries such as Israel or the United Arab Emirates, by contrast, a relatively low percentage of income is spent on food and early stabilization of domestic food prices was been successful. These countries were spared from protests and social conflicts during the same time period (Sternberg 2013). It must be noted, however, that some Gulf monarchies purchased or leased agricultural land from highly volatile nations and regions, such as Ethiopia, Sudan, and countries in South Asia to meet their domestic demand (ILC et al. 2014; Spiess, 2012). This is in line with the conclusions of Gemenne et al. (2014) and Adger et al. (2014) that a government response to price and scarcity signals is necessary to manage access to resources and markets. Lagi et al. (2011) suggest that the food price is crucial for nations' social stability, and that persistently high food prices might result in a global increase in social disruptions.

[57] Wheat production in 2010 was down 32.7 percent in Russia, 19.3 percent in Ukraine, 13.7 percent in Canada, and 8.7 percent in Australia (Sternberg, 2011, 2013).

**Figure 4.23:** Aggregated FAO Food Price Index and its sub-indices.




The Food Price Index score in January 2011, when the Egyptian crisis broke out (black dashed line), was 238. This is particularly due to the high Sugar Price and Oils Price Indices, together weighted with 0.207, which is about one-fifth of the Food Price Index. The low Meat Price Index pulled it downward, constituting one third of the Food Price Index. Data taken from FAO (2014c). Weight data from FAO (2014a).

Even though the link between the drought in China, harsh climatic conditions in other countries, and social conflicts in Egypt is plausible, it is not directly verifiable (Sternberg 2012). These findings should therefore be treated with caution. In addition, there is no evidence so far that the late 2010 and early 2011 drought events in China and Eurasia can be attributed to climate change. Attention should be given to the methodologies of the two major studies scrutinized in this chapter. Whereas Sternberg (2011, 2012 and 2013) used the world market price for wheat in his analysis, Lagi et al. (2011) used the FAO Food Price Index, which is a composite index of five differently weighted sub-indices (FAO 2014a). Since wheat was identified as the critical commodity in the Egyptian food crisis (Sternberg 2012), results based on the aggregated Food Price Index by Lagi et al. (2011) seem somewhat biased, as wheat is only represented in the Cereals Price Index along with rice and maize, while the Meat Price Index is the sub-index with the greatest influence on the Food Price Index (Figure 4.23). This suggests that the results by Lagi et al. (2011) are less confident than those of Sternberg (2012)—and that the conclusion on the relationship between FAO Price Index and the Egyptian food crisis, by Lagi et al. 2011, should be treated carefully.

In summary, it can be said that countries with well-established institutions have the capacity to build high levels of resilience and to respond to climatic changes, extreme events, and other shocks such as climate-related increases in food prices over time. Countries and institutions weakened by crisis or war have limited capacity to build resilience and, as a consequence, have less capacity to cope with and adapt to climate change. The case of the Arab Spring indicates that climate-related extremes and market mechanisms together may have serious implications for food security. Findings on the link between climate change, human security, and conflict are in agreement with recent IPCC analyses on human security (Adger et al. 2014).

## 4.4.5 Coastal Infrastructure and Tourism

Globally, human populations, as well as agricultural, industrial, and other economic activity, tend to be concentrated in coastal zones. Historically this has been amplified in MENA countries, where coastal cities and agricultural areas have been particularly important due to the aridity of inland regions (Verner 2012). The population of MENA's coastal cities was approximately 60 million in 2010, with the number expected to reach 100 million by 2030 (World Bank 2011b). In Morocco, for example, more than 60 percent of the population and over 90 percent of industry is located in key coastal cities (Snoussi et al. 2009).

As coastal populations and assets in coastal areas continue to grow, exposure to impacts associated with sea-level rise is also increasing. This is particularly true as populations expand into low-lying areas, and as wetlands and other ecosystem protections against floods are removed (World Bank 2011b). One study has estimated that annual global flood losses are expected to increase from $5 billion in 2005 to $52 billion by 2050 due to socioeconomic changes alone (Hallegatte et al. 2013). Climate change and coastal subsidence will exacerbate this growing vulnerability.

#### 4.4.5.1 Types of Physical Impacts

The key impacts of climate change in coastal zones, and in rapidly growing urban areas in particular, are expected to include inundation resulting from slow onset sea-level rise, floods, damage caused by extreme events (including storms and storm surges), and increased erosion (Brecht et al. 2012; Hunt and Watkiss 2011).

Several MENA countries are highly exposed to sea-level-rise-related inundation due to their low-lying topographies. One study found that with one meter of sea-level rise, Qatar could lose 2.7 percent of its total land area and Egypt would lose 13.1 percent of its agricultural area (Dasgupta et al. 2009). In terms of the percentage of urban area lost to one meter of sea-level rise, Egypt (5.52 percent), Libya (5.39 percent), the United Arab Emirates (4.8 percent), and Tunisia (4.5 percent) were all found to be highly vulnerable (Dasgupta et al. 2009).

Global comparative studies have identified Egypt's Nile Delta coastline as one of the most vulnerable areas to sea-level rise (Dasgupta et al. 2009; Syvitski et al. 2009). Sea-level rise impacts in the Nile Delta will be exacerbated by land subsidence, especially in the eastern part of the delta, and by extensive landscape modifications resulting from both coastal modification and changes in the Nile's hydrogeology (Frihy and El-Sayed 2013; El Sayed et al. 2010; Wöppelmann et al. 2013).

A study in Abu Dhabi found that, in the absence of adaptation measures, a 2-meter sea-level rise would inundate 15.9 percent of Abu Dhabi's urban area, increasing to 39.6 percent for a 3-meter sea-level rise (Ksiksi et al. 2012). The study estimates that 20 percent of Abu Dhabi's total land area would be inundated by a 2-meter sea-level rise, and 30 percent by a 3-meter sea-level rise (Ksiksi et al. 2012).

Apart from direct inundation, sea-level rise is expected to have serious impacts in terms of saltwater intrusion, the salinization of groundwater, rising water tables, and impeded soil drainage (Hunt and Watkiss 2011; Werner and Simmons 2009). These effects can reach inland for several kilometers following relatively small increases in sea level (Werner and Simmons 2009) (see Section 4.4.2, Salinization).

Saltwater intrusion into coastal aquifers has been documented across MENA, including in Tunisia, Egypt, and Israel (Kashef 1983; Kerrou et al. 2010; Kouzana et al. 2009; Yechieli et al. 2010). The principal causes of observed saltwater intrusion have been identified as the over-extraction of water for supplementary irrigation and reductions in the recharge of aquifers. These factors are likely to remain immediate challenges, although they will be aggravated by the effects of sea-level rise (Kouzana et al. 2009; Zarhloule et al. 2009).

#### 4.4.5.2 Impacts of Sea-Level Rise and Storms on Coastal Areas

Several global studies have noted that while regions such as Asia and Sub-Saharan Africa tend to be more vulnerable in terms of the total population exposed to the impacts of sea-level rise, MENA countries tend to be more vulnerable in terms of the percentage of population at risk (Dasgupta et al. 2011; Dasgupta et al. 2009; Ghoneim 2009; Nicholls et al. 2011).

In terms of the percentage of population exposed to a 1-meter sea-level rise, Dasgupta et al. (2009) identified three MENA countries among the ten most vulnerable in the world: Egypt (9.28 percent), Tunisia (4.89 percent), and the United Arab Emirates (4.59 percent). One study of Africa suggested that, in the absence of adaptation, 1.97 million people in Egypt could be affected by a sea-level rise of 0.54 m and 1.82 million people in Morocco could be affected by a sea-level rise of 0.44 m with 2.6°C global warming compared to 1990 levels (Brown et al. 2011) (Table 4.7). Another study identified Egypt, Tunisia, Morocco, and Libya as among the most vulnerable African countries in terms of total population affected by sea-level rise under scenarios of 0.42–1.26 meters in sea-level rise by 2100, assuming no adaptation (Hinkel et al. 2012).

In terms of the GDP impact of a 1-meter sea-level rise, Egypt (6.44 percent) and Tunisia (2.93 percent) were also in the top ten countries globally (Dasgupta et al. 2009). In the absence of adaptation, the annual economic impact of sea-level rise in 2100 under the A1B scenario with 2.6°C global warming compared to 1990 has been calculated at $6.55 billion for Algeria, $6.52 billion for Egypt, $5.52 billion for Morocco, $3.46 billion for Tunisia, and $1.76 billion for Libya (Brown et al. 2011). Table 4.7 shows the corresponding sea-level rise and the economic impacts with different global warming scenarios.

Another study considered a 1.26-meter sea-level rise in the absence of adaptation and calculated Egypt's annual losses at $5 billion per year, while the annual losses for Tunisia, Morocco, and Libya were estimated at less than $500 million per year (Hinkel et al. 2012). When the effects of adaptation were included in the projections, Tunisia, Morocco, and Libya were no longer among the most vulnerable countries and Egypt's ranking had fallen from first to third (Hinkel et al. 2012). This indicates that for most North African countries adaptation could be effective at reducing vulnerability to sea-level rise.

Another expected consequence of climate change is a greater intensity of storms (Knutson et al. 2010). Coupled with higher sea levels, more intense storms are likely to result in more powerful storm surges.

One study has calculated that under a 1-meter sea-level rise and a 10 percent increase in storm intensity, 50 percent or more

**Table 4.7:** Damage and people affected by sea-level rise.

| | TOTAL COSTS OF RESIDUAL DAMAGE (MILLIONS $/YR) | LAND LOSS DUE TO SUBMERGENCE (KM²/YR) | NET LAND LOSS DUE TO EROSION (KM²/YR) | PEOPLE FLOODED (THOUSANDS/YR) | RELATIVE SEA-LEVEL CHANGE SINCE 1995 (M) | SEA FLOOD COSTS (MILLIONS $/YR) |
|---|---|---|---|---|---|---|
| **B1** | | | | | | |
| Algeria | 328.1 | 0 | 0 | 35.2 | 0.17 | 328.1 |
| Djibouti | 174.5 | 0 | 0 | 9.5 | 0.15 | 174.5 |
| Egypt | 2,134.5 | 38.6 | 0.79 | 927.6 | 0.25 | 1,482.9 |
| Libya | 186.7 | 3.2 | 0.31 | 3.7 | 0.21 | 167.1 |
| Morocco | 1,195.7 | 0 | 0.07 | 47.1 | 0.16 | 1,178.0 |
| Tunisia | 722.8 | 0 | 0.36 | 17.0 | 0.20 | 710.3 |
| **A1B** | | | | | | |
| Algeria | 6,546.6 | 7.1 | 0 | 435.4 | 0.46 | 916.7 |
| Djibouti | 232.0 | 0.3 | 0 | 85.5 | 0.42 | 213.6 |
| Egypt | 6,518.5 | 19.4 | 1.4 | 1970.3 | 0.54 | 3,482.5 |
| Libya | 1,756.8 | 16.1 | 0.8 | 39.4 | 0.50 | 477.6 |
| Morocco | 5,524.3 | 14.5 | 0.4 | 1820.2 | 0.44 | 3,388.3 |
| Tunisia | 3,459.7 | 73.3 | 0.8 | 263.9 | 0.49 | 1,798.1 |
| **A1F1** | | | | | | |
| Algeria | 5,238.0 | 21.7 | 0 | 708.1 | 1.06 | 1,454.8 |
| Djibouti | 295.4 | 2.0 | 0 | 92.4 | 0.99 | 237.4 |
| Egypt | 12,476.3 | 43.6 | 2.9 | 3600.7 | 1.14 | 5,362.4 |
| Libya | 1,325.0 | 12.8 | 1.9 | 131.2 | 1.11 | 745.2 |
| Morocco | 5,886.5 | 4.8 | 1.1 | 2078.9 | 1.04 | 4,001.3 |
| Tunisia | 4,541.0 | 17.8 | 1.7 | 802.8 | 1.09 | 2,375.0 |

Numbers are for 2100 without adaptation in six MENA countries under SRES B1, A1B and A1F1 with global warming of 1°C, 2.6°C and 6.1°C relative to 1990, respectively. Source: extracted from (Brown et al. 2011).

## Box 4.3: The Nile Delta

For Egypt, and assuming no adaptation, annual damages have been projected in the range of $5 billion by 2100 for a 1.26-meter sea-level rise (Hinkel et al. 2012) and $14.8 billion by 2100 under the A1B scenario (Brown et al. 2009). Dasgupta et al. (2009), meanwhile, projected losses of 25 percent of the Nile Delta's land area, affecting 10.5 percent of the population and 6.4 percent of GDP with a 1-meter sea-level rise (Dasgupta, Laplante, Meisner et al. 2009). Another study estimated the value of assets exposed to a 0.5-meter sea-level rise by 2070 at $563 billion in the city of Alexandria alone (Hanson et al. 2011).

The Nile Delta, however, has an extensive history of coastal defense that dates back to the construction of the Mohamed Ali Sea Wall in 1830. Modern defensive works and other infrastructure, including the International Coastal Road, provide further protection against flooding (Frihy and El-Sayed 2013).

Studies by Egypt's Coastal Research Institute concluded that, under the A1F1 scenario, 14.4 percent of the Nile Delta would be at risk from inundation by 2100; this fell to three percent when taking into account the value of the Mohamed Ali Sea Wall (EEAA 2010). Another study found that, although 22.5–29.2 percent of the area was vulnerable to inundation depending on the sea-level rise scenario and assuming no adaptation, much of that impact would fall on undeveloped lands and wetlands, with built-up land accounting for less than five percent of the impact (Table 4.8) (Hassaan and Abdrabo 2013).

**Table 4.8:** Results for three scenarios of sea-level rise in the Nile Delta assuming no adaptation.

| SCENARIO | PROJECTED RELATIVE SLR | INUNDATED DELTA AREA | | DISTRIBUTION OF INUNDATION IMPACT | | |
|---|---|---|---|---|---|---|
| | | $KM^2$ | % | BUILT LAND | CULTIVATED LAND | UNDEVELOPED LAND AND WETLANDS |
| **A1F1** | 1.04 m | 4,006 | 22.5 | 4.4% | 42% | 53.6% |
| **Rahmstorf** | 1.85 m | 7,336 | 42.2 | 3.8% | 60.7% | 35.5% |
| **Pfeffer** | 2.45 m | 8,769 | 49.2 | 3.7% | 64% | 32.3% |

Source: Extracted from Hassaan and Abdrabo (2013).

of the coastal population in Kuwait, Djibouti, the United Arab Emirates, and Yemen will be at greater risk from storm surges (Dasgupta et al. 2011). The effects of climate change would leave 2.7 million more people in Alexandria and 1.2 million more people in Aden exposed to storm surges (Dasgupta et al. 2011). The same study calculated that, for the MENA region, storm intensification would cause additional annual losses to GDP of $12.7 billion by 2100, with exposure particularly high in Kuwait, the United Arab Emirates, Morocco, and Yemen (Dasgupta et al. 2011).

Dasgupta et al. (2011) considered only the local effects of sea-level rise in developing their projections. But the MENA region benefits from being bordered by semi-enclosed bodies of water,[58] and only those MENA nations exposed directly to the Indian Ocean (e.g., Yemen, Oman, and Djibouti) are regularly exposed to tropical storms, while the west coast of Morocco is exposed to Atlantic storms (Becker et al. 2013; Knapp et al. 2010). This could mean that their projections for MENA countries other than Djibouti and Yemen are less conservative than they might otherwise appear.

Urban growth in coastal areas means that, even in the absence of sea-level rise, increasing losses and damages can be expected due to higher concentrations of people and assets exposed to flooding. By separating socioeconomic drivers of vulnerability from the effects of sea-level rise, a study of 136 coastal cities[59] identified Alexandria, Benghazi, and Algiers as particularly vulnerable to 0.20.4 m sea-level rise by 2050 (Hallegatte et al. 2013). The study estimates that, in the event of a failure of flood defenses, the effects of 0.2 m sea-level rise would increase damages from $16.5 billion to $50.5 billion in Alexandria, from $1.2 billion to $2 billion in Benghazi, and from $0.3 billion to $0.4 billion in Algiers. Annual losses would increase to $58 billion, $2.7 billion, and $0.6 billion with 0.4 m sea-level rise for these three cities respectively. A study for the city of Tunis found that a 0.2-meter sea-level rise, with assumptions for expected coastal urbanization by 2030 and increases in both storm frequency and the extent of the coastline at high risk of erosion, could lead to adaptation costs of $12 million per year (Ennesser et al. 2010).

In Morocco, Snoussi et al. (2009) showed that significant potential land and infrastructure losses would result from a relative 0.86-meter sea-level rise by 2100 for the city of Tangiers. These potential losses included 36 percent of roads, 79.2 percent of railways, 99.9 percent of port infrastructure, 90.8 percent of water diversion canals, 63.4 percent of the city's industrial zone, and 34.8 percent of the city's high density urban area, largely due to the increased area at risk from storm surges (Snoussi et al. 2009).

### 4.4.5.3 Impacts on Coastal Tourism

Egypt, Morocco, Tunisia, Jordan, Lebanon, and Syria have developed tourism services aimed at the international market (Safa and Hilmi 2012). In 2006, international visitor spending contributed more than 10 percent of GDP to the economies of Morocco, Bahrain, Lebanon, and Jordan, and more than five percent to the economies of Egypt, Tunisia, and Syria (Gössling et al. 2009). In addition to beach tourism, cultural tourism has been highly important in Jordan and Egypt in particular, and religious tourism has played a key role in Saudi Arabia (Khattabi 2009; Safa and Hilmi 2012). Many MENA countries also have well-developed domestic beach tourism, with domestic tourists visiting the relatively cool coastal areas during the hot summer months.

Tourism infrastructure in coastal areas (e.g., hotels and marinas) and tourism assets (e.g., protected areas) are vulnerable to sea-level rise, although few specific assessments have been conducted for the MENA region (see Box 4.4 for the example of Morocco). Comparison of slow-onset sea-level rise and shocks to tourism demand have, however, indicated that short-term shocks resulting from fluctuations in tourist demand[60] have a

[58] The Mediterranean Sea, Red Sea, and Arabian Gulf are all semi-enclosed seas.

[59] Including Alexandria, Beirut, Benghazi, Tel Aviv, Kuwait City, Dubai, Jeddah, and Rabat.

[60] Tourist demand relates to demand in tourism destination choices and tourist demand for recreational activities, hotels, restaurants, and related expenditures.

## Box 4.4: Impacts of Climate Change on Tourism in Morocco

In Morocco, different studies have explored the complex interlinkages between coastal development, climate vulnerabilities, and tourism. During the peak summer months, the population of Morocco's Mediterranean area doubles from eight to 16 percent of the national population; this has driven rapid coastal urbanization (Anfuso et al. 2011). Urbanization has contributed to the increased erosion of Morocco's sandy beaches, thereby increasing vulnerability to coastal flooding (Ahizoun et al. 2009; Anfuso et al. 2011). Ambitious plans to expand coastal tourism in Morocco could exacerbate coastal vulnerabilities by increasing the amount of exposed assets and as coastal modifications weaken the coast's natural defenses (Anfuso et al. 2011).

Snoussi et al. (2009) found that 99.9 percent of sandy beaches and 84.5 percent of tourism infrastructure in Tangiers would be lost to an 0.86-meter sea-level rise by 2100. Snoussi et al. (2008) projected that for the area between Saidia and Ras el Ma, 50 percent of sandy beaches would be eroded by 2050 under a 0.39-meter sea-level rise and 70 percent by 2100 for a scenario of a 0.86-meter sea-level rise, with consequent impacts on tourism.

Other studies in Morocco have shown that climate change impacts on water supply and demand are likely to increase competition for water between tourism and other uses, which may ultimately affect the economic performance of specific tourism services (Tekken et al. 2009, 2013; Tekken and Kropp 2012). This is a particular issue in the context of growing luxury tourism, which requires high water demand for golf courses, swimming pools, and other leisure facilities (Tekken et al. 2013; Zarhloule et al. 2009). Together, these factors could contribute to a structural water deficit, requiring policy, planning, and investment to manage (Tekken and Kropp 2012).

larger economic impact than slow onset changes, particularly in developing countries (Bigano et al. 2008).

Beach tourism services are also vulnerable to other aspects of climate change, including temperature increases and changes in water and energy supplies (Gössling et al. 2012; Moreno and Amelung 2009; Perch-Nielsen 2010; Scott et al. 2011). A multi-criteria analysis of the vulnerability of beach tourism in 51 countries found that, of the MENA destinations, Egypt and Saudi Arabia are moderate to highly vulnerable to climate change and that Morocco and Israel are low to moderately vulnerable (Perch-Nielsen 2010).

Some studies modeling the impact of climate change on international tourism have found overall reductions in international tourism, with tourist preferences shifting to higher latitudes and altitudes. One study found that a 1°C temperature rise by 2025 would result in declines of 10–25 percent in international arrivals across the MENA region (Hamilton et al. 2005). Another study projected a reduction in tourism demand of eight percent under the A1B scenario by 2050 (Bigano et al. 2008). However, these models do not necessarily capture the seasonal dynamics of tourism markets, and reductions in summer months may be matched by increases in spring and autumn arrivals (Amengual et al. 2014; Giannakopoulos et al. 2013).

Coastal tourism in the MENA region may also experience indirect impacts of climate change through pathways such as biodiversity loss and ocean acidification (Rodrigues et al. 2013). Of particular concern are the potential impacts of ocean acidification and warming on coral reefs, which provide ecosystem services valuable to tourism in MENA countries, especially Egypt (Hoegh-Guldberg et al. 2007). Perceptions of poor ecological health can create additional vulnerabilities for tourism operators and reduce the economic value of ecosystems to tourism (Marshall et al. 2011).

These assessments have raised concerns regarding the viability of tourism as a central economic strategy in developing countries under conditions of climate change (Gössling et al. 2009). Developing countries that invest in tourism infrastructure are dependent on future tourist numbers, whilst tourists are able to make short-term decisions each season in response to warmer conditions. However, a pleasant climate is just one draw for tourists, who can also be drawn to a location by its culture, proximity, safety, standards, level of service, and the cost of food and accommodations (Gössling et al. 2012). Overall, the effects of climate change on tourism are likely to be small in comparison to changes induced by population and economic growth and/or conflict and political stability (Gössling et al. 2012; Hamilton et al. 2005; Safa and Hilmi 2012).

### 4.4.6 Energy Systems

Energy access is a key requirement for development. Many economic activities depend on ample and reliable electricity access (Akpan et al. 2013); similarly, at the individual and household level, electricity access enables income-generating activities, increases safety, and contributes to human development (Deichmann et al. 2011). In the Middle East and North Africa, almost all of the population has access to electricity in both rural and urban areas. However, in several countries (notably Yemen, Morocco, Tunisia, and Algeria) electricity consumption per capita remains low compared to other nations in the region (see Table 4.9) (World Bank 2013l).

Climate change impacts are projected to affect electricity production and distribution both globally and within the region (Sieber 2013), and MENA countries will have to increase or at least maintain electricity production at current levels in order to support economic development and population growth. In general, three types of climate-change-related stressors could potentially affect thermal power and hydropower generation: (1) increased air temperatures that reduce thermal conversion efficiency; (2) decreased water availability (and increased temperatures) for cooling; and (3) extreme weather events (Han et al. 2009; Sieber 2013). Indeed, extreme weather events and climate change affect not only power plants but also the grid systems and overall reliability of electricity production; this may contribute to an increase in the price of electricity and could even lead to power outages (Ward 2013). In this context, thermal electricity and hydroelectricity are projected to be the most vulnerable electricity sources.

#### *4.4.6.1 Energy Mix*

The MENA countries are heavily dependent on thermal electric sources for electricity production. The main characteristics of these thermoelectric sources, including natural gas, coal, oil, and nuclear, is the use of a cooling system to ensure the safe transformation of heat produced by the combustion of fuels into electricity. A much smaller fraction of the electricity consumed in the MENA region is generated by hydroelectric plants, which are also vulnerable to the impacts of climate change as river runoff is projected to be modified, with a more pronounced seasonality and an overall decrease in water volume expected (Evans 2008, 2009). Table 4.9 displays the percentage of electricity production by source and the total electricity power consumption per capita in the different MENA countries.

With the exception of Yemen, close to 100 percent of the population of the MENA region has access to electricity. In Yemen, only about 40 percent of the population had access in 2011 (World Bank 2013k), which is particularly low compared to the other countries of the region. Electricity production capacity in Yemen could progressively increase according to the increasing electricity demand in the country. Taking into account demographic and socioeconomic development trends, it is projected that demand for

**Table 4.9:** Electricity production from hydroelectric and thermoelectric sources, including natural gas, oil, coal, and nuclear in 2011.

| COUNTRY NAME | ELECTRICITY POWER CONSUMPTION (kWh PER CAPITA) | ELECTRICITY PRODUCTION FROM HYDROELECTRIC SOURCES (% OF TOTAL) | ELECTRICITY PRODUCTION FROM THERMOELECTRIC SOURCES (% OF TOTAL) |
|---|---|---|---|
| United Arab Emirates | 9,389 | 0 | 100 |
| Bahrain | 10,018 | 0 | 100 |
| Djibouti | – | – | – |
| Algeria | 1,090 | 1.0 | 99.0 |
| Egypt, Arab Rep. | 1,743 | 8.3 | 91.8 |
| Iran, Islamic Rep. | 2,649 | 5.0 | 95.0 |
| Iraq | 1,343 | 7.6 | 92.4 |
| Israel | 6,926 | 0 | 100 |
| Jordan | 2,289 | 0.4 | 99.5 |
| Kuwait | 16,122 | 0 | 100 |
| Lebanon | 3,499 | 4.9 | 95.1 |
| Libya | 3,926 | 0 | 100 |
| Morocco | 826 | 7.5 | 92.5 |
| Oman | 6,292 | 0 | 100 |
| Qatar | 15,755 | 0 | 100 |
| Saudi Arabia | 8,161 | 0 | 100 |
| Syrian Arab Republic | 1,715 | 8.0 | 92.0 |
| Tunisia | 1,297 | 0.3 | 997 |
| West Bank and Gaza | – | – | – |
| Yemen, Rep. | 193 | 0 | 100 |

Data sources: World Bank (2013e, f; g; h; i; j).

electricity in the Middle East is going to increase from 822 TWh to 2010 TWh in 2030 (Granit and Löfgren 2010). In order to meet this increased demand for electricity, it is estimated that the countries of the region may have to invest approximately $4 trillion (Granit and Löfgren 2010).

MENA countries depend on both hydroelectricity and thermal electricity for their power needs. With a projected change in water availability, notably induced by a projected overall decrease in precipitation and river runoff and/or increased seasonality due to climate change impacts, thermal electricity plant cooling systems may become less efficient and electricity production could therefore be affected (Mika 2013; Sieber 2013). A similar threat can be observed for hydroelectric power generation, for which a change in water availability is also projected to affect electricity generation (Hamududu and Killingtveit 2012).

#### 4.4.6.2 Climate Change and Energy Production

There appears to be a lack of studies specifically quantifying, at the regional level, the impacts of climate change on thermo-electricity generation in the MENA region. However, drawing upon the conclusions of studies assessing the impacts of climate change on energy systems at the global level or in other regions provides qualitative and quantitative indications regarding the potential effects of climate change on electricity generation in the MENA region.

##### Thermal Electric Generation

Assessment of the impacts of climate change on thermal electric generation in the Middle East and North Africa are lacking. However, these impacts have been studied for European countries and the United States; they provide qualitative and quantitative indications for potential climate change impacts. A study by van Vliet et al. (2012) took into account the effects of changes in river water temperature and river flows on thermal electricity production. The study evaluated these impacts under the IPCC SRES A2 and B1 scenarios for the 2040s (2031–2060) and 2080s (2071–2100).[61] They found that the capacity of nuclear and fossil-fueled power plants could decrease by 6–19 percent in Europe and by 4–16 percent in the United States during the period 2031–2060 (2040s) compared to the production levels observed from 1971–2000. Furthermore, due to the increased incidence of droughts and extremely low river flows, the mean number of days during which electricity production will be reduced by more than 90 percent was projected to be multiplied by three compared to present level, from 0.5 day per year to 1.5 days per year in Europe, and from 0.8 days to 1.3 days per year in the US, both from 2031–2060 in the A2 scenario.

As a substantial share of the electricity produced in the MENA region originates from thermal electric sources, the findings of the study by van Vliet et al (2012) give relevant insights into the potential exposure of the sector. According to studies such as those from Bozkurt and Sen (2013) and Kaniewski et al. (2012), MENA could similarly be exposed to reduced river runoff, increased seasonality, and increased water temperatures, which are the main biophysical drivers impacting electricity generation in the regions studied by van Vliet et al. (2012).

As climate change impacts thermal electric production, the vulnerability of power generation in all the MENA countries is high. In addition, it is projected that economic development and a growing population in the region will increase energy demand (EIA 2013). In addition to increased energy demand induced by socio-economic development, climate change is projected to decrease the production of thermal electric power plants in other regions—the countries in the MENA region could also be put under increasing pressure, contributing to a rise in electricity prices and a risk of electricity shortages in the absence of any adaptation measures.

##### Hydropower

Hydropower plays a minor role in electricity production in the MENA region. Some countries, such as Iraq (7.6 percent of the total electricity produced), Egypt (8.3 percent), Morocco (7.5 percent), and Syria (8.0 percent), generate more than five percent of their electricity from hydroelectric sources (see Table 4.9 for more details). In this regard, it is therefore also prudent to examine hydroelectric production in the MENA region in the context of climate change.

The core resource for hydroelectricity is river runoff, which needs to be stable (both inter- and intra-annually) in order for hydropower plants to operate most efficiently (Hamududu and Killingtveit 2012; Mukheibir 2013). According to the projections for river runoff and water availability in the MENA region under climate change (see Section 4.4.1 The Agriculture-Water-Food Security Nexus), river runoff is projected to decrease and rainfall seasonality to increase across all scenarios in the coming decades (Bozkurt and Sen 2013; Kaniewski et al. 2012).

A global study by Hamududu and Killingtveit (2012) assembled 12 different climate models[62] to project future rates of river runoff and, therewith, to project the electricity produced by hydroelectric plants both at the national level and aggregated at the regional level. Applying the scenario IPCC SRES A1B, which corresponds to a 2.3°C increase by the middle of the 21st century (compared to pre-industrial levels), the authors estimated changes in hydropower generation across the region. For North Africa, they found that production would decrease by 0.08TWh (or –0.48 percent)

[61] The SRES A2 scenario corresponds to a temperature increase of 3.2°C and 1.5°C above pre-industrial levels in 2080 and 2040, respectively. The SRES B1 scenario corresponds to temperature increases of 2.3°C and 1.4°C above pre-industrial levels in 2080 and 2040, respectively. The following three models—ECHAM5/MPIOM, CNRM-CM3 and IPSL-CM4—were used.

[62] The models used were CGHR, ECHOG, FGOALS, GFCM20, GFCM21, GIEH, HADCM3, HADGEM, MIHR, MPEH5, MRCGCM, and NCCCSM.

compared to 2005 production levels. For the Middle East,[63] which in the study also includes Central Asian countries, production was projected to decrease by 1.66TWh (or –1.43 percent).

The results of the study by Hamududu and Killingtveit (2012) need to be interpreted with care, however, as the authors highlighted two key limitations to their projections. First, the study did not take into account changes in the timing of flows (just annual river flow). Therefore, the potential impacts of floods and droughts, which have very significant impacts on hydroelectricity generation and are projected to occur more frequently and with a greater intensity in the coming decades, is not taken into account (Bozkurt and Sen 2013; Kaniewski et al. 2012). Second, changes in river runoff were calculated at the country level and not at the river basin level. This simplification does not reflect potential spatial variability and changes occurring over short distances. Furthermore, in the Middle East and North Africa, surface water is projected to be significantly affected by changes in precipitation and decreases in snow coverage at high altitudes (Abdulla et al. 2008; Samuels et al. 2010) (see Section 4.4.1, The Agriculture-Water-Food Security Nexus). River runoff is therefore projected to decrease or be subject to large fluctuations, which could decrease hydropower supply and reliability.

#### 4.4.6.3 Climate Change and Energy Demand

As global mean temperatures and the occurrence and intensity of heat extremes are projected to increase under climate change (see Section 4.3, Regional Patterns of Climate Change), the demand for air conditioning is also expected to rise (Cozzi and Gül 2013). At the global level, Isaac and van Vuuren (2009) modeled the projected demand of cooling as measured in cooling degree days (accumulated daily temperatures above 18°C). For this simulation, the TIMER/IMAGE model was used under an emissions scenario in which temperatures increase by 3.7°C by the end of the century. They estimated that by 2100 the number of cooling degree days will rise from 12,800 during the period 1971–1991 to 19,451 in 2100; this corresponds to a 51.9 percent increase compared to the baseline period. For the same interval, demand for heating (measured in heating degree days) is projected to remain almost constant.

The International Energy Agency (Cozzi and Gül 2013) estimates that demand for space cooling in the MENA region could increase by seven percent (or 1450 cooling degree days) in 2035 and by 11 percent in 2050 compared to the 2005 energy demand for space cooling in the residential sector. These projections are made using the IEA World Energy Model, under the New Policies Scenarios which correspond to a 2°C temperature increase by 2050 (and 3°C by the end of the century) compared to pre-industrial levels. Demand for space heating in the MENA region is projected to remain marginal (Cozzi and Gül 2013).

#### 4.4.6.4 Synthesis

Based on the current energy mix in the Middle East and North Africa, and the projected impacts of climate change on the region, it is difficult to reach a robust conclusion regarding the projected vulnerability of the region's energy systems. Whether defining vulnerability as the predisposition to being adversely affected by the impacts of climate change (IPCC 2012) or as a function of the system's sensitivity, exposure, and adaptive capacity (IPCC 2007), it appears that the MENA countries are vulnerable to differing extents.

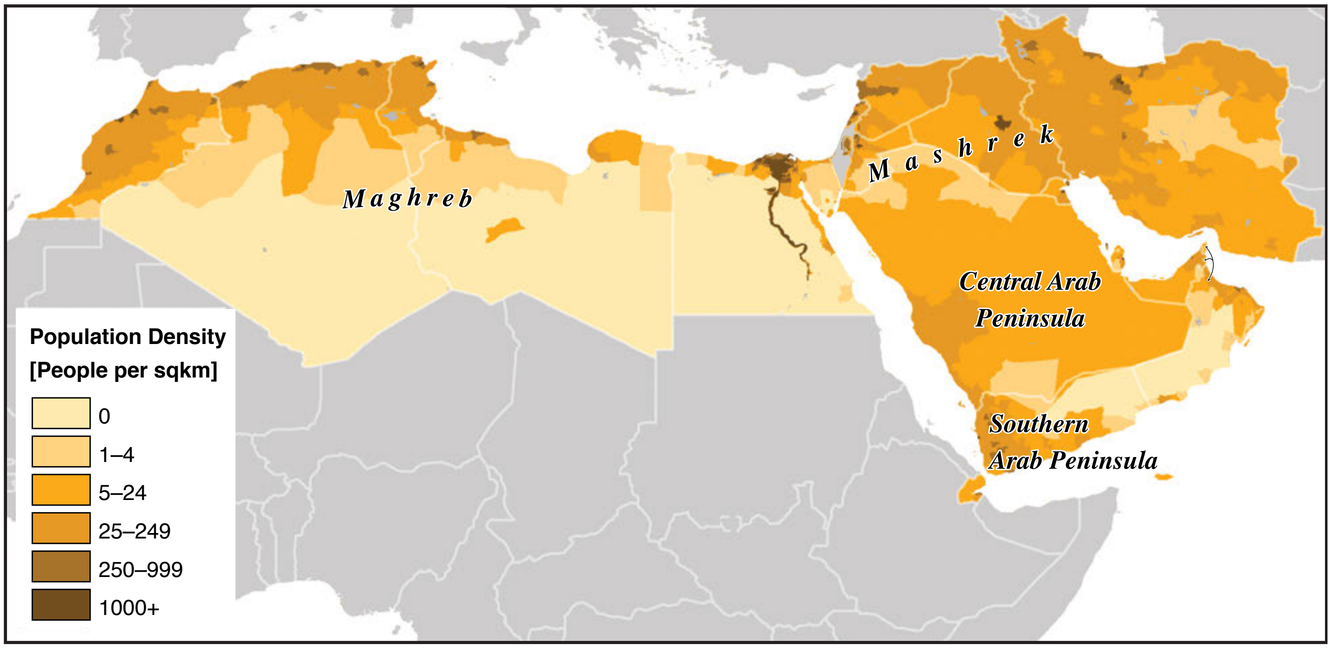
Some countries in the region have a very high economic capacity (GDP per capita) that could support the implementation of adaptive measures, whereas others, such as Yemen, have a weak economic and technical capacity that would not allow them to anticipate and cope with the projected impacts of climate change on energy systems. In this context, the vulnerability of the region should not be regarded as homogeneous, but rather heterogeneous and wideranging. Furthermore, the MENA countries have one of the highest wind and solar energy potentials in the world (OECD 2013). Exploiting this wind and solar potential would strongly help these countries, enabling them to decrease the vulnerability of their existing energy systems to the projected impacts of climate change (OECD 2013). This would also increase electricity production, which is important as demand in the majority of the countries is expected to increase steeply in coming decades due to demographic and economic development as well as to the increasing need for space cooling as temperatures rise (Cozzi and Gül 2013).

## 4.5 Regional Development Narratives

The following implications of climate change are discussed in this section in order to relate climate change impacts to existing and future vulnerabilities in the MENA region: (1) the implications for agriculture, water resources, and food security; (2) the implications for human health and thermal discomfort; and (3) the implications for migration, security, and urban areas. It is important to note that each development narratives presents only one of the many possible ways in which climate change can put key development trajectories at risk. Table 4.10 summarizes the key climate change impacts under different warming levels in the Middle East and North Africa region and Figure 4.24 summarizes the key sub-regional impacts.

[63] Armenia, Azerbaijan, Bahrain, Cyprus, Georgia, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, the United Arab Emirates, and Yemen.

**Figure 4.24:** Sub-regional risks for development in the Middle East and Northern Africa under 4°C warming in 2100 compared to pre-industrial temperatures.




**Maghreb**

Strong warming reduction in annual precipitation, increased water stress and reduced agricultural productivity. Large coastal cities exposed to sea level rise.

*Climate change risks will have severe implications on farmers' livelihoods, country economy, and food security. Exposure of critical coastal assets would have impact on the economy, including tourism. There is risk for accelerated migration flows to urban areas and social conflict.*

**Mashrek and Eastern Parts**

Highly unusual heat and decrease in annual precipitation will increase aridity, decrease in snow water storage and river runoff for example in Jordon, Euphrates and Tigris. Adverse consequences for mostly rain-fed agricultural and food production.

*Climate change risks will have severe implications on farmers' livelihoods, country economy, and food security. There is a risk for accelerated migration flows to urban areas and social conflict.*

**Arabian Peninsula**

Highly unusual heat extremes in central Arabian Peninsula. In southern parts relative increase in annual precipitation, but uncertain trend of annual precipitation in central part. Sea level rise in the Arabian Sea likely higher than in Mediterranean and Atlantic coasts with risk of storm surges and adverse consequences for infrastructure.

*More heat extremes expected to increase thermal discomfort, posing risk to labor productivity and health.*

Data sources: Center for International Earth Science Information Network, Columbia University; United Nations Food and Agriculture Programme; and Centro Internacional de Agricultura Tropical—(2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). This map was reproduced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

### 4.5.1 Changing Precipitation Patterns and an Increase in Extreme Heat Pose High Risks to Agricultural Production and Regional Food Security

Farmers in the MENA region have traditionally coped with harsh climatic conditions, and climate change adds to the existing challenges. Most agricultural activities in MENA take place in the semi-arid climate zones close to the coast or in the highlands, where rainfall, and thus water availability, are predicted to decline most strongly. Rainfall is low and water is scarce, while potential evapotranspiration is high due to high temperatures. Increases in average temperatures and in the frequency of heat waves will represent an additional stressor for agricultural systems.

As agriculture employs more than one third of the MENA population and contributes 13 percent to the region's GDP, climate change impacts have important implications for farmers' livelihoods, national economies, and food security. In addition, as MENA countries are heavy food importers, the region also indirectly suffers from climate change impacts in distant food-producing regions. Some countries (e.g. Egypt, Syria, and Iraq) strongly depend, for their water supply and food security, on precipitation in upstream countries situated in different climatic zones.

Climate impacts in the region are likely to be highly unevenly distributed, with the poor being most affected by both the direct effects of a dwindling resource base and the market effects of productivity shocks in remote agricultural regions. Yield reductions and increased food import dependency may affect everyone, but urban populations are particularly vulnerable to rising food prices, while poor farmers in rural areas are particularly vulnerable to hunger and malnutrition as a direct consequence of yield losses.

The sector most vulnerable to negative climate change impacts is rain-fed agriculture that represents an important source of livelihood for rural populations across MENA. Rain-fed agriculture accounts for 70 percent of the farmed land and representing the main occupation and source of income for rural populations (particularly in marginal areas). The prevalence of poverty is extensive among highland farmers because of poor infrastructure and the degradation of natural resources; among small farmers in dryland farming systems because of low rainfall and weak market linkages; and among small herders in pastoral farming systems for the same reasons (Dixon et al. 2001).

In the context of increasing climate change impacts, farmers in rain-fed areas with moderate poverty are at risk of extreme poverty without extensive off-farm income opportunities. Yet poverty in the first place results from lack of access to resources, including inequitable sharing of water, food, and energy resources. Land management practices are often inefficient and many policies favor urban populations and the supply of cheap food instead of supporting rural development (Dixon et al. 2001).

MENA countries have traditionally invested in irrigation as a way to improve the performance of the agriculture sector. Irrigation was introduced to complement rainfall and to increase and stabilize production. About 25 percent of the agricultural land is irrigated, using on average 85 percent of water resources in the region while offering a substantial contribution to incomes and employment. Countries throughout the region have also focused on infrastructural investments to increase irrigation water supply. Further mobilization of water resources will become increasingly difficult, however, because of constraints on water availability. While there is still some room in the region to increase water supplies through the exploitation of both conventional and unconventional water resources (e.g. desalination), the extent of this increase will be more limited than in the past. Thus, regional agriculture will be confronted with mounting water restrictions in favor of other sectors because of the generally relatively low net returns when compared to other water uses.

Climate change will further reduce the availability of water for irrigation. Making the most of the limited available water in irrigated agriculture can contribute to achieving the goals of improving the rural economy. Increasing water productivity in irrigated agriculture, in its broadest sense of yielding more (in physical and economic terms) with the same amount or less water, will be important to any solution to the region's water scarcity problem. Indeed, it is generally accepted that the efficiency of the irrigation sector in the region is suboptimal.

Management of the water-agriculture nexus in the MENA region still has a strong supply-side bias. In particular, large-scale and centralized supply-side measures are seen as solutions to the growing demand-supply gap. There is less emphasis on more diverse, distributed, decentralized, and small-scale solutions which would increase flexibility, diversity, and resilience to climate change and other pressures (Folke 2003; Sowers et al. 2011).

Large increases in world food prices do not automatically lead to increased poverty for low-income groups, as households may adjust their consumption. Thus, even in the low-productivity scenario examined by Hertel et al. (2010), an increase in world prices for staple grains by more than 30 percent raised the cost of living at the poverty line by just 6.3 percent. Nonetheless, relatively small increases of this kind would in particular affect urban poor households dependent on wage labor income.

Child malnutrition levels could be affected if food production and poor people's livelihoods are affected, or if food prices rise sharply. Child malnutrition levels are already high in parts of the Middle East and North Africa, with 18 percent of the region's children under age five stunted (UNICEF 2013); the rates are higher in some countries (notably Yemen). Evidence from previous food price shocks suggests that child malnutrition levels would be at risk. For example, the prevalence of stunting in children under age five rose in Egypt from 23 percent in 2000 and 2005 to 29 percent in 2008 (UNICEF 2013). This increase may be attributable to the global food crisis in 2007 (Marcus et al. 2011), itself partially driven by weather-related factors.

### 4.5.2 Heat Extremes Will Pose a Significant Challenge for Public Health Across the Region

The number of days with exceptional high temperatures is expected to increase in several capital cities in the MENA region which can cause heat-related illnesses, including heat stress, heat exhaustion, and heat stroke. This is a particular risk for people with chronic diseases, those who are overweight, pregnant women, children, the elderly, and people engaged in outdoor manual labor (Bartlett 2008; IPCC 2014c; Kjellstrom and McMichael 2013). Conditions for workers in the construction industry in the region are already very tough today, with workers reported to suffer from heat exhaustion and dehydration. Measures to limit working hours during peak heat periods, such as those implemented by Qatar (Verner, 2012), may become increasingly necessary, with implications for productivity. Thermal discomfort is expected to increase, in particular in southern parts of the Arabian Peninsula. Thermal discomfort will challenge people's health, especially in densely populated large cities (because of urban heat island effects) that already experience high maximum temperatures. Heat stress is likely to be worse for the urban poor who cannot afford cooling and may also lack access to electricity (Satterthwaite et al. 2007), as in Yemen, for example, where only about 40 percent of the population has access to electricity. Changes in climatic factors could also affect the incidence of malaria in the MENA region because malaria distribution and seasonal occurrence is linked to temperature, elevation, humidity, and rainfall. Malaria endemicity is low in North Africa and the Middle East, with cases reported in Iran, Iraq, and Saudi Arabia and prevalent in Djibouti and Yemen. Poor children under age five are at greatest risk of mortality from malaria and other vector-borne diseases (Costello et al. 2009; WHO 2009).

### 4.5.3 Climate Change Might Act as a Threat Multiplier for the Security Situation

Climate change might act as a threat multipler for the security situation in the MENA region by imposing additional pressure on already scarce resources and by reinforcing pre-existing threats connected to migration following forced displacement.

#### *4.5.3.1 Migration*

Rising temperatures and the risk of drought seriously affect rural livelihoods, possibly leading to increasing migration flows in the future. However, whilst many people will be forced to move, others will be forced to stay because they lack the financial resources or social networks that facilitate mobility. This indicates that climate-induced migration should be addressed not only within the framework of climate change, but also within other economic, cultural, technological or political conditions that might foster or limit migration (Gemenne 2011).

Evidence of migration flows as a response to climate change is scarce. The EACH-FOR studies, a series of local qualitative household surveys investigating the motivation to migrate in Egypt, Morocco, and Western Sahara (Afifi, 2009, Hamza et al. 2009; Gila et al. 2009) appear to be among the only comprehensive studies on migration and climate change in the MENA region. Wodon et al. (2013) also conducted household interviews in five Arab countries on migration, climate change, and related topics.

Within the MENA region, most migration is internal. Urbanization is the predominant migration pattern, and more than 80 percent of the population is currently living in urban areas in Bahrain, Israel, Jordan, Kuwait, Lebanon, Qatar, Saudi Arabia, and United Arab Emirates (UN-DESA 2014). As rural livelihoods are more affected by climate change, especially where a high proportion of the population is employed in agriculture, the urbanization trend will likely continue. In Algeria, for example, migrants move from rural areas to mid-sized towns (Gubert and Nordman 2010).This movement is partly due to slow-onset environmental degradation, including water scarcity, soil erosion, and desertification, which threatens agricultural livelihoods in rural Algeria (Wodon et al. 2014).

Several studies bring attention to the quality of housing in urban centers and the capacity of urban infrastructure to accommodate an increasing population. Migrants to urban areas often live in marginal land with poor infrastructure, liable to flooding or on unstable slopes, and this at great risk from extreme events. The migrants are likely to be poor, face health risks related to low-income urban environments (e.g., overcrowding, poor water quality, poor sanitation). Such areas are also typically at higher risk of crime (Black et al. 2012; Hugo 2011). In some areas, migrants also face discrimination based on their ethnicity, making it harder for them to access services and find employment, with the risk that poor migrant children may have more limited access to education than other local children (Marcus et al. 2011). The urban poor have also been shown to be the worst hit by rising food prices; this poses a particular risk to the MENA region. MENA is likely to be exposed to the complex challenges of rising urbanization rates and mounting direct and indirect pressures on its resource base while simultaneously developing a higher vulnerability to global food prices.

Social ties play an important role in finding employment and housing in migration destinations. Migrants, especially those coming from rural areas, are often disadvantaged since they usually have less education and lower language capabilities (e.g., not speaking both French and Arabic in Morocco). Furthermore, many migrants live in overcrowded apartments and in slums. Lack of permanent access to electricity for cooling in the night can lead to loss of sleep and lower productivity during the day.

If current migration patterns continue, the majority of migrants are likely to be men migrating without their families, at least initially. Women left behind in rural areas may thus face more intensive workloads in agriculture, domestic work, and the management of scarce water supplies (Verner, 2012). If rural women taking on new roles do not have the skills to generate productive livelihoods, as a result of discriminatory social norms and limited education opportunities, then they are at risk of falling into poverty. Promoting gender equity, by tackling both discriminatory norms and inequalities in access to resources, is thus a vital component in climate-change adaptation strategies (Verner, 2012).

#### *4.5.3.2 Security*

Climate change might act as a threat multiplier for the security situation in the MENA region by placing additional pressures on already scarce resources and by reinforcing such preexisting threats as political instability, poverty, and unemployment. This creates the potential for social uprising and violent conflict. Due to food imports and international migration, MENA is increasingly vulnerable to climate change impacts in other parts of the continent and the world.

For example, the literature described how droughts in China, Russia, and Ukraine, and heavy rainfall in Australia and Canada, combined with market mechanisms to contribute to high bread prices in Egypt in 2011 (Lagi et al. 2011; Sternberg 2013). The studies contend that this, together with a previous food crisis in 2008, the country's weak bread subsidy system, and an already unstable food supply situation, made the country more vulnerable to world market prices and reductions in wheat imports.

Transit migration places an additional external pressure on scarce resources in MENA. The Maghreb countries in particular serve as receiving and transit countries for Sahelian and other Sub-Saharan African migrants who leave their home countries due to poverty, conflicts, and environmental degradation (see Section 4.4.4, Migration and Security).

Building resilience and institutional capacity is crucial in order to react and adapt to climatic changes, extreme weather events, or shocks such as climate-variability-related increases in food prices. Institutions weakened by conflicts or crises have a lower capacity to build resilience to climatic changes and extreme events. Further research is needed to investigate the strength of links between long-term climate change, instead of single climatologic hazards, to migration and social unrest.

## 4.6 Synthesis Table—Middle East and North Africa

**Table 4.10:** Synthesis table of climate change impacts in MENA under different warming levels. The impacts reported in several impact studies were classified into different warming levels (see Section 6.4, Warming Level Attribution and Classification).

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Regional Warming (summer temperatures)** [1] | | | 1.5°C | 2.2°C | 2.5°C<br>Parts of inland Algeria, Libya, and large parts of Egypt warm by 3°C<br>Warming over the Sahel is more moderate (2°C) | 4.5°C | 7.5°C<br>Mean summer temperatures of up to 8°C warmer in parts of Algeria<br>Warming over the Sahel is more moderate (5°C) |
| **Heat Extremes** | **Heat Waves** | Abadan, Iran: 6 days<br>Amman, Jordan: 4 days<br>Baghdad, Iraq: 8 days<br>Damascus, Syria: 1 day<br>Jerusalem: 7 days<br>Riyadh, Saudi Arabia: 3 days<br>Tehran, Iran: 5 days<br>Tripoli, Libya: 3 days[2] | | Abadan, Iran: 43 days<br>Amman, Jordan: 31 days<br>Baghdad, Iraq: 47 days<br>Damascus, Syria: 36 days<br>Jerusalem: 26 days<br>Riyadh, Saudi Arabia: 81 days<br>Tehran, Iran: 48 days<br>Tripoli, Libya: 13 days[3]<br>30 and 40 days in a year with high maximum temperatures in the Mediterranean Basin and the Sahara respectively[4] | Abadan, Iran: 82 days<br>Amman, Jordan: 62 days<br>Baghdad, Iraq: 90 days<br>Damascus, Syria: 71 days<br>Jerusalem: 46 days<br>Riyadh, Saudi Arabia: 132 days<br>Tehran, Iran: 92 days<br>Tripoli, Libya: 22 days[3] | | Abadan, Iran: 134 days<br>Amman, Jordan: 115 days<br>Baghdad, Iraq: 162 days<br>Damascus, Syria: 129 days<br>Jerusalem: 102 days<br>Riyadh, Saudi Arabia: 202 days<br>Tehran, Iran: 159 days<br>Tripoli, Libya: 59 days[3]<br>150 and 210 days in a year with maximum temperatures in the Mediterranean Basin and the Sahara respectively, with hotspots in the Maghreb, Iran and Yemen |
| | **Highly unusual Heat Extremes** | | 5% of land area | 25%–33% of land | 30% of land area[5] | | Almost all summer months |
| | **Unprecedented Heat Extremes** | | Absent | 2–5% of land area | 5–10% of land area, only present in some isolated coastal regions in Egypt, Republic of Yemen, Djibouti, and Oman | | 65% of land area by 2071–2099, 80% of land area by 2100 |

**Table 4.10:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Precipitation** | **Summer and Annual** | | | | Increase (50% more rain) south of 25°N[6], decrease by 20–40%, in parts of area north of 25°N. | | Increase south of 25°N[6], decrease by up to 40%, in parts of area north of 25°N. |
| | **Winter** | | | | Drier in the eastern part of the Sahel. | | Drier in the eastern part of the Sahel. |
| **Drought** | | < 0.1 months per year with moderate drought[7]<br>Regional hotspots of drought exposure (i.e. 7 out of 100,000 inhabitants exposed to drought)[8] | | < 0.5 months per year with moderate drought[7]<br>Increase in length of the longest period of consecutive dry days by 10 days in the Sahara and by 5 days in the Mediterranean[9] | | ~1.5 months per year with moderate drought[7]<br>Increase in length of the longest period of consecutive dry days by 10 days in the Sahara and by 15 days in the Mediterranean<br>Little change on the Arab Peninsula, and reduction in future droughts for the Maghreb states and the Middle East[10]<br>Number of rainy days decrease in the Middle East[11] | 6 months per year with moderate drought[7]<br>Increase in length of the longest period of consecutive dry days by 15 days in the Sahara and by 20 days in the Mediterranean<br>20% increase in days under drought conditions for the MNA region, too little data for the Arab Peninsula, and > 60% increase for Morocco and the Middle East[12] |
| **Extreme Precipitation** | | No change in extreme precipitation[13]<br>No change in return values of baseline precipitation maxima[14] | | No change in MNA region, ~5% increase in Iran[13]<br>No change in return values of baseline precipitation maxima[14]<br>10% increase in maximum 5-day precipitation[15] | | No change for North Africa, 10–20% increases in Arabian Peninsula and Iran[13]<br>No change for North Africa, 10–15 years for the Arab Peninsula, and Iran.[14]<br>10% increase in maximum 5-day precipitation[15] | No change in North Africa, 10–20% increase in Arabian Peninsula and Iran, and >50% increase in the Republic of Yemen[13]<br>10 years for North Africa and the Arabian Peninsula, 7–10 for the Islamic Republic of Iran and the Republic of Yemen[14]<br>~ 20% increase in maximum 5-day precipitation[15] |
| **Aridity** | | 69% of land area is hyper-arid, 13% arid, 7% semi-arid, and 2% sub-humid[16] | | | 71% of land area is hyper-arid and reduction in arid, semi-arid and sub-humid areas[16] | | 74% of land area is hyper-arid (5% increase) and reduction in arid, semi-arid and sub-humid areas |

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Sea-level Rise Above Present (1985–2005)** | | Sea level changes during the 20th century: rise of 1.1–1.3 mm/yr[17] | < 0.1m | Mediterranean Sea, Atlantic Ocean: 0.20m –0.57m; Arabian Sea: 0.22m –0.64m; maximum rate of rise between 6.4mm/yr and 7.8mm/yr | | | Mediterranean Sea, Atlantic Ocean: 0.38m –0.96m Arabian Sea: 0.44m –1.04m in 2081–2100, maximum of 1.24m in 2100; maximum rate of rise between 20mm/yr to 21.4mm/yr |
| **Desertification** | | 65–89% of land critically sensitive in Egypt, 39% in Algeria, 28% in Morocco, 0–22% in Iran, and 28% in Iraq[18] 83% of land in Oman with decreasing biomass trend between 1986–2009[19] | | | | Strong increase of more arid ecosystems, higher risk of desertification in North Africa and the Western Mashrek[20] | Strong increase of more arid ecosystems, higher risk of desertification in North Africa and the Western Mashrek[20] 16% of Africa's grassland become desert[21] and 23% of Africa's desert become grassland[22] |
| **Water Availability** | **Runoff** | | | | 17% reduction in mean daily runoff for the tributaries of the Jordan River[23] reduction in discharge exceeding 15% in parts of the region Decrease in runoff with 10–50% likelihood in Maghreb[24] | 17% reduction in mean daily runoff for the tributaries of the Jordan River[23] reduction in discharge exceeding 15% in parts of the region Decrease in runoff with 10–50% likelihood in Maghreb[24] | 25–55% decrease in eastern Anatolian mountains (headwaters of Euphrates and Tigris rivers)[25] reduction in discharge exceeding 45% in parts of the region |
| | **Snow** | | | | 55% reduction in snow water equivalent in Euphrates/Tigris headwaters[25] | 77–85% reduction in snow water equivalent in Euphrates/Tigris headwaters[25] | 87% reduction in snow water equivalent in Euphrates/Tigris headwaters[25] |
| | **Groundwater Recharge** | | | | 7% to 37% reduction in the West Bank[26] | | 14–44% reduction in the West Bank and 21–51% reduction for temperatures above 4°C |
| **Crop Areas and Food Production** | **Crop Growing Areas** | | | | Decrease of over 8,500 km² in viable rain-fed agriculture; land over Israel, Lebanon, Syrian Arab Republic, Iraq, and Iran at a significance level of 0.9 [27] | | Decrease of over 170,000 km² viable rain-fed agricultural land over Israel, Lebanon, Syrian Arab Republic, Iraq, and Iran at a significance level of 0.9[27] |

**Table 4.10:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Yields** | **Cereals** | | | 3.4% reduction in the southwestern Mediterranean and 4.9% reduction in the southeast Mediterranean [28]<br>10–50% reduction in wheat yields in Tunisia[29]<br>1% reduction in wheat yields, 3% reduction in maize yields, and 5% reduction in rice yields in West Asia[30]<br>1% increase in barley and sorghum yields in West Asia[30] | 3.8% reduction in the southwestern Mediterranean and 10.1% reduction in the southeast Mediterranean[28] | | |
| | **Oil Crops** | | | 6% reduction in sunflower yields in West Asia[30] | | | |
| | **Tubers** | | | 1% reduction in sugar beet yields, 3% increase in potatoes yields in West Asia[30]<br>13.3% reduction in the southwestern Mediterranean and 4.3% reduction in the southeast Mediterranean[28] | 1.5% reduction in the southwestern Mediterranean and 5.7% reduction in the southeast Mediterranean[28] | | |
| | **Legumes** | | | 24% reduction in the southwestern and southeastern Mediterranean[28] | 18.5% reduction in the southwestern Mediterranean and 30.1% reduction in the southeast Mediterranean[28] | | |
| | **All Crops** | | | | | | 26%–39% reduction in Algeria and Morocco[33] |
| | **Growing Period** | | | Shortening of the wheat growing period by 10 days in Tunisia.[34] | Shortening of the wheat growing period by 16 days in Tunisia.[34] | | Shortening of the wheat growing period by 30 days in Tunisia.[34] |

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Coastal Areas*** | **Infrastructure and Land** | | | Sea-level rise of 0.2 m would result in damages of $16.5–50.5 billion in Alexandria, and of $1.2–2 billion in Benghazi[35]<br>1.8 million and 1.9 million people affected by flooding in Morocco and Egypt with 0.44–0.54 m sea-level rise[36] | | | $5 billion[37] in damages with 1.26 m sea-level rise in Egypt; losses of 25% of the Nile Delta's land area, 10.5% of national population, and 6.4% of GDP with 1m sea-level rise[38]<br>2.1 million and 3.6 million people affected from flooding in Morocco and Egypt with 1.04–1.14 m sea-level rise[36] |
| | **Tourism** | | | | 50% of sandy beaches in the area between Saidia and Ras el Ma eroded[39] | | 99.9% of sandy beaches and 84.5% of tourism infrastructure in Tangier lost[40]<br>70% of sandy beaches in the area between Saidia and Ras el Ma eroded[40] |
| **Energy Systems** | | | Capacity of nuclear and fossil-fueled power plants could decrease due to changes in river water temperature and in river flows. Mean number of days during which electricity production is possible reduces due to the increase in incidence of droughts and extreme river low flow[41] | | | | |
| **Human Health** | **Vector-borne Diseases** | Malaria present in the Middle East, with cases reported in Iran, Iraq, and Saudi Arabia. It is prevalent in Djibouti and Yemen[42]<br>Lymphatic filariasis present only in Egypt's Nile Delta and in Yemen<br>Zoonotic cutaceous leishmaniasis (ZCL) increases in Tunisia with changes in rainfall and humidity[43] | No overall increase in malaria incidence[44] | | Lymphatic filariasis could extend to include much of the North African coastline with a 75–100% probability[45] | | 39–62 million more people exposed to risk of malaria[46] |

**Table 4.10:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Human Health** | **Diarrheal Disease** | Climate change was estimated to be responsible in 2000 for approximately 2.4% of worldwide cases of diarrhea[47] | | North Africa: Increase by 6–14%, Middle East: 6–15%[48] | | | |
| | **Other Food and Water-borne Disease** | | | Increase in the incidence of morbidity associated with food and water-borne diseases in Beirut of 16–28%[49] | | | Increase in the incidence of morbidity associated with food and water-borne diseases in Beirut of 35–42%[49] |
| | **Thermal Discomfort** | 100 thermal discomfort days in North Africa and eastern and southern parts of the Arabian Peninsula[50] Number of emergency hospital admissions in Tel Aviv increases by 1.47% per 1°C temperature increase[51] | | | | | |
| **Migration & Security** | | 40,000 to 60,000 households migrated to urban areas after droughts in the Syrian Arab Republic[52] | | | | | |

Please note that the 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), and not in mitigation scenarios limiting warming to these levels, or below; in the latter case, the year of exceeding would always be 2100 or not at all. Exceedance with a likely chance (>66 percent) generally occurs in the second half of the decade cited. Impacts are given for warming levels irrespective of the timeframe (i.e. if a study gives impacts for 2°C warming in 2100, then the impact is given in the 2°C column). Impacts given in the observations column do not necessarily form the baseline for future impacts. Impacts for different warming levels may originate from different studies and therefore may be based on different underlying assumptions—meaning that the impacts are not always fully comparable (e.g., crop yields may decrease more in 3°C than 4°C because underlying the impact at 3°C warming is a study that features very strong precipitation decreases. Moreover, this report did not systematically review observed impacts. It highlights important observed impacts for current warming but does not conduct any formal process to attribute impacts to climate change.

* Impacts of sea-level rise on coastal land, infrastructure, and tourism might have been calculated with different warming levels than reported here but have been moved to a lower warming level in the table to be consistent with the sea-level rise reported at the top of the table. Please see Chapter 2—The Global Picture for more information on the reason for different sea-level rise projections and Section 4.4.5, Coastal Infrastructure and Tourism for details on the individual impact studies.

# Endnotes

[1] Temperature projections for the Middle East and North African land area, for the multi-model mean during the months of June, July and August.

[2] Klok and Tank (2009).

[3] Lelieveld et al. (2013). Number of days in a year when maximum temperatures are above the 90th percentile for six consecutive days or longer relative to the baseline. Equals the WSDI index. Please note that the numbers given are multi-annual mean values (which is why values below six for the observation period are possible), whereas Lelieveld et al. (2013) derive median values for the non-zero entries only.

[4] Sillmann et al. (2013b). Warm spell duration index (WSDI, WSDI, and CSDI count the number of days in a year when TX is above the 90th percentile for six consecutive days or longer relative to the 1961–1990 base period. The Sahara is the region spanning from 18N to 30N latitude and from 20W to 65E longitude. The Mediterranean Basin is the region spanning from 30N to 48N latitude and from 10W to 40E longitude. See Figure 2 in Sillmann et al. (2013b).

[5] On average one of the summer months (June, July or August) each year will exceed temperatures warmer than three standard deviations beyond the 1951–1980 mean.

[6] Note that these relatively large percentage changes projected for regions south of 25°N occur in a region that is very dry today. Thus, the absolute changes are small.

[7] Orlowsky and Seneviratne (2013). Months with Standard Precipitation Index (12 month) in a 20-year windowed analysis < –1 which indicates moderate drought. The region studied is the Mediterranean, comprising southern Europe as well as North Africa and the Middle East. Morocco, Algeria, and Tunisia, as well as the Middle East, appear as hotspots.

[8] Physical exposure to drought, a product designed by UNEP/GRID-Europe for the Global Assessment Report on Risk Reduction (GAR). It was modeled using global data. It is based on three sources: (1) a global monthly gridded precipitation dataset obtained from the Climatic Research Unit (University of East Anglia); (2) a GIS modeling of global Standardized Precipitation Index based on Brad Lyon (IRI, Columbia University) methodology. (3) a population grid for the year 2010, provided by LandScanTM Global Population Database (Oak Ridge, TN: Oak Ridge National Laboratory). Unit is expected average annual population exposed (inhabitants). This product was designed by Pascal Peduzzi (UNEP/GRID-Geneva, ISDR). Credit: GIS processing UNEP/GRID-Europe.

[9] Sillmann et al. (2013b). Increase in the CMIP5 ensemble median in 2081–2100 compared to the reference period 1981–2000. Dry days are days with precipitation of less than one mm. The Sahara region is defined as a box stretching from 18N–30N latitude and 20W–65E longitude. The Mediterranean region is defined as a box stretching from 30N–48N latitude and 10W–40E longitude (only land grid points).

[10] Dai (2012).

[11] Lelieveld et al. (2013).

[12] Prudhomme et al. (2013). Percentage change in the occurrence of days under drought conditions determined by the runoff deficit index (DI).

[13] Kharin et al. (2013). Relative changes (percent) of 20-year return values of annual extremes of daily precipitation rates as simulated by CMIP5 models in 2081–2100.

[14] Kharin et al. (2013). The multi-model median of return periods (or waiting times), in years, for late 20th century precipitation extremes as simulated by CMIP5 models in 2081–2100 relative to 1986–2005. Changes are statistically significant at the 5-percent level for the Arab Peninsula but are not statistically significant at the 5-percent level for North Africa.

[15] Sillmann et al. (2013b). Projected changes (in percent) in annual maximum 5-day precipitation (RX5day) over the time period 2081–2100 relative to the reference period (1981–2000).

[16] See Section 4.3.5.

[17] Tsimplis and Baker (2000).

[18] Various authors used the MEDALUS model to quantify the vulnerability against desertification in the MNA region. The MEDALUS model integrates regional information on vegetation, soil, climate, erosion, and management and quantifies the sensitivity of a region against desertification in four classes: critical, fragile, moderate, and non-sensitive.

[19] Brinkmann et al. (2011).

[20] Gao and Giorgi (2008).

[21] Scheiter and Higgins (2009). Under the influence of fire.

[22] Higgins and Scheiter (2012). Only potential vegetation is considered.

[23] Samuels et al. (2010). For the period 2036–2060 relative to 1980–2004.

[24] Gerten et al. 2013.

[25] Bozkurt and Sen (2013).

[26] Mizyed (2008).

[27] Evans (2008). Using the 200 mm isohyet to indicate the limit of rain-fed agriculture.

[28] Giannakopoulos et al. (2009). Southwest Mediterranean includes Tunisia, Algeria, and Morocco; southeast Mediterranean includes Jordan, Egypt, and Libya.

[29] Mougou et al. (2010). A crop modeling study with stylized temperature (1.5°C) and precipitation scenarios (–10 percent).

[30] Lobell et al. (2008). Median changes in crop yields. West Asia covers parts of the MENA region, and includes the Arabian Peninsula (except Kuwait, the United Arab Emirates, and Qatar), Iraq, Iran, Jordan, Turkey, Georgia, Azerbaijan, and Armenia.

[31] Verner and Breisinger (2013).

[32] Al-Bakri et al. (2011). A crop modeling study with stylized temperature (1°C–4°C) and precipitation scenarios (+/–20 percent).

[33] Schilling et al. (2012).

[34] Mougou et al. (2010).

[35] Hallegatte et al. (2013).

[36] Brown et al. (2011).

[37] Hinkel et al. (2012).

[38] Dasgupta et al. (2009).

[39] Snoussi et al. (2008).

[40] Snoussi et al. (2009).

[41] See Section 4.5.5.3.

[42] WHO and EMRO (2009); WHO (2013a).

[43] Toumi et al. (2012). Incidence increases by 1.8 percent with a one mm increase in rainfall lagged by 12–14 months and by 5 percent when there is a 1-percent increase in humidity from July to September in the same epidemiologic year.

[44] Ebi (2008). Number of additional malaria cases calculated using relative risk of disease estimations from WHO Global Burden of Disease Study. The results are not directly comparable to van Lieshout et al. (2004) as they do not take into account additional population growth and as they use different emissions scenarios and a different climate model.

[45] Slater and Michael (2012).

[46] van Lieshout et al. (2004). Increases in population (in millions) exposed to risk of malaria for at least one month of the year including population growth. The population at risk in the B1 scenario is higher than in the B2 scenario because population projections for the WHO region EMR-B are higher for this scenario. No additional population is exposed to risk of malaria for three months or more in any of the SRES scenarios. The WHO region EMR-B includes Bahrain, Iran, Jordan, Kuwait, Lebanon, Libya, Oman, Qatar, Saudi Arabia, Syria, Tunisia, and the United Arab Emirates.

[47] WHO (2002).

[48] Kolstad and Johansson (2011). Increased relative risk of diarrheal disease.

[49] El-Fadel et al. (2012). It was assumed in this study that the climate is evolving slowly and continuously beyond 2050 and that the increase in average yearly temperature is linear within the simulation period 2050–2095. Thus, the average increase in decadal temperatures from 2010 to 2095 was linearly interpolated.

[50] Giannakopoulos et al. (2013). The number of days characterized by high thermal discomfort (humidex, an index used to express the temperature perceived by people, $> 38°C$).

[51] Novikov et al. (2012).

[52] Wodon et al. (2014). In total, 1.3 million people have been affected and 800,000 people lost their livelihoods. Please note that there has been no determination that the drought of 2010 in Syria was a climate change event.

# Chapter 5

# Europe and Central Asia

The Europe and Central Asia region encompasses a wide range of geographic features ranging from the mountains to coasts in the Western Balkans and from the vast plains of Central Asia to Russia's boreal forests. In the Western Balkans and Central Asia, heat extremes and reduced water availability become threats as temperatures rise toward 4°C. This includes earlier glacier melt in Central Asia and shifts in the timing of water flows, and a higher risk of drought in the Western Balkans, with potential declines for crop yields, urban health, and energy generation. In Macedonia, for example, yield losses are projected of up to 50 percent for maize, wheat, vegetables and grapes at 2°C warming. Flood risk is expected to increase slightly along the Danube, Sava and Tisza rivers, and a slight decrease in 100-year flood events is projected in the southern parts of the Western Balkans. At 2°C warming, methane emissions from melting permafrost could increase by 20–30 percent across Russia in the mid-21st century.

## 5.1 Regional Summary

The Europe and Central Asia region in this report covers 12 countries[64] within Central Asia, the Western Balkans, and the Russian Federation. The region encompasses a wide range of geographic features ranging from the mountainous and partly coastal Western Balkans to the vast plains of Central Asia and Russia's boreal forests. The region is inhabited by 226 million people; the population is, however, unequally distributed, with Kazakhstan having only six inhabitants per square kilometer and Kosovo as many as 166 inhabitants per square kilometer. The urbanization rate is about 50 percent. The population in Russia and the Western Balkans is projected to decline slightly, while the population of Central Asia is projected to increase sharply by 2050.

The region's importance is closely related to its rich natural resources, including gas and oil reserves as well as carbon stored in the boreal forests (the extraction and maintenance of which affect worldwide climate mitigation goals). Due to the geographical exposure as well as a relatively high share of agriculture in regional GDP, poverty rates that are increasing in recent years, inequalities and relatively poor social services and public infrastructure, the region is highly vulnerable to climate change impacts.

In climatic terms, the region displays a clear dipole: regions in the southwest become drier and regions in the northeast become wetter as the world warms toward 4°C. These warming conditions lead to a high risk of drought in the west and challenges to stable freshwater supplies in the east, where changes in precipitation combine with glacial melt to affect the seasonality of river discharge.

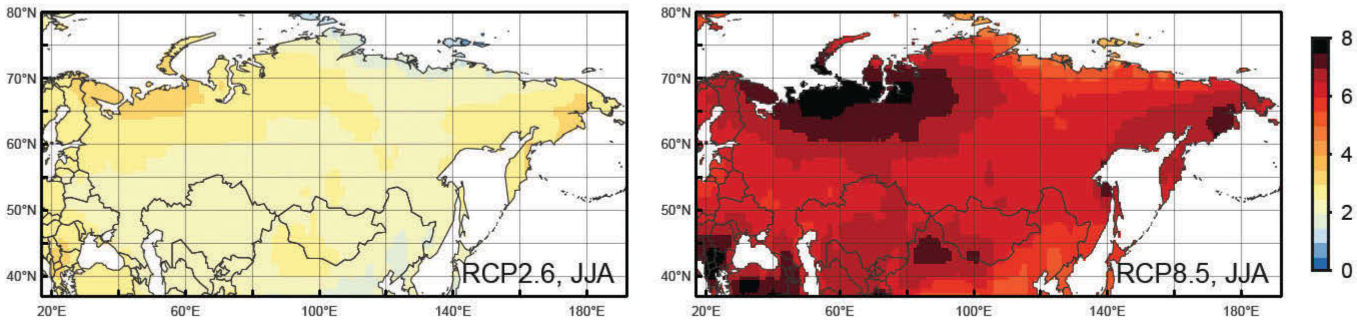
### 5.1.1 Regional Patterns of Climate Change

#### *5.1.1.1 Temperature*

Warming over Europe and Central Asia is projected to be above the global mean land warming. In a 2°C world, the multi-model mean warming by the end of the century is about 2.5°C above the 1951–1980 base period. This level of warming is reached by mid-century and then remains constant until the end of the century in a 2°C world. In contrast, in a 4°C world, summer warming continues almost linearly until the end of the century, reaching about 8.5°C above the 1951–1980 baseline by 2100 for the region's land area (Figure 5.1). The most pronounced warming is projected to occur in Northern Russia in the region bordering the Barents-Kara Sea, along the Black Sea coast (including the Balkans), and

[64] The Europe and Central Asia region in this report includes the following countries: Albania, Bosnia and Herzegovina, Kazakhstan, Kosovo, the Kyrgyz Republic, the Former Yugoslav Republic of Macedonia, Montenegro, the Russian Federation, Serbia, Tajikistan, Turkmenistan, and Uzbekistan.

**Figure 5.1:** Multi-model mean temperature anomaly for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the months of June-July-August for the Europe and Central Asia region.




Temperature anomalies in degrees Celsius are averaged over the time period 2071–2099 relative to 1951–1980.

in Northern China and Mongolia. In these areas, mean summer temperatures by 2071–2099 will increase by about 3.5°C in a 2°C world and by about 7.5°C in a 4°C world.

### 5.1.1.2 Heat Extremes

One of the clearest climate change signals is the strong increase in threshold-exceeding heat extremes[65] in the region surrounding the Black Sea, (and, in particular, the Balkans). Here, even in a 2°C world, *highly unusual* heat extremes, with temperatures warmer than three standard deviations beyond the baseline average, will occur in about 20–30 percent of summer months by 2100, and *unprecedented* heat extremes will occur between 5–10 percent of summer months. For the whole region, about 15 percent of the land area is projected to be affected by *highly unusual* heat extremes in a 2°C world by the end of the century, while *unprecedented* heat extremes will remain almost absent. In contrast, in a 4°C world, 85 percent of land area in the region is projected to be affected by *highly unusual* heat extremes; 55 percent of the area is projected to be affected by *unprecedented* heat extremes by 2100. Most of the heat extremes will occur south of approximately 50°N, stretching from the Balkans all the way to Japan. The number of tropical nights south of approximately 50°N is expected to increase by 20–30 days in a 2°C world and by 50–60 days in a 4°C world.

### 5.1.1.3 Precipitation

The basic concept of the "dry-getting-drier and wet-getting wetter" under climate change is a good first order estimate for Europe and Central Asia. The relative wetting of the Northeast, (i.e., Siberia) is the most pronounced signal, possibly associated with a shift in storm tracks. The increase in precipitation is far more pronounced during the winter than during the summer.

Despite an overall negative trend in extreme precipitation events, regional and seasonal projections for the Balkans remain inconclusive in a 2°C world. However, 20–30 percent reductions are projected for a 4°C world. Although projections of precipitation for the Central Asian countries suffer from substantial model uncertainties, the overall trend for heavy precipitation intensity is below the global average.

Central and Eastern Siberia is one of the regions expected to experience the strongest increase in heavy precipitation events. Heavy precipitation events with a 20-year return time are projected to intensify by over 30 percent in this region and the return time of such extremes from the 20-year reference period (1986–2005) in a 4°C world is projected to fall below five years by the end of the 21st century. Changes are much weaker (greater than 10 percent increase in intensity and 10–15 year return times) in a 2°C world.

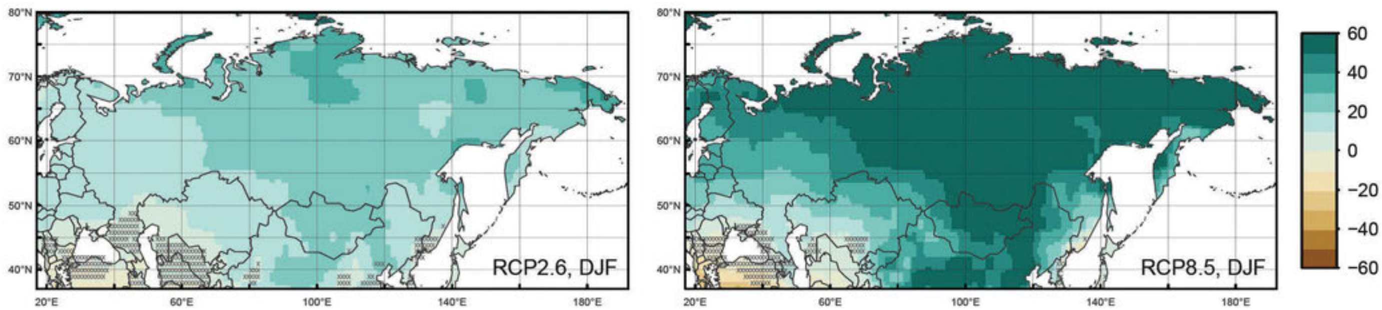
### 5.1.1.4 Drought and Aridity

In a 2°C world around five percent more land in the region will be affected by aridity; in a 4°C world, the land area classified as hyper-arid, arid, or semi-arid will increase by more than 30 percent (Figure 5.2). The Western Balkans is projected to suffer from increased drought conditions. Though changes in annual precipitation are weak, the Balkans and the region surrounding the Caspian Sea are projected to become more arid due to warming-induced drying.

Projections for future drought also mimic the overall trend toward a wetter climate. Some projections even show a negative change in drought risk for the eastern Siberia under a 4°C world. Projections for central and eastern Russia, meanwhile, are inconclusive.

[65] In this report, *highly unusual* heat extremes refer to 3-sigma events and *unprecedented* heat extremes to 5-sigma events (see Appendix).

**Figure 5.2:** Multi-model mean of the percentage change in the aridity index (AI) for RCP2.6 (2˚C world ) (left) and RCP8.5 (4˚C world) (right) for the Europe and Central Asia region by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that a negative change corresponds to a shift to more arid conditions.[66]

## 5.1.2 Regional Sea-level Rise

The countries of the ECA region considered here (excluding Russia) cover a relatively short stretch of coast that is affected by sea level rise. The sea-level rise in the region is projected to reach 0.52 m on average (0.37–0.9 m) in a 4°C world from 2081–2100 above the 1986–2005 baseline, with rates of increase of 10.1 mm per year (5.9–19.6 mm/yr) from 2081–2100. This is slightly below the global mean. One of the most vulnerable coasts in the region is the Drini-Mati River Delta in Albania. The sea level in the Caspian Sea, that is completely isolated from the global ocean, is projected to fall by 4.5 m by the end of the century due to increased evaporation.

## 5.1.3 Sector-based and Thematic Impacts

### *5.1.3.1 Glaciers and Snow*

The enhanced runoff from the glaciers is expected to continue over the 21st century. Projections of glacier change use different scenarios applied to different geographical regions for different reference periods, making direct scenario comparisons rather difficult. In all projections, however, glaciers are expected to lose more than half of their volume by 2100. The loss of stored water implies increased runoff in the coming decades, followed by a significant shortage until the store is completely emptied.

The principal driver behind the glacier volume and snow cover change is air temperature. Projections show approximately 50 percent (31–66 percent) glacier volume loss in Central Asia in a 2°C world and approximately 67 percent (50–78 percent) glacier volume loss in a 4°C world. A temperature rise higher than 1.1°C will cause the small glaciers of the Balkans (Albanian Alps and Montenegrin Durmitor) to melt completely within decades.

### *5.1.3.2 Water*

River flows in Central Asia will in general be lower during the summer months when the vegetation is present, while winter runoff may increase. Climate change in the region is likely to have consequences for runoff seasonality, and a shift in the peak flows from summer to spring can be expected due to earlier snow melt. This may increase water stress in summer, in particular in unregulated catchments. The annual amount of water in rivers is not likely to decrease considerably, at least until the middle of the century when glacier depletion will cause a distinct decrease in water volume of Central Asian rivers. Over the short-term, enhanced glacier melt rates will provide an inflow of additional water into the rivers, though in the more remote future, when glaciers are shrinking, their buffer effect will disappear. This effect will be more pronounced for the Amu Darya, because of its actual higher share of glacier melt water, than for the Syr Darya.

Very few scientific studies about regional impacts on water resources and river runoff levels are available for the Western Balkan countries, with most projections done on a broader European level. In particular, there is a lack of area-wide hydrological data, especially since the 1990s. Water availability over summer months In the Balkans is assumed to decrease considerably until the end of the century. In the northern parts of the Balkans, spring and winter riverine flood risk can increase. Results from a global

[66] Some individual grid cells have noticeably different values than their direct neighbors. This is due to the fact that the aridity index is defined as a fraction of total annual precipitation divided by potential evapotranspiration (see Appendix). It therefore behaves in a strongly non-linear fashion and year-to-year fluctuations can be large. As the results are averaged over a relatively small number of model simulations, this can result in local jumps.

study show severe decreases in annual discharge in the Western Balkans of more than 45 percent in a 4°C world.

#### 5.1.3.3 Agriculture

Central Asia's agricultural sector is highly dependent on irrigation water availability, and the impact climate change will have on agriculture in both Central Asia and the Western Balkans is significant. Changing precipitation patterns, reduced runoff in the major river basins, and increasing temperatures will put additional pressure on available water resources (and, at the same time, increase agricultural water demand). Prolonged periods of above average temperatures will exacerbate heat stress of agricultural crops, leading to decreasing plant productivity. Droughts, meanwhile, are very likely to increase desertification in the Kyrgyz Republic and Kazakhstan.

- **Yields.** Yields for a few crops, including alfalfa, grasslands, and wheat in parts of the region are projected to increase in parts of the region. The overwhelming majority of results, however, point toward decreasing crop yields. Climate change is also likely to increase heat stress and change river runoff reducing agricultural yields in the long term. In the Western Balkans, the increasing occurrence of droughts will be a major threat to agricultural production under climate change; conversely so will the increasing appearance of extreme rain and flood events.
- **Livestock.** Increasing temperatures and reduced water availability will negatively impact livestock production. Pasture growth and regeneration rates are expected to decline in parts of Central Asia. If producers react to the changes by increasing livestock numbers, pastures might be at added risk from overgrazing and erosion. In the areas where productivity of alfalfa and grasslands is projected to increase (e.g., in Uzbekistan), the indirect effect of climate change on livestock production might be positive.
- **Food Security.** The rural population in Central Asia is at a particular risk of food insecurity, and there have been recent cases of a direct hunger threat. Rising food prices that might follow production declines will affect the poorest social groups (i.e., people who spend a large portion of their income on food). There are, however, opportunities to increase regional agricultural production efficiency by, for example, improving agricultural policies and institutions as well as by improving production infrastructure and technology. Finally, while access to international food markets could lead to higher food security and lower prices, the region is not well integrated into international trade networks.

#### 5.1.3.4 Human Health

A number of diseases and adverse health conditions are already present across Eastern Europe and Central Asia, and it is anticipated that some of these will be affected by such climatic changes as increased temperatures and more frequent and intense rainfall and drought events. A lack of certainty about the mechanisms through which climate change affects the incidence of diseases, however, prevents strong claims about future trends. In general, however, higher temperatures correlate to an increased occurrence of tick-borne encephalitis and mosquito transmitted malaria and dengue fever. Malaria is endemic in Tajikistan; since the 1990s, it has reoccurred in Uzbekistan, the Kyrgyz Republic, and Turkmenistan. Furthermore, there is evidence providing stronger indications of an increased risk of dengue in the Western Balkans.

Historical observations show that increased temperatures, as well as extreme weather events such as floods can lead to drinking water contamination, salmonellosis, cholera, typhoid, and dysentery. Evidence from Albania and Macedonia in the Western Balkans, as well as Tajikistan and Kazakhstan in Central Asia, show an increased vulnerability of heat related strokes and mortalities. Severe floods, like those that occurred in recent years in Serbia, as well as glacial outbursts in the mountains of Tajikistan, Uzbekistan and the Kyrgyz Republic, increase vulnerability to injuries and drowning.

#### 5.1.3.5 Energy

Climate change will have a strong impact on the region's energy sector. In Central Asia, the demand for electricity is expected to rise as a consequence of population growth, and current and projected economic growth. Hydroelectricity can play a major role in the future energy mix of the Central Asian countries, as only 8 percent of the hydropower potential of the region has been developed. Changes in climate and melting of glaciers generally mean that the amount of water available for power generation could increase, but the new pattern of intra-annual runoff distribution means that less water will be available for energy generation in the summer. Changes in reservoir management and the need to balance water requirements for agriculture may also have a negative impact on energy availability over the summer months.

Due to changes in river water temperatures and river flows, the capacity of nuclear and fossil-fueled power plants in Southern and Eastern Europe could decrease from 6.3 percent to 19 percent in Europe from 2031–2060 compared to the production levels observed from 1971–2000. Furthermore, due to the increased incidence of droughts and extreme river low flows, the mean number of days during which electricity production will be reduced by more than 90 percent is projected to increase threefold; from 0.5 days per year (in present days) to 1.5 days per year from 2031–2060 under 1.5°C global warming. The challenge to meet growing energy demands in the Western Balkans will be further intensified by a reduction in energy generation from hydropower sources as the result of decreases in precipitation.

#### *5.1.3.6 Security and Migration*

Climate change impacts will intensify in Central Asia and contribute to increasing the population's overall physical, economic, and environmental insecurity. A key vulnerability is the high exposure of the densely populated, agriculturally productive Fergana Valley region to catastrophic floods and mudflows as a result of glacial lake outbursts.

Forecasting migration patterns is a challenge because of both the complexity of these phenomena and the low reliability of and significant gaps in existing datasets particularly with respect to information on environmental problems (including disasters) and environmentally induced migration.

The Western Balkans, especially those nations bordering the sea, are projected to experience sea-level rise and hotter temperatures; this is expected to result in growing numbers of people moving from coastal zones to cooler mountainous zones. Migration in the Western Balkans has already led to severe demographic changes, which coupled with an aging population is expected to lead to further increased regional climate change sensitivity as a result of decreased adaptive capacity.

In Central Asia, the majority of the population lives in climate hotspot areas, with projected increase in the intensity and frequency of extreme events (e.g. forest fires, heat waves, floods). The rural population is among those that is the most vulnerable, and an increased rural-to-urban migration could be expected. Women are particularly vulnerable, since they typically remain behind in the countryside to manage their households as men migrate to urban areas. Taking into account the urbanization trends in Central Asia, the vulnerability of cities to catastrophes might increase.

#### *5.1.3.7 Forests of the Russian Federation*

Russia's forest covers a large area with a huge amount of carbon stored in the soil and vegetation. Future projections highlight changes in productivity (both increasing and decreasing, depending on species, region, site and so forth) and vegetation composition which will typically be stronger under a 4°C world than a 2°C world. Changes in species composition toward better-adapted tree species may buffer productivity losses, but they will also lead to a change in the forest structure and biodiversity.

The region includes a large forest area affected by permafrost which contains large stock of carbon and methane. In general, changes in the carbon, water and energy fluxes of Russia's forests may strongly affect local, regional, and global forest resource availability, ecosystem functioning, services such as carbon storage and biodiversity, and even feedback on the global climate system. Substantial research gaps exist, for example, regarding the effect of disturbances such as fire and insect outbreaks on vegetation cover or carbon stocks and how climate change will change forest productivity under concomitant changes of growing conditions, disturbance regimes, and forest management practices.

### 5.1.4 Overview of Regional Development Narratives

The development narratives build on the climate change impacts analyzed in this report (cf., Table 5.7) and are presented in more detail in Section 5.5. Increasing climate variability and changing climate are expected to threaten agricultural and energy production in the region by changing the hydrological snow, and glacial regimes. Furthermore, climate change in interaction with vegetation shifts and fires threaten forest productivity and carbon storage in the Eurasian forests. The exposure to climatic changes in combination with the regional social vulnerability patterns could have negative consequences on key development trends.

- **Water resources in Central Asia are projected to increase during the first half of the century and decline thereafter, amplifying the challenge of accommodating competing water demands for agricultural production and hydropower generation.** The timing of river flows is projected to shift from summer to spring, with adverse consequences for water availability in critical crop-growing periods. An intensification of the runoff variability is expected to increase in all river basins in the region. The competition for water resources between key sectors (e.g., agriculture and energy), as well as between upstream and downstream water users, can therefore be expected to intensify. Until 2030 the contribution of glacial melt water to river runoff might lead to an increase in river runoff and partially offset the runoff variability. In the second half of the century, however, runoff generation of melt water in the mountainous parts of the river basins is likely to decline substantially. An increasing population, followed by increased water and energy demand, will put an additional pressure on scarce resources. Improving irrigation water management and efficiency of irrigation infrastructure, institutional and technical advancements in agriculture, integrated transboundary river management, and new employment opportunities outside agriculture could counterbalance the negative impacts of these environmental changes.
- **Climate extremes in the Western Balkans pose major risks to agricultural systems, energy and human health.** The vulnerability of the Western Balkans to climatic changes is mainly related to rain-fed agricultural production and the high share of the population that is dependent on income from agriculture. There are, however, projections showing production increases for irrigated crops in parts of the region (for example, C4 summer crops and tubers in Serbia). Increased temperatures as well as both droughts and extreme river flows could pose further challenges to energy production. Recent floods and landslides illustrate the threats of extreme events to human health and well-being. In addition, the climatic conditions in the region are becoming increasingly suitable to dengue fever and other vector-transmitted diseases such as dengue fever.

- **The responses of the permafrost and the boreal forests of Russia to climate change have consequences for timber productivity and global carbon stocks.** Changes to carbon fluxes in response to rising temperatures, changing precipitation patterns, and interactions with disturbance regimes in the forest and permafrost areas in the region can have far-reaching repercussions—affecting the global carbon stock and having an effect on albedo in the northern hemisphere. While climate change can increase the productivity of some tree species, heat waves, water stress, forest fires, and an increased incidence of tree pests and diseases could counterbalance any positive effects. Improving forest management and sustainable wood extraction are of key importance as is sustainable and far-sighted management of Russian forest ecosystems, including addressing key research gaps.

## 5.2 Introduction

### 5.2.1 General Characteristics

The report covers 12 countries located in the Europe and Central Asia region (ECA) in three sub-regions:

- Central Asia: Kazakhstan, the Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan.
- Western Balkans: Albania, Bosnia and Herzegovina, Kosovo, the Former Republic of Macedonia, Montenegro, and Serbia.
- Russia.

The total population of the region is 226 million people, with the highest share living in Russia and the fewest people living in Uzbekistan and Montenegro. The population is unevenly distributed across the region. Central Asia is less densely populated, with Kazakhstan (with six people per square kilometer) and Russia (with nine) being the least densely populated and Uzbekistan (with 70 people per square kilometer) and Tajikistan (with 57) being the more densely populated. In the Western Balkans, the least densely populated country is Montenegro (with 46 people per square kilometer) and the most densely populated countries are Kosovo (with 166 people) and Albania (with 102 people per square kilometer). On average, half of the region's population lives in urban areas (World Bank 2013b). In most countries in the region population numbers have stabilized in recent years and population projections show on average 27 percent population declines for Russia and Eastern Europe (including Western Balkans) and 50 percent population increases in Central Asia by 2050 (Lutz 2010).

ECA is a region with relatively low levels of per-capita annual GDP, ranging from $800 in Tajikistan to $14,000 in Russia. Agricultural production contributes an important share to the local economies, especially in Tajikistan, the Kyrgyz Republic, Uzbekistan, and Albania (World Bank 2013b)(see Table 5.1).

### 5.2.2 Socioeconomic Profile of ECA

All countries in the ECA region underwent a transition at the end of the 20th century from various types of closed, plan-based economies to more open and free market-based ones. This transition, with the dissolution of trade networks and production shifts, was accompanied by a steep increase in poverty and inequality within the region. In 1990, only 1.9 percent of the population in the ECA region was affected by poverty; this number grew to

**Table 5.1:** Basic socioeconomic indicators in ECA countries.

| INDICATOR | POPULATION | URBAN POPULATION | URBAN POPULATION GROWTH | GDP PER CAPITA | AGRICULTURE, VALUE ADDED[1] | LIFE EXPECTANCY AT BIRTH[2] |
|---|---|---|---|---|---|---|
| UNIT | MILLION | % OF POPULATION | ANNUAL % | CURRENT 1000 US$ | % OF GDP | YEARS |
| YEAR | 2011 | 2012 | 2012 | 2012 | 2009–2010 | 2011 |
| ID | SP.POP.TOTL | SP.URB.TOTL.IN.ZS | SP.URB.GROW | NY.GDP.PCAP.CD | NV.AGR.TOTL.ZS | SP.DYN.LE00.IN |
| **Central Asia** | | | | | | |
| Kazakhstan | 16.5 | 54 | 1.3 | 11.9 | 4.8 | 69 |
| Kyrgyz Republic | 5.5 | 35 | 1.5 | 1.2 | 19.4 | 70 |
| Tajikistan | 7.8 | 27 | 2.7 | 0.8 | 21.2 | 67 |
| Turkmenistan | 5.1 | 49 | 2.0 | 5.5 | 14.5 | 65 |
| Uzbekistan | 29.3 | 36 | 1.6 | 1.7 | 19.3 | 68 |
| **Western Balkans** | | | | | | |
| Albania | 3.1 | 54 | 2.2 | 4.4 | 19.1 | 77 |
| Bosnia and Herzegovina | 3.8 | 49 | 1.0 | 4.4 | 7.6 | 76 |
| Kosovo | 1.8 | – | – | 3.4 | 12.0 | 70 |
| Macedonia, FYR | 2.1 | 59 | 0.3 | 4.6 | 11.5 | 75 |
| Montenegro | 0.6 | 63 | 0.4 | 6.8 | 9.3 | 75 |
| Serbia | 7.2 | 57 | 0.1 | 5.2 | 9.0 | 75 |
| | | | | | | |
| Russian Federation | 142.9 | 74 | 0.6 | 14 | 4.0 | 69 |

[1]Agriculture corresponds to ISIC divisions 1–5 and includes forestry, hunting, and fishing, as well as cultivation of crops and livestock production. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. It is calculated without making deductions for depreciation of fabricated assets, or depletion and degradation of natural resources.
[2]Life expectancy at birth indicates the number of years a newborn infant would live if prevailing patterns of mortality at the time of its birth were to stay the same throughout its life. Source: World Bank (2013b).

7 percent by 2010. The highest poverty rates are currently observed in the Kyrgyz Republic (38 percent in 2012), Uzbekistan (17.7 percent in 2010), and Albania (14.3 percent in 2010). Meanwhile, Kazakhstan (3.8 percent in 2012) has the lowest poverty rate in the region. However, the number of people that are affected by extreme poverty has been declining since 1999. Due to very cold winters that require people to have a higher caloric intake (and, hence, higher food expenditures), higher spending on clothing, energy, and transportation, and differences in economic and social development, the regional poverty line was set at a $2.5–5 per day (World Bank 2011d). The total number of people living on less than $5 per day fell from 240 million in 1999 to 91 million in 2010.

There are also pronounced inequalities in the region. In the Kyrgyz Republic in 2009, for example, the income share of the lowest 10 percent of the population was 2.8 percent compared to an income share of 27.79 percent for the highest 10 percent of the population (World Bank 2013t). Other issues that increase the vulnerability of the population in the region include rural poverty, unemployment (particularly among women and youth), a shortage of adequate living conditions, poor medical care, and deficient water management infrastructure (Lioubimtseva and Henebry 2009). Adaptive capacity in the region is negatively affected by weak governance. A few countries in Central Asia are among 20 percent of countries performing the worst in the World Governance Indicator. For example Kazakhstan, Russia, Tajikistan, and Turkmenistan are among 20 percent of countries that have the lowest ranks in the voice and accountability indicator that captures perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media. Moreover, Turkmenistan, Uzbekistan, Tajikistan, and Kyrgyz Republic are among the 20 percent of countries that have the lowest ranks in the rule of law indicator that captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence (Worldwide Governance Indicators, 2014). The lack of good governance is one of the key challenges that will have to be addressed by the future mitigation and adaptation strategies in the region. Strengthening local institutions and citizen engagement is very important in water management and biodiversity protection and is relevant for the sectors such as agriculture and forestry (McEvoy et al. 2010; Otto et al. 2011).

People and poverty in ECA are located along a spatial spectrum with sparsely populated rural areas and dense urban areas at the ends. However, most poor are concentrated in smaller and medium-sized towns. In Albania, 42 percent of the population is urban but resides almost entirely in very small, small, and medium-sized towns. The share of the poor in urban areas is 31 percent, and nearly all of the poor reside in similar sized towns. Similarly, in Kazakhstan, 57 percent of the population and 43 percent of the poor live in urban areas—but very large cities house only eight percent of the population and one percent of the poor (Global Monitoring Report, 2013). Generally, urbanization can be a force that helps in the achievement of the Millennium Development Goals but the slums in the Kyrgyz Republic show that it can also worsen poverty. The failure of rural migrants to find better paying urban jobs forces them to live in informal settlements where without proof of residence they cannot have access to health services (Global Monitoring Report, 2013).

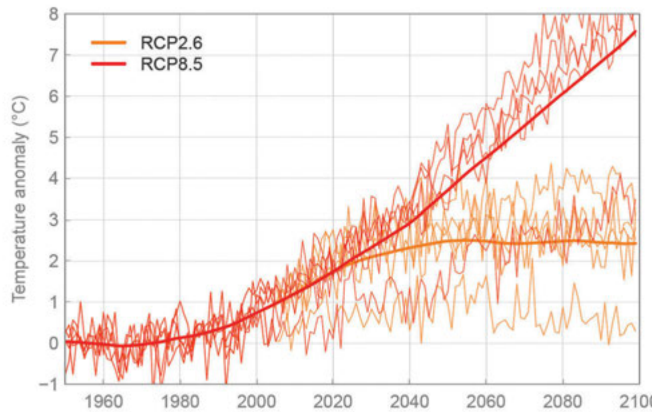
## 5.3 Regional Patterns of Climate Change

### 5.3.1 Projected Temperature Changes

Figure 5.3 shows projected boreal summer (June, July, August or JJA) temperatures for the European and Central Asian land area in a 2°C and 4°C world. Warming across the Northern Hemisphere land area is projected to be somewhat more than the global mean. In the 2°C warming scenario, the multi-model mean warming by the end of the century is about 2.5°C above the 1951–1980 baseline (i.e., about 0.5°C more than the global mean) (World Bank 2013). This level of warming is reached by mid-century and then remains constant until the end of the century. In contrast, in a 4°C world, summer temperatures continue to increase up to and beyond the end of century in an almost linear trend, reaching about 8.5°C above the 1951–1980 baseline by 2100. The multi-model mean warming for the 2071–2099 period reaches about 6.5°C (see Figure 5.3) and is reduced due to one model which warms far less than the others. Because the transient climate sensitivity of this model is lower than the others, results can therefore show pronounced regional differences.

The most pronounced warming is projected to occur in three distinct regions: (1) Northern Russia bordering the Barents-Kara Sea, (2) the Black Sea coastal region, including the Balkans, and (3) northern China and Mongolia. In these hotspot regions (see Figure 5.4) summer warming is projected to be roughly 1°C higher

**Figure 5.3:** Temperature projections for the European and Central Asian region, compared to the 1951–1980 baseline for the 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 JJA.



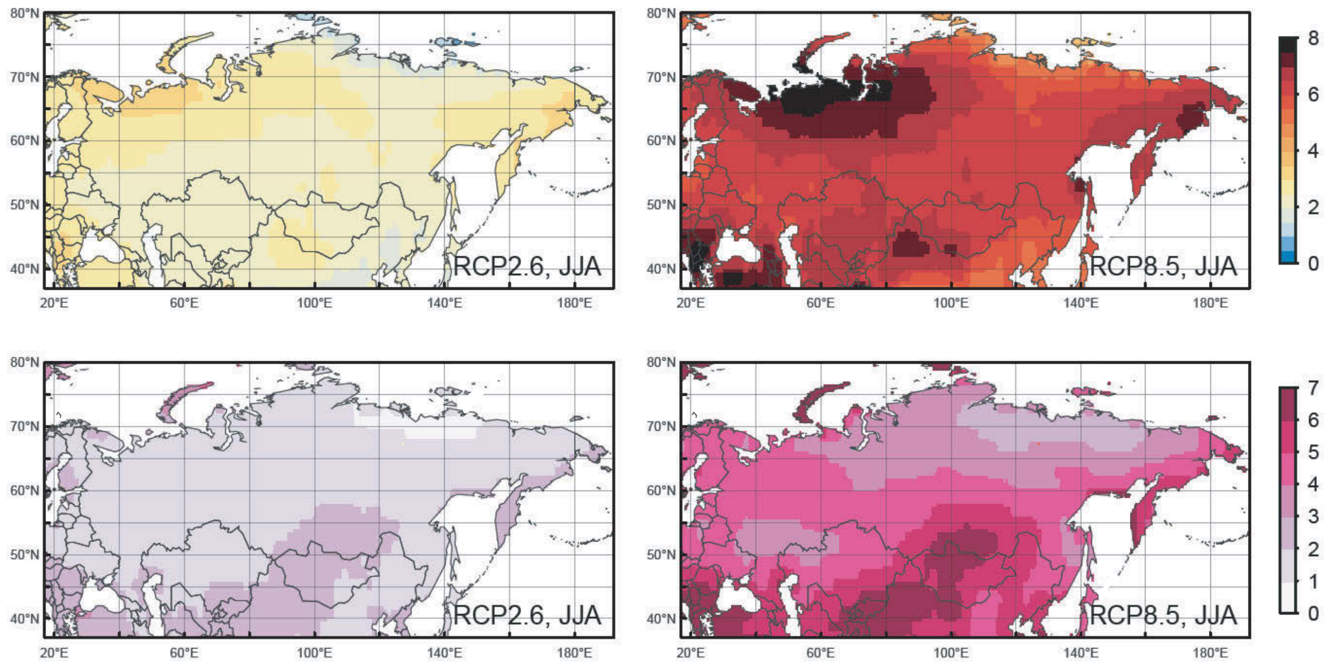

The multi-model mean has been smoothed to give the climatological trend.

than the Eurasian mean. Thus, in these regions, mean summer warming by 2071–2099 will be about 3.5°C in a 2°C world, and about 7.5°C in a 4°C world.

The normalized warming (i.e., the warming expressed in terms of the local year-to-year natural variability—see Section 6.1) is a useful diagnostic tool as it indicates how unusual the projected warming is compared to fluctuations experienced in the past (Coumou and Robinson 2013; Hansen et al. 2012; Mora and Frazier et al. 2013). The geographical patterns of normalized warming (see the lower panels in Figure 5.4) show that the southern hotspot regions (i.e., the Black Sea coastal region and northern China/Mongolia) experience the strongest shifts. In a 2°C world, the monthly temperature distribution here shifts by 2–3 standard deviations toward warmer conditions. In a 4°C world, these southerly regions see a shift of up to six standard deviations. Such a large shift implies that summer temperatures in these regions will move to a new climatic regime by the end of the century. The northern regions will see a less pronounced shift in normalized temperature because the standard deviation of the natural year-to-year variability is larger (i.e., temperatures are already naturally more variable) (Coumou and Robinson 2013). Nevertheless, a shift by at least 1-sigma (in the 2°C world) or 2-sigma (in the 4°C world) is projected to occur here during the 21st century.

Warming in southern Siberia during the 20th century is already evident, and 1990–1999 was the warmest decade in the last century. Average summer temperatures increased in the observed regions by between 0–0.5°C from 1960 to 1999, but with a significantly higher increase of 1–2°C in the 1990s. Average winter temperatures

**Figure 5.4:** Multi-model mean temperature anomaly for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the months of JJA for the European and Central Asian region.




Temperature anomalies in degrees Celsius (top row) are averaged over the time period 2071–2099 relative to 1951–1980, and normalized by the local standard deviation (bottom row).

increased between 1–4.5°C within the 40 years analyzed (1960–1999), with an increase greater than 2–3°C in the 1990s (Soja et al. 2007). Precipitation patterns have also become more diverse. Whereas precipitation on windward slopes in the Urals and the Altai has increased by up to 130–260 mm per year within the 40 years that were analyzed, a drastic decrease in precipitation of 230 mm per year between 1960 and 1999 has been noted on leeward slopes of the Sayans in the interior of Siberia (Soja et al. 2007).

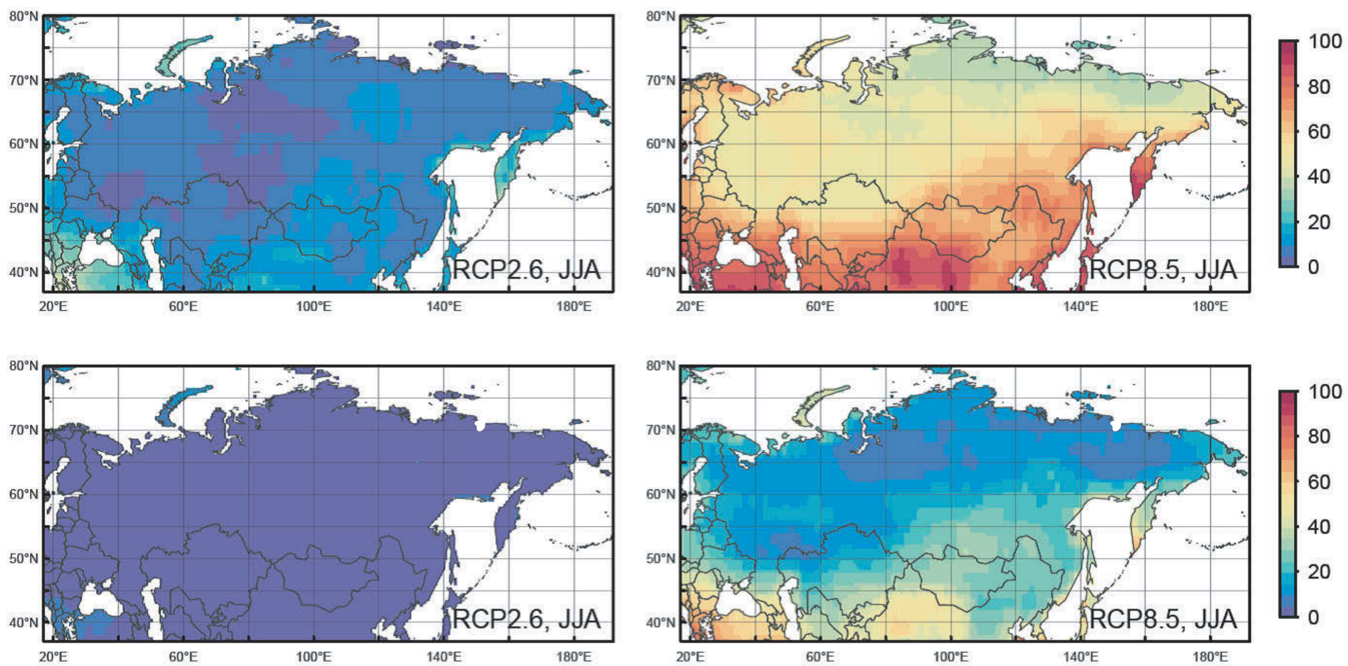
For the ECA region, IPCC (2001) predicted a warming of between 2 and 10°C in the 21st century as compared to the 20th century; warming rates are expected to be the largest in 10,000 years. Recent climate projections for the 21st century range from –0.1°C to 12°C mean winter temperature and from 0°C to 8°C mean summer temperature for all climate scenarios in this region (IPCC 2013). All projections suggest precipitation increases for the entire region of up to 58 percent in autumn and only up to 35 percent in spring. While projections of local temperature and precipitation changes are unevenly distributed across the region, both factors are projected to be more pronounced in the northern area. Temperature projections for south-central Siberia range from 4–6°C (Gustafson et al. 2010), although winter temperatures are expected to increase by up to 10°C.

Most studies focusing on Central Asia agree that the warming trend in mean annual temperatures is less pronounced in the high altitudes than in the lower elevation plains and protected intramontane valleys (Unger-Shayesteh et al. 2013). For the winter months, a stronger warming trend can be detected at higher elevations of the Tien Shan mountains (Kriegel et al. 2013; Mannig et al. 2013; Zhang et al. 2009a)

### 5.3.2 Heat Extremes

Figure 5.5 shows the projections of the percentage of boreal summer months warmer than 3-sigma and 5-sigma (see Section 6.1) over the ECA region from 2071–2099 for both 2°C and 4°C warming. One of the clearest signals identified is the strong increase in threshold-exceeding heat extremes in the region surrounding the Black Sea, and in particularly in the Balkans. Here, even in a 2°C world, 20–30 percent of summer months are expected to rise beyond the 3-sigma threshold by the end of the century; 5-sigma events are also expected to occur (between 5–10 percent of summer months). The Balkan region is thereby expected to experience substantially higher frequencies of extreme heat events than those projected for the ECA region as a whole for which about

**Figure 5.5:** Multi-model mean of the percentage of boreal summer months (JJA) in the time period 2071–2099 with temperatures greater than 3-sigma (top row) and 5-sigma (bottom row) for scenario RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) over the European and Central Asian region.



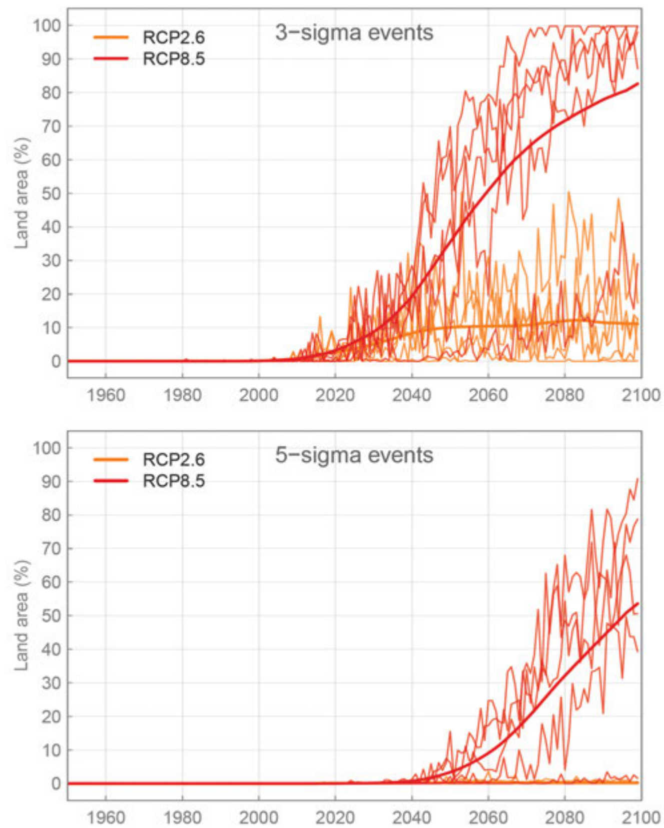

10–15 percent of the land area is projected to be affected by 3-sigma events by the end of the century and 5-sigma events essentially remaining absent in a 2°C world (see Figure 5.6). Similar to the Balkans, Northern China/Mongolia will also see a substantial increase in 3-sigma events (~15 percent of summer months) but 5-sigma events are not expected to occur. The stronger increase in summer heat extremes in these two hotspots is thus consistent with the broader shift in the mean of the normalized temperature distribution (Figure 5.3).

Compared to the 2°C world, the 4°C world will see a much more pronounced increase in the frequency of summer months warmer than 3- and 5-sigma. Whereas in the 2°C world the increase in frequency levels-off by mid-century, it continues in the 4°C world as seen in projections of the mean summer warming (see Figure 5.3 and Figure 5.4). The multi-model mean projects 85 percent of land area to be affected by events hotter than 3-sigma and 55 percent of land area to be affected by hotter than 5-sigma events by 2100 (Figure 5.6). The bulk of these events occur in a widespread region south of approximately 50°N, stretching from the Balkans all the way to Japan. Here, over the 2071–2099 period, about 80 percent of summer months will be beyond 3-sigma, and 45–55 percent beyond 5-sigma. Although the 3-sigma threshold level will become the new normal in regions north of 60°N (being exceeded in about half of the summer months), 5-sigma heat extremes will remain largely absent.

The increase in the frequency of summer months warmer than 3-sigma or 5-sigma, as shown in Figure 5.6, is quantitatively consistent, even on the country scale, with published results analyzing the full set of climate models (Coumou and Robinson 2013). The published literature also clearly indicates a strong increase in heat extremes south of 50°N and a much more moderate increase to the north of that latitude (Sillmann et al. 2013b). In fact, the decrease in frequency of cold extremes in this northern region may potentially have beneficial effects. Sillmann et al. (2013b) reported that, over Russia, the minimum nighttime temperatures in boreal winter are projected to increase by 3–4°C in a 2˚C world, and by 10°C in a 4˚C world. Likewise, the number of frost days in the European part of Russia is expected to be reduced by between approximately 25 days (2˚C world) and 65 days (4˚C world). This reduces the cold spell duration in this region by up to seven days in a 4°C world (Sillmann et al. 2013b).

South of approximately 50°N, the projections of temperature extremes provide a totally different picture. Here the number of tropical nights increases by 20–30 days in a 2˚C world and by 50–60 days under a 4˚C world (Sillmann et al. 2013b). Temperatures experienced during the warmest 10 percent of summer nights during the 1961–1990 period are expected to occur in about 30 percent (2˚C world) or 90 percent (4˚C world) of summer nights by the end of the century. These changes will cause a strong increase in

**Figure 5.6:** Multi-model mean (thick line) and individual models (thin lines) of the percentage of land area in the European and Central Asian region warmer than 3-sigma (top) and 5-sigma (bottom) during boreal summer months (JJA) for scenarios RCP2.6 (2˚C world) and RCP8.5 (4˚C world).




the length of warm spells, by up to 90–150 days in a 4˚C world (Sillmann et al. 2013b).

## 5.3.3 Regional Precipitation Projections

Figure 5.7 shows that future changes in annual precipitation exhibit a southwest-northeast dipole pattern, with regions in the southwest becoming drier and regions in the northeast becoming wetter. Thus the basic concept of the "dry-getting-drier and wet-getting-wetter" under climate change is a good first order estimator for the ECA region. The relative wetting of the northeast (i.e., Siberia) is the most pronounced signal, possibly associated with a shift in storm tracks. The increase in precipitation is far more pronounced during the winter (DJF) than during summer (JJA).

The multi-model mean drying signal in the southwest, including the Balkans and the Caucasus region, is very weak (almost flat) under low-emissions scenarios (2°C world), and the models disagree about the direction of change. There is robust model agreement, however, that under the high-emissions scenario (4°C world), the Balkans, the Caucasus region, and Turkmenistan will receive less rain, with the multi-model mean annual precipitation dropping by about 20 percent.

## 5.3.4 Extreme Precipitation and Droughts

The footprint of climate change on climatological extremes in the 21st century is very different for the three sub-regions in ECA.

### Central Asia

Despite a robust warming trend over Central Asia, no clear trend for precipitation extremes emerges from the observational record (Dai 2012; Donat, Alexander et al. 2013). While uncertainties are large, the overall trend regarding heavy precipitation intensity is below the global average (Kharin et al. 2013; Sillmann et al. 2013b). A similar picture emerges from the projections for future droughts. A moderate increase in drought risk for Central Asia is generally projected (Dai 2012; Prudhomme et al. 2013), but confidence in the projections is very low (Sillmann et al. 2013b). Although drought projections remain vague, regional water availability will be strongly affected by changes in river runoff due to glacier melting (see Section 5.4.1, Water Resources).

### Western Balkans

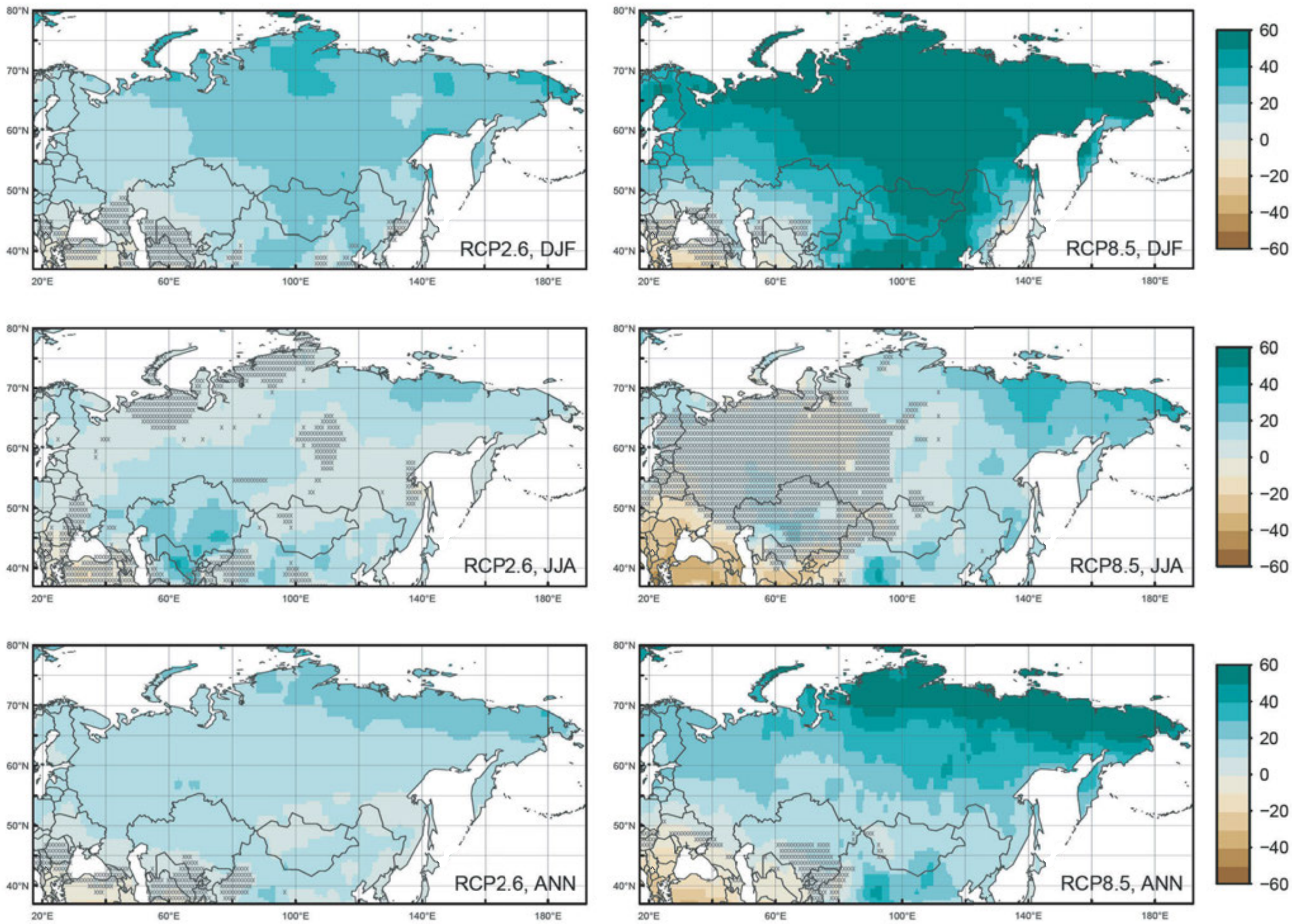
For the Western Balkans region, little to no increase in extreme precipitation events is projected over the 21st century (Kharin et al. 2013; Sillmann et al. 2013b) despite a global increase of about 20 percent in heavy precipitation event intensity in a 4°C world (Kharin et al. 2013). Regional models suggest, however, that the region's complex topography may strongly influence extreme precipitation (Gao et al. 2006). Thus, despite an overall negative trend in extreme precipitation events, regional and seasonal projections for this region remain inconclusive.

This picture changes for drought projections. The Western Balkans are robustly projected to suffer from an increase in drought conditions based on global analysis; this is similar to that expected for the greater Mediterranean region, as discussed in the MENA section (Dai 2012; Orlowsky and Seneviratne 2013; Prudhomme et al. 2013; Sillmann et al. 2013b). Prudhomme et al. (2013) project a 20 percent increase in the number of drought days in a 4°C world. However, regionally resolved climate projections suggest that the Western Balkans might be less affected, with no significant increase in drought risk (Gao and Giorgi 2008), while the greater Mediterranean region is considered a global hotspot for future drought projections Dai (2012).

### The Russian Federation

Within Russia, the projections of changes in future climatological extremes are diverse. Central and Eastern Siberia is one of the regions expected to experience the strongest increase in heavy

**Figure 5.7:** Multi-model mean of the percentage change in winter (DJF, top), summer (JJA, middle), and annual (bottom) precipitation for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the European and Central Asian region by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertainty regions with two or more out of five models disagreeing on the direction of change.

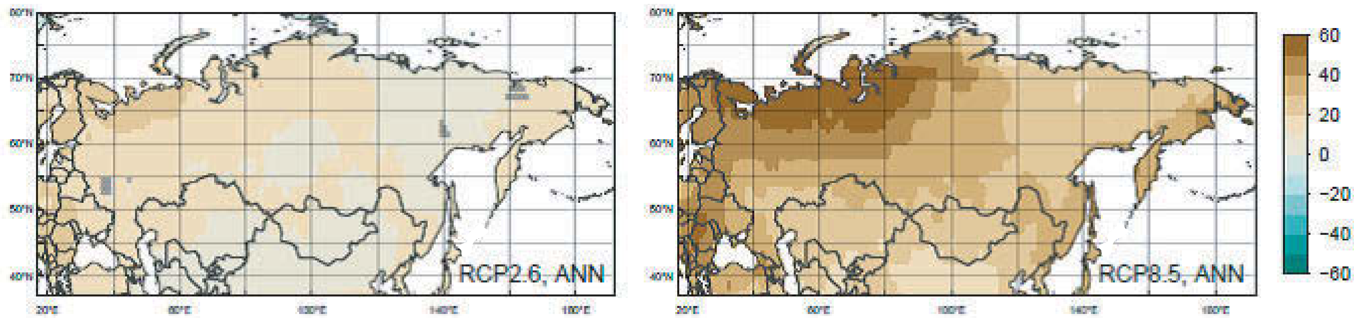
precipitation events (Sillmann et al. 2013b). Heavy precipitation events with a 20-year return time are projected to intensify by over 30 percent in this region, and the return time is projected to fall below five years by the end of the 21st century under a 4°C warming scenario (Kharin et al. 2013). The changes are much weaker (less than 10 percent increase in intensity and 10–15 years return time) under a 2°C warming scenario (Kharin et al. 2013).

Projections for central and western Russia point in a similar direction, although the intensification of heavy precipitation events with a 20-year return time is less pronounced (between 10 and 30 percent). While an increase in extreme precipitation is projected throughout Russia for all seasons in a 4°C world, it is strongest in boreal winter (DJF). This would lead to a substantial increase in the absolute amount of snow-water equivalent (Callaghan et al. 2011; Shkol'nik et al. 2012), with far reaching consequences for the regional hydrological cycle.

### 5.3.5 Aridity

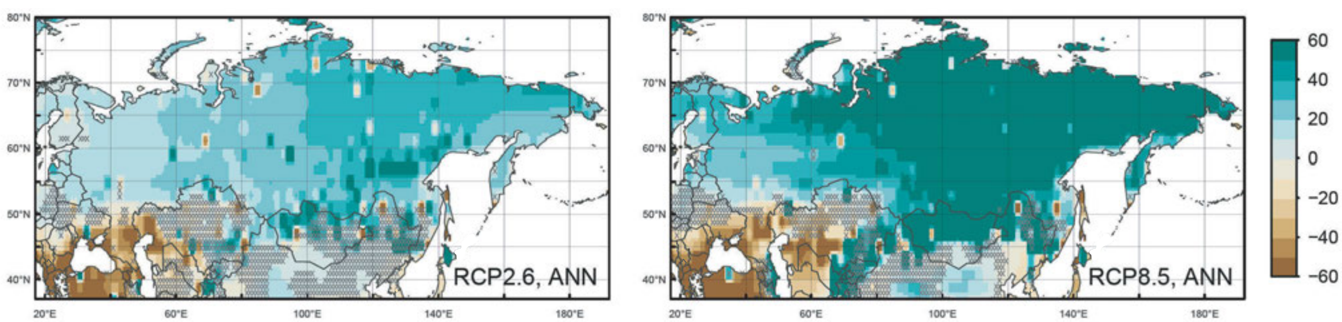
Figure 5.8 shows the relative changes in the aridity index (AI), which captures the long-term balance between water supply (precipitation) and demand (evapotranspiration) (see Section 6.1) for the ECA region by 2071–2099. The AI is defined as the total annual precipitation divided by the annual potential evapotranspiration, and fundamentally determines whether ecosystems and agricultural systems are able to thrive in a certain area. A decrease in AI

**Figure 5.8:** Multi-model mean of the percentage change in the annual-mean of monthly potential evapotranspiration for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the European and Central Asian region by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change.

**Figure 5.9:** Multi-model mean of the percentage change in the aridity index (AI) for RCP2.6 (2°C world, left) and RCP8.5 (4°C world, right) for the ECA region by 2071–2099 relative to 1951–1980.




Hatched areas indicate uncertain results, with two or more out of five models disagreeing on the direction of change. Note that a negative change corresponds to a shift to more arid conditions.[67]

value indicates that water becomes more scarce (i.e., more arid conditions), with areas classified as hyper-arid, arid, semi-arid and sub-humid as specified in Table 5.2.

The geographical patterns of the relative change in the annual mean AI, as shown in Figure 5.9, are similar to those for precipitation. Thus shifts in annual mean precipitation primarily determine which regions become more or less arid. In the 4°C warming scenario, this drying region expands further to the east, covering Kazakhstan, Uzbekistan, and Turkmenistan. Because these regions are already drought-prone, this could have major consequences

**Table 5.2:** Multi-model mean of the percentage of land area in the European and Central Asian region which is classified as Hyper-Arid, Arid, Semi-Arid and Sub-Humid for 1951–1980 and 2071–2099 for both 2°C and 4°C degrees warming levels.

| | 1951–1980 | 2071–2099 (RCP2.6) | 2071–2099 (RCP8.5) |
|---|---|---|---|
| **Hyper-Arid** | 2.2 | 2.1 | 2.7 |
| **Arid** | 3.7 | 4.1 | 5.1 |
| **Semi-Arid** | 7.3 | 7.7 | 9.7 |
| **Sub-Humid** | 4.0 | 4.3 | 4.8 |

[67] Some individual grid cells have noticeably different values than their direct neighbors. This is due to the fact that the aridity index is defined as a fraction of total annual precipitation divided by potential evapotranspiration (see Appendix). It therefore behaves in a strongly non-linear fashion and year-to-year fluctuations can be large. As the results are averaged over a relatively small number of model simulations, this can result in local jumps.

for water scarcity. Trends in AI over the Southeastern region (i.e., Northern China and Southern Mongolia) are weaker, and models disagree over the direction of change (partly due to similar uncertainty in projections of precipitation changes).

Northern regions will see an increase in the AI (i.e., wetter conditions) as would be expected from the projected increase in annual-mean precipitation. The signal is especially strong over the Northeast (i.e., the Asian part of Russia), with a 20–30 percent increase forecast under RCP2.6 and a 50 percent forecast in a 4˚C world.

The shift in AI shown in Figure 5.9 causes some regions to be classified in a different aridity class. In a 4˚C world, the area of land classified as hyper-arid, arid, or semi-arid will grow from about 13 percent in 1951–1980 to 17.5 percent in 2071–2099, which is an increase of more than 30 percent (see Table 5.2). In a 2˚C world, this increase in arid regions is much more limited (only about five percent larger).

### 5.3.6 Regional Sea-level Rise

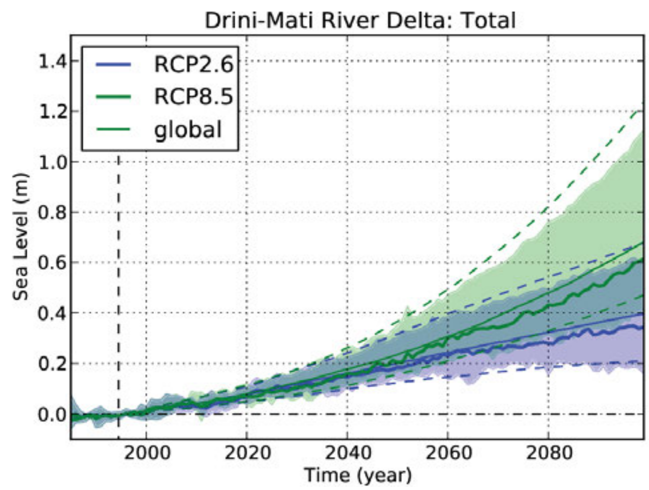
The region's coastal area is relatively limited (if excluding the Russian Federation), and this section focuses in on the Western Balkan coastline. This is where the Drini-Mati River Delta in Albania was identified as a vulnerable area in a recent UNDP report (Le Tissier 2013), and it serves as an example for the whole Western Balkan coastline (see Figure 5.10). This analysis projects a sea-level rise of 0.52 m (0.37–0.9 m) in a 4˚C world in 2081–2100 above the 1986–2005 baseline, with rates of rise of 10.1 mm per year (5.9–19.6 mm per year) (see Figure 5.10 and Table 5.3). This is slightly below the global mean. The Caspian Sea, which is isolated from the ocean, exhibits a completely different behavior, with variations of several meters over the past millennia (Naderi Beni et al. 2013) and a projected 4.5 m sea-level fall by the end of the century of due to increased evaporation in a warming climate (Renssen et al. 2007).

**Table 5.3:** Sea-level rise (SLR) projection for the Drini-Mati River Delta.

| | RCP2.6 (1.5˚C WORLD) | RCP8.5 (4˚C WORLD) |
|---|---|---|
| SLR in 2081–2100 | 0.32 (0.21, 0.54) | 0.52 (0.37, 0.9) |
| SLR in 2046–2065 | 0.21 (0.17, 0.32) | 0.26 (0.21, 0.39) |
| Rate of SLR in 2081–2100 | 3.0 (–1.5, 5.8) | 10.1 (5.9, 19.6) |
| Rate of SLR in 2046–2065 | 4.6 (0.6, 7.1) | 7.6 (5.3, 12.1) |

The sea-level rise (SLR) is expressed in meters above the 1986–2005 baseline period, while rate of SLR refers to a linear trend over the period indicated in the table, in mm/yr. Numbers in parentheses refer to lower and upper bounds (see Section 6.2, Sea-Level Rise Projections for an explanation of the 1.5° world).

**Figure 5.10:** Sea-level rise projection for Drini-Mati River Delta in Albania.




Time series for sea-level rise for the two scenarios RCP2.6 (blue, 1.5˚C world) and RCP8.5 (green, 4˚C world). Median estimates are given as full thick lines and the lower and upper bound given as shading. Full thin lines are global median sea-level rise, with dashed lines as lower and upper bound. Vertical and horizontal black lines indicate the reference period and reference (zero) level.

## 5.4 Regional Impacts

### 5.4.1 Water Resources

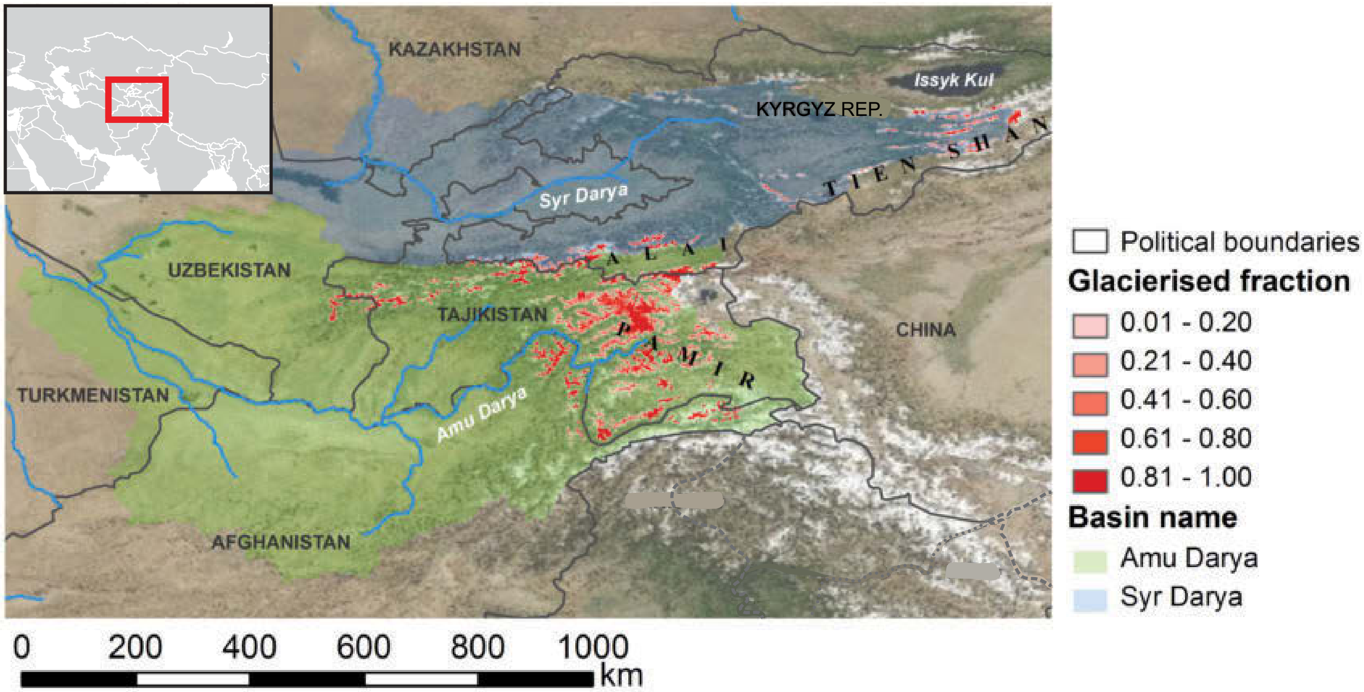
#### *5.4.1.1 Central Asia*

**Glaciers: Current Situation and Observed Changes**

Central Asian glaciers cover four percent of the Kyrgyz Republic (Tien Shan) and six percent of Tajikistan (Pamir); some glaciers also exist in Kazakhstan and Uzbekistan (Figure 5.11). The total glaciered area is about 10,300 $km^2$ in the Amu Darya basin and 1,600 $km^2$ in the Syr Darya basin (Arendt et al. 2012; Lutz et al. 2013a). This corresponds to a total volume of frozen water of about 1,000 $km^3$—the equivalent of about 10 years of water flowing down the rivers Amu Darya and Syr Darya (Novikov et al. 2009).

Figure 5.12 shows the loss of glacier area in the Altai-Sayan, Pamir and Tien Shan in the period from the 1960s to 2008. As ice stocks decline, a reliable water resource is disappearing, and additional reservoirs and an improved water management may be needed. In the Amu Darya and Syr Darya Basin, however, most of the potential for reservoirs has already been exploited (Immerzeel and Bierkens 2012). This implies a high risk of water scarcity in the future once the peak in glacial melt runoff has passed.

**Figure 5.11:** Upstream parts of the Amu and Syr Darya river basin (green and pale blue), the river basin (blue lines), and the glacierized fraction of each 1 km model grid cell (red shades).




Source: Lutz et al. (2013a), Figure 1.

## Snow Cover: Current Situation and Observed Changes

An increase in air temperature can generally change the proportion of precipitation falling as either rain or snow and shorten the duration of seasonal snow cover. The impact of snowfall changes on the Central Asian rivers is very high, since the seasonal snowmelt is a key source of water. Snow reserves in the mountainous river basins will respond differently to an increase in air temperatures depending on the elevation and topography of the mountain area. While glaciers store water over decades and centuries, the seasonal snowpack stores water mainly at an intra-annual time scale. At its maximum annual extent in late winter, the snow cover in the Aral Sea basins extends over major parts of the Amu Darya and Syr Darya basins and contributes to a larger share of the mean annual runoff than glaciers (Ososkova et al. 2000).

## Projected Snow Cover Changes

The IPCC refers to an expected decrease in Northern hemisphere snow cover of 25 percent under a high warming scenario (IPCC 2013 AR5 WGI). Despite the high relevance of snow cover for the water management of Central Asia, only a few studies address the future evolution of snow cover with respect to a warming climate, and these studies only provide general trends. Based on a global assessment (Christensen et al. 2007), a smaller fraction of precipitation is expected to fall as snow, as the snow line rises by about 150 m per 1°C of warming. The depth and duration of seasonal snow cover are also expected to decrease, with a shift in the onset of snowmelt toward earlier spring. Through a reduction in the snow-albedo feedback, the reduced snow coverage is expected to affect both the melting rate and the regional climate, thereby reinforcing the warming trend in Central Asia (Unger-Shayesteh et al. 2013).

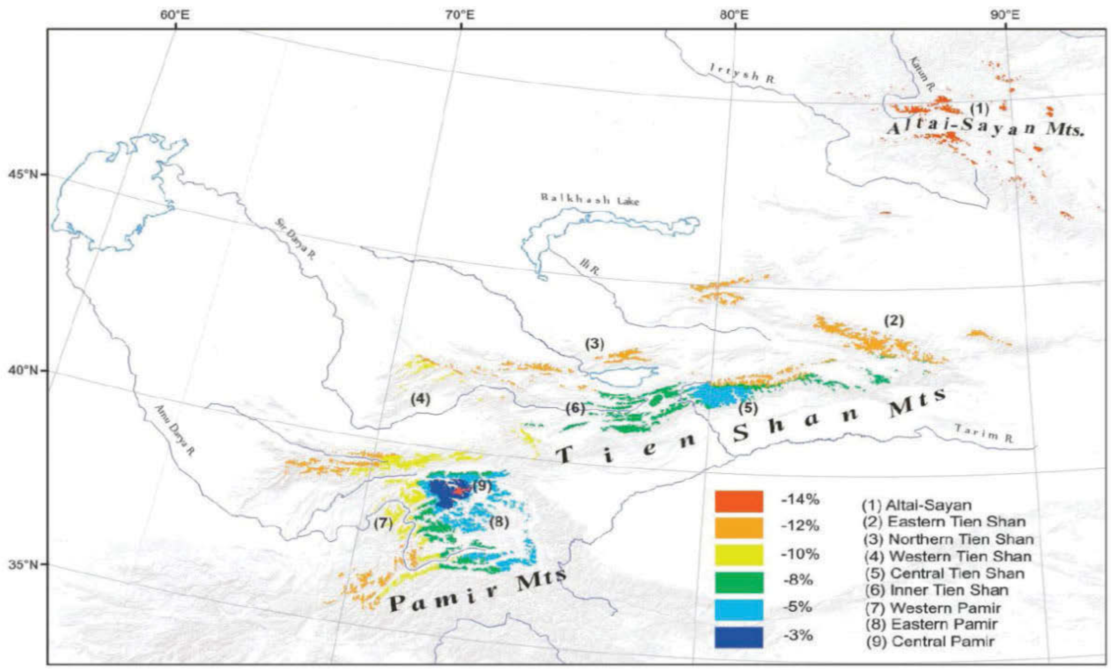
## Projections of Glacial Volume Loss

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (Church et al. 2013) states that current glacier extents are out of balance with current climatic conditions and indicates with high confidence that glaciers will continue to shrink in the future, even without further temperature increases.

In a 2°C warming scenario, projections show glacier volume losses of about 50 percent (31–66 percent) for Central Asia, which represents a mass of about 2800 Gt (Marzeion et al. 2012).

There are only a limited number of regional studies currently available that address the timing and evolution of projected glacier shrinkage and related changes in runoff in Central Asia. Siegfried

**Figure 5.12:** Losses of glacier area in the Altai-Sayan, Pamir, and Tien Shan.




Remote sensing data analysis is from the 1960s through to 2008. Source: Hijioka et al. (2014), Chapter 24, Figure 24–3.

et al. (2012) performed projections for the Syr Darya basin under 2°C warming by 2050; they projected a loss of mass of 31 ± 4 percent (50 Gt) in this region compared to 2010 (see Figure 5.13). However, the signal varies greatly across the different catchments (Siegfried et al. 2012).

Lutz et al. (2013a) investigated the model spread for projections of glacial retreat in the Amu and Syr Darya region and projected a retreat in glacial extent in the range of 54–65 percent for the period 2007–2050 (see Figure 5.14).

In a 3°C world, the glaciers of the region are projected to lose about 57 percent (37–71 percent) of their current mass, equivalent to 3200 Gt (Marzeion et al. 2012). Radić et al. (2013) considered a different sub-region of Central Asia (including Tibet but excluding Altai and Sayan, and comprising 5,830 Gt of ice in total). They inferred a 55 percent loss for the period 2006–2100, corresponding to 3150 ± 900 Gt of ice. Giesen and Oerlemans (2013) obtained comparable results for the same sub-regions.

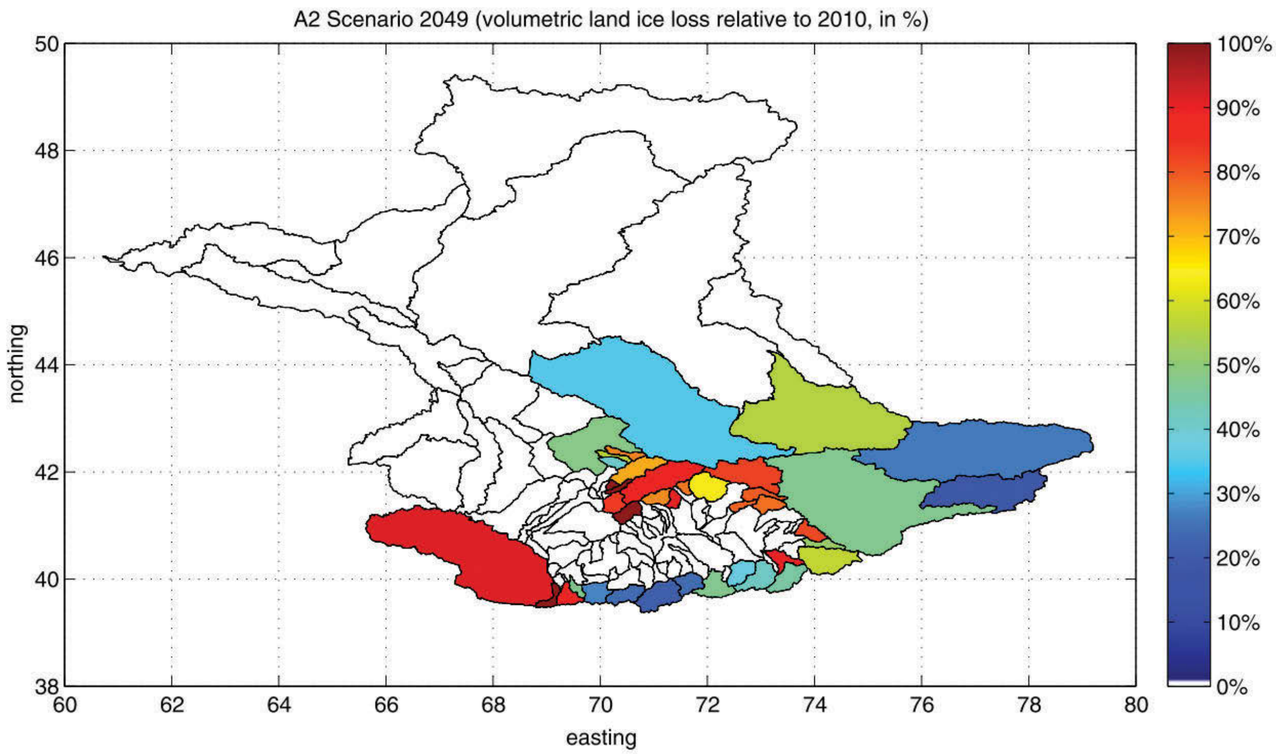
Bliss et al. (2014) went a step further and projected monthly glacier runoff through 2100 from all mountain glaciers in Central Asia. They inferred a 41 percent decrease in average annual runoff, from 136 Gt per year to 80 Gt per year, for the reference periods 2003–2022 and 2081–2100. The study further indicates that the net annual mass loss from glacial melt will peak in the middle of the 21st century.

For a 4°C world, Marzeion et al. (2012) projected that glacier mass loss in Central Asia will reach 67 percent (50–78 percent) by the year 2100, which is a mass loss of about 3800 Gt (also stated in Hijioka et al. 2014). For a slightly different sub-region, Radić et al. (2013) projected a mass loss of 75 percent, which is the equivalent of about 4,300 Gt of ice.

### Impacts on River Flow and Riverine Floods

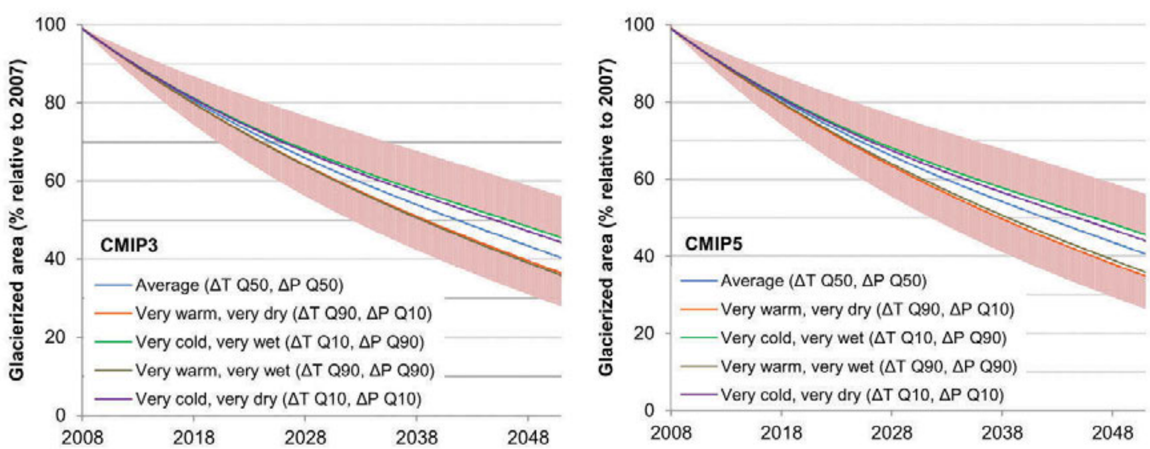
The large transboundary rivers, the Amu Darya and Syr Darya, are the main freshwater suppliers for the arid and semi-arid areas of Central Asia (see Figure 5.15). The volume of water in these rivers strongly depends on conditions in the headwater catchments, located in the mountains of Tien Shan and Pamir-Alay (Tajikistan, Kyrgyz Republic, and Afghanistan), where winter precipitation is stored in snow and ice and released during the spring and summer months (Aus der Beek et al. 2011; Krysanova et al. 2010). As the water supply (e.g., for irrigated agriculture) in the arid downstream areas largely relies on the rivers, changes in the volume and seasonality of river runoff have major implication for the region's water management (Unger-Shayesteh et al. 2013).

**Figure 5.13:** Map of Syr Darya catchment showing mean percentage loss of glacier ice by 2049 relative to 2010 for sub-regions.



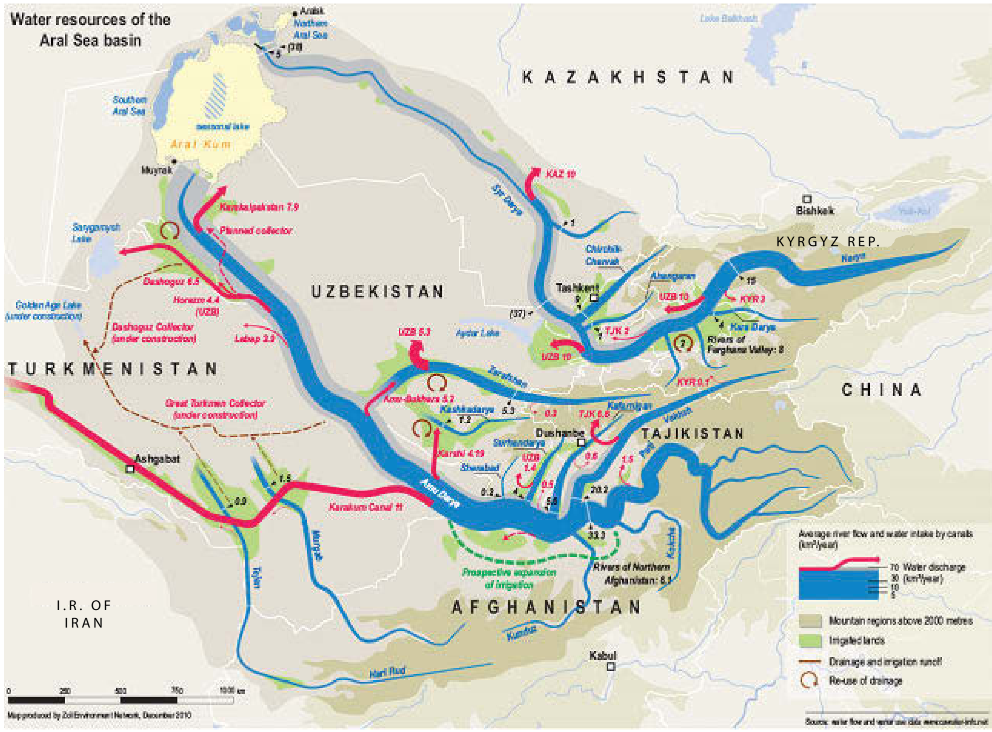

Source: Armstrong et al. (2005) as cited in Siegfried et al. (2012), Figure 8.

**Figure 5.14:** Decrease in total glacier area in the Amu Darya and Syr Darya basins combined for 2008–2050 based on the CMIP3 (left panel) and CMIP5 (right panel) model runs for the median and extreme values of temperature and precipitation change.




Source: Lutz et al. (2013a), Figure 13.

**Figure 5.15:** Water resources of the Aral Sea basin.




Source: ENVSEC and UNEP (2011), p.15.

The Amu Darya River is characterized by two major high-flow periods, which often merge into a 4–5 month flood season. With more than 90 percent of the total annual runoff of the Amu-Darya forming in the mountain catchment (Pamir-Alay), the river runoff has a very high share of melt water (Hagg et al. 2013). The first high-flow period of the Amu Darya usually takes place in the late spring, when snow melts in the lower mountain areas and the spring rains fall. The second high-flow period is induced by melt water from snow and glaciers in the alpine Pamir Mountains. The Tien Shan Mountains, where the headwaters of the Syr Darya River originate, have fewer glaciers than the Pamir. Hence, the Syr Darya usually has just one mainly snowmelt-induced flood season, which occurs in late spring (Dukhovny and Schutter 2011).

## Projected Changes in River Flows and Seasonality

The impact that climate change will have on river runoff rates in Central Asia is unclear due to the uncertainty of future precipitation patterns (Davletkeldiev et al. 2009; Dukhovny and Schutter 2011; Krysanova et al. 2010). In the next decades, enhanced glacier melt rates are expected to somewhat counterbalance increasing evaporation rates. Climate change will most likely affect snow and glacier storage and melting rates in the Pamir and Tian Shan Mountains, hence altering the hydrological regimes of the major Central Asian rivers. More than 80 percent of the annual runoff of Amu Darya and Syr Darya is formed by snow and glacier melt (Dukhovny and Schutter 2011). The Amu Darya has a higher annual share of glacier melt water ( > 20 percent), and this is the main cause of the annual summer flood. The Syr Darya, meanwhile, is less influenced by glacier melt water. As observed in the last decades, higher surface temperatures are leading to higher glacier melt rates and significant glacier shrinkage; this trend is expected to continue into the future.

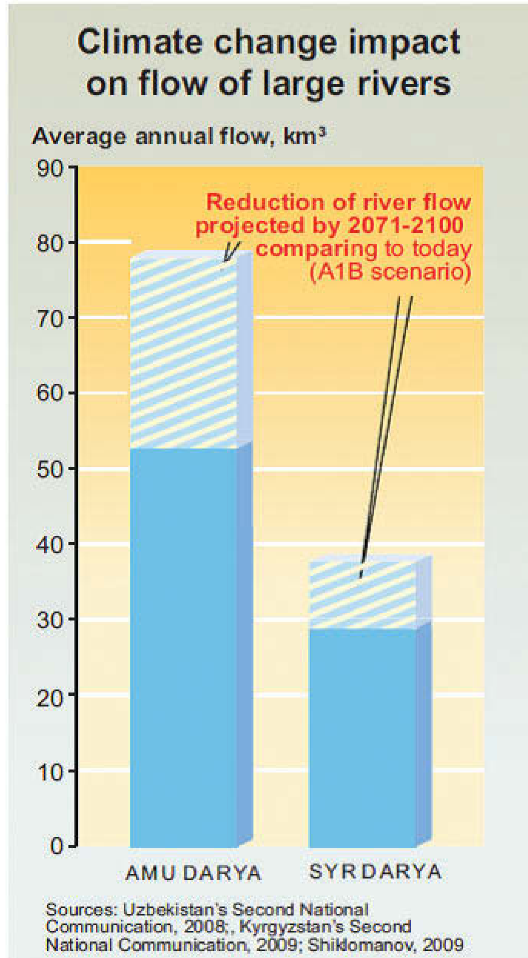
By 2030, river runoff is expected either to increase slightly or not to change beyond the natural runoff variability, even in the case of potentially higher precipitation rates (Main Administration of Hydrometeorology 2009). Model projections for 2055, for a headwater catchment (Panj) of the Amu Darya river, revealed a seasonal shift in peak river flow rates from summer to spring (Hagg et al. 2013). The study indicates that, in the near future, the reduction in glacial area will be partly compensated by enhanced melt rates in a warmer atmosphere, leading to only slight changes in total annual river flow. Under a 3.1°C warming scenario, by 2055 runoff will increase in spring and early summer due to an earlier and intensified snowmelt. Under these conditions, the peak flow will shift from July to June, leading to a reduction in discharge in

July and August of approximately 25 percent, which will further limit water availability in the summer (Hagg et al. 2013).

Climate change will also influence the snow regime in the mountains. This will further contribute to a shift of the spring floods to earlier periods. River flow will be lower in the vegetation period and the winter runoff may increase. Siegfried et al. (2012) found for Central Asia that climate changes are likely to affect runoff seasonality due to earlier snowmelt. Based on a model set up for 2050 for the Syr Darya, they projected a shift in the peak flows from summer to spring. This may increase water stress in the summer, particularly in unregulated catchments (Siegfried et al. 2012).

By the end the 21st century, climate change is expected to lead to a distinct decrease in the water volume of the Syr Darya (see Figure 5.16) and an even more distinct decrease in the Amu Darya River due to its higher share of glacier melt water (Davletkeldiev et al. 2009; Main Administration of Hydrometeorology 2009). This is due to decreasing precipitation and enhanced glacial retreat (see Figure 5.17 for an example). Glacier retreat will continue to diminish the stock of water stored in the high mountain areas as snow and ice; this will provide enhanced runoff during the next few decades, followed by a severe water shortage as the stock becomes depleted. In particular, the summer floods of the Amu Darya, highly important for irrigation, are expected to decline substantially by 2100. A further reduction in surface water flow is projected to be caused by an increase in evaporation rates, due to higher temperatures. By the end of the 21th century, runoff generation rates in the mountainous areas of Central Asia are likely to decline substantially (Main Administration of Hydrometeorology 2009).

**Figure 5.16:** Climate change impact on flow of large rivers in Central Asia.




Source: Novikov et al. (2009).

### Impacts on the Aral Sea and Major Lakes

More than 50 years of unsustainable water use for irrigation in arid deserts has led to a profound depletion of water resources in the Aral Sea basin, with consequences for society, the economy and nature. Starting in the 1960s, the Aral Sea has shrunk drastically, mainly due to water withdrawals for irrigation purposes and the construction of water reservoirs along the Syr Darya and Amu Darya Rivers.

Climate change is expected to affect the Aral Sea indirectly through changes in river contributions from the Amu Darya and Syr Darya as well as directly through water evaporation and precipitation changes (Cretaux et al. 2013).

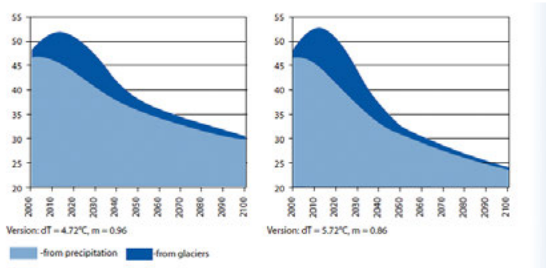
Projections of the future development of lake volumes and levels for Central Asia are scarce. The national communication report of the Kyrgyz Republic displays modeling results for the water level of Lake Issyk-Kul in the Kyrgyz Republic under the B2-MESSAGE scenario and indicates a decrease in the average water level of the lake of between 5 m (2°C world) and 15 m (4°C world) (Davletkeldiev et al. 2009).

### Geohazards and other Water-related Impacts

Climate change is contributing to an increased risk of floods and landslides in Central Asia. As glaciers retreat, large volumes of melt water are being released into the highland rivers. While this does not directly cause flooding, melt water may become trapped behind the glaciers' terminal moraines so that water pressure builds up until the natural moraine dam bursts (see also Nayar (2009) for a related discussion on the Himalayas). Glacier lake outbursts can cause catastrophic flooding downstream. During the last 50 years, more than 70 glacial lake outbursts have been reported in the Kyrgyz Republic alone, with the largest one in 1998 at Ikedavan lake resulting in more than 100 deaths and causing damage to five villages (Slay and Hughes 2011). In the southwest Pamir region (Tajikistan), meanwhile, any glacier lake outbursts have been observed (Mergili and Schneider 2011).

The potential for outburst floods is expected to increase with rising temperatures as well as with a rising number and size of moraine-dammed lakes (Armstrong 2010; Bolch et al. 2011; Marzeion et al. 2012). This is associated with an increased risk in

**Figure 5.17:** Dynamics of surface water-flow structure [in km³] for the Kyrgyz Republic (all rivers) for different temperature-rise scenarios calculated from the difference between the annual sum of atmospheric precipitation and annual evaporation; m-annual sum of precipitation compared to the baseline period 1961–1990 (climate scenario B2-MESSAGE).




Source: Davletkeldiev et al. (2009), Figure 5.4.

inhabited areas, such as the densely populated and agriculturally productive Fergana Valley region. The Fergana Valley is particularly exposed to these geohazards because glaciers surround the valley to the south, the east, and the north (Bernauer and Siegfried 2012; Siegfried et al. 2012).

### *5.4.1.2 Western Balkans*

#### Impacts on Water Resources

The Western Balkans is currently one of the most water-rich regions in Europe and has relatively abundant freshwater resources. Changes in water availability are especially relevant in areas where water is a limiting factor for agriculture, industry, and livelihoods in general. In the Mediterranean areas, water is scarce and mainly depends on runoff from the mountainous headwaters (García-Ruiz et al. 2011)(see Figure 5.18).

#### Projected Trends in Water Resources

Changes in the temperature and precipitation regime directly affect the amount of water that reaches the soil, and eventually the magnitude and seasonality of river discharge. The available studies indicate that a progressive decline in water availability, especially for the summer months, is expected in the near future and will become more pronounced by the end of the 21st century (Arnell and Gosling 2013; García-Ruiz et al. 2011; Ministry for Spatial Planning Construction and Ecology 2013; Ministry of Environment and Spatial Planning 2010).

Schneider et al. (2013) found that under a regional warming of ~2°C by the 2050s, the impacts of climate change on the natural flow characteristics of most Balkan rivers will be "medium"; for the rivers of southern Serbia, Kosovo, and FYR Macedonia, the impacts will be "severe." Dakova (2005) projected a decrease in long-term annual mean runoff for Serbia of approximately 12 percent by 2025, and approximately 19 percent by 2100, due to a projected decrease in annual precipitation and an increase in temperatures. Albania's water resources are projected to decline by between 14 percent (Chenoweth et al. 2011) and 40 percent (Dakova 2005) by the end of the 21st century. Results from a global study show severe decreases in annual discharge in the Western Balkans of up to 15 percent in a 2°C world and more than 45 percent in a 4°C world (Schewe et al. 2013).

Climate change, through rising winter temperatures, directly affects snow accumulation and snowmelt by elevating the winter 0°C isotherm (snow line), leading to a decrease in the accumulation of snow in the headwater catchments.

More rainfall in the winter months will increase winter runoff and decrease the snowmelt flood in spring (Islami et al. 2009). Model projections show a reduction of up to 20 days in the snow cover duration across the Balkans by 2050 and of up to 50 days in the Dinaric Alps (Schneider et al. 2013). Snow-fed river basins are very sensitive to climate change, as snow responds rapidly to slight variations in temperature and precipitation. In snowmelt-driven river regimes like the Sava river, climate change is therefore expected to result in earlier spring floods and, in some cases, higher winter runoff (Arnell and Gosling 2013; García-Ruiz et al. 2011).

Changes in temperature and precipitation patterns can also affect the timing, frequency, and intensity of flood, droughts, and other extreme events (Dankers and Feyen 2009). Regions under Mediterranean climate conditions are expected to experience longer low-flow periods during the summer season and a distinct reduction in low-flow magnitudes (Arnell and Gosling 2013; Dakova 2005; Dankers and Feyen 2009; Schneider et al. 2013). On the other hand, projections also suggest an increase in riverine flood risk, mainly in spring and winter, caused by more intense snowmelt and increased rainfall in the winter months. Modeling results, at the European scale, indicate that more floods with a current 100-year return time will occur by the end of the 21st century. Dankers and Feyen (2009) project a slight increase (less than 20 percent) in the frequency of 100-year floods for large rivers such as the Danube, Sava, and Tisza in the northern parts of Serbia and Bosnia and Herzegovina, and a slight decrease in 100-year flood events in the southern parts of the Balkans. For highly snowmelt-influenced rivers, the time of greatest flood risk may shift, with peak flows occurring earlier in spring or in late winter. For FYR Macedonia, with a more Mediterranean climate, a slight reduction in the magnitude of peak flows is projected (Schneider et al. 2013).

### *5.4.1.3 Synthesis*

For the region of Central Asia, there exist several peer-reviewed studies examining the observed changes in water availability (Lioubimtseva and Henebry 2009; Unger-Shayesteh et al. 2013). Reliable model-based projections are very scarce, however, and no multi-model approaches have yet been applied (Hagg et al. 2013; Siegfried et al. 2012).

**Figure 5.18:** River water discharge in the Western Balkans.


Source: ENVSEC and UNEP (2012).

River flows in Central Asia are expected to be lower in the summer vegetation period while the winter runoff is projected to increase. Siegfried et al. (2012) found that, for Central Asia, climate change is likely to affect the seasonality of river runoff due to earlier annual snowmelt. Using a climate, land-ice, and rainfall-runoff model for the Syr Darya basin, they projected that by 2050 there will be a shift in peak river flows from summer to spring. This may increase water stress in summer, in particular in unregulated catchments (Siegfried et al. 2012). However, the total annual river runoff is not likely to decrease considerably until at least the middle of the century when glacier depletion is projected to cause a distinct decrease in the water volume of the Central Asian rivers. Over the short-term, enhanced glacier melt rates will provide an inflow of additional water into rivers (Hagg et al. 2013). In the medium to long term, however, as glaciers shrink, this buffer effect will be reduced and will eventually disappear. This effect will be more pronounced for the Amu Darya than for the Syr Darya because of its higher share of glacier melt water.

For the Western Balkan countries, only a few scientific studies on the regional impacts of climate change on water resources and river runoff levels are available. There is a lack of comprehensive region-wide hydrological data (Dankers and Feyen 2009; García-Ruiz et al. 2011; Schneider et al. 2013). The available scientific studies suggest that across the Balkans water availability over the summer months is expected to decrease considerably by the end of the century. In the northern parts of the Balkans, however, spring and winter riverine flood risk is expected to increase. Results from a global study show severe decreases in annual discharge in the Western Balkans of more than 45 percent in a 4°C world.

## 5.4.2 Agricultural Production and Food Security

### *5.4.2.1 Central Asia*

#### Projected Impacts of Climate Change on Agriculture

Sutton et al. (2013a) analyzed the potential impact of climate change on Uzbekistan's agricultural sector. Without implementing adaptation measures and technological progress, yields for almost all crops are expected to drop by as much as 20–50 percent (in comparison to the 2000–2009 baseline) by 2050 in a 2°C world due to heat and water stress. Under a lower warming scenario (1.42°C warming), the declines are projected to be less pronounced, with wheat yields expected to decline by up to 13 percent with the exception of eastern parts of the country where yield increases of up to 13 percent are possible. For cotton, yield decreases of 0–6 percent are projected. Crops which might benefit from changing climatic conditions are alfalfa and grasslands. When including the effects of reduced water availability, yield decreases are much more pronounced. Irrigation water demand is also likely to increase by up to 25 percent by the middle of the century, while water availability could decline by up to 30–40 percent during the same period (Sutton et al. 2013a).

According to Sommer et al. (2013), due to the high irrigation rates in Central Asia, agriculture is less dependent on precipitation than on surface water availability. The authors concluded that wheat yields across all periods and scenarios increase by an average of 12 percent, this ranges from four percent to 27 percent. It is necessary to note that their simulations did not include changes in irrigation water availability. Sommer et al. (2013) argued that irrigation water demand does not necessarily increase under the influence of climate change. Instead, they stated that yield increases are a consequence of higher winter and spring temperatures, less frost damage and $CO_2$ fertilization.

In an assessment of global hotspots, Teixeira et al. (2013) came to a different conclusion concerning the influence of heat stress on yields; their study does not include the $CO_2$ fertilization effect. The authors simulated the risk of heat stress for wheat, maize, rice, and soybeans for the period 2071–2100 relative to the baseline period of 1971–2000. They concluded that Central Asia, especially Kazakhstan, is likely to be a major future hotspot of heat stress for wheat in a 3°C world (Teixeira et al. 2013).

In Tajikistan, increased water stress due to climate change will be the main influencing factor for the agricultural sector. According to the World Bank (2013u), yields could drop by up to 30 percent by 2100 in some parts of the country.

Desertification is already a problem in Kazakhstan, affecting up to 66 percent of the country's land area. A projected temperature increase of up to 4.6°C in 2085, and highly heterogonous changes in precipitation patterns, could increase desertification and threaten agricultural production, especially winter wheat (World Bank 2013v). Similar to the impacts in Kazakhstan, the Kyrgyz Republic is likely to suffer from increasing desertification. The country's arid and semi-arid deserts could spread, covering up to 23–49 percent of the country's territory by 2100, in comparison to roughly 15 percent in 2000 (World Bank 2013r).

In Turkmenistan climate change is likely to impact the Amu Darya River, reducing its runoff by 10–15 percent by 2050 and putting pressure on existing irrigation systems and crop production. Degradation of soils and increased risk from desertification are more likely to occur when surface water availability decreases (World Bank 2013w). The runoff in the Syr Darya River is expected to decrease by 2–5 percent by 2050. At the same time, irrigation demand in Uzbekistan could increase by up to 16 percent by 2080, increasing the competition for water and imposing risks on current agricultural production systems. Uzbekistan's crop yields could be reduced by as much as 10–25 percent by 2050 (World Bank 2013x).

By 2050, a shift in peak river flow and the increasing appearance of extreme events (e.g., floods and droughts) are expected for the river basins of the Syr Darya and Amu Darya (Schlüter et al. 2010). Many water management systems are not equipped to deal with the increasing occurrence of drought events (Schlüter et al. 2010).

In the Fergana Valley, climate change is likely to affect the water availability for large-scale irrigation. Siegfried et al. (2012), for example, modeled changes in runoff for the year 2050. They concluded that the runoff peak of the Syr Darya will shift by 30 to 60 days, leading to water deficits in the vegetation period of the Fergana Valley (Siegfried et al. 2012).

#### Livestock

The direct effects of climate change on livestock are likely to be negative. In particular, increasing temperatures and reduced water availability will put pressure on the sector. With changing precipitation patterns and increasing temperatures, growth and regeneration of pastures for livestock grazing will decline in the Tian-Shan and Alai valleys as well as in other regions of Central Asia (World Bank 2013r). Moreover, as water demand for livestock increases with rising temperatures, this will put pressure on existing water resources in water-scarce regions (Thornton et al. 2009).

The indirect effects of climate change on livestock may be positive in some cases, such as in Uzbekistan, where the productivity of alfalfa and grasslands is expected to increase under warming conditions (Sutton et al. 2013b).

If livestock productivity decreases, producers could react by enlarging livestock numbers in order to maintain current levels of production. This could lead to overgrazing and degradation of pastures as well as to erosion, thereby increasing the negative impact on the region's ecosystems (Fay et al. 2010).

### *5.4.2.2 Western Balkans*

#### Projected Impacts of Climate Change on Agriculture

A study by Sutton et al. (2013a) analyzed two countries in the Western Balkans: Albania and the Former Yugoslav Republic of Macedonia. Albania regularly suffers from floods, which are problematic for agriculture when they delay the planting of crops or destroy harvests. Projections up to 2050 for Albania indicate that flooding events could increase in both frequency and intensity under the influence of climate change. Yield changes in the Albanian agricultural sector are projected to be most severe for rain-fed grapes and olives, with yield declines of up to 20 and 21 percent respectively compared to the baseline (2000–2009) under 1.81°C of warming. However, under this scenario wheat yields are projected to increase by up to 24 percent due to an extended growing season and more moderate temperatures in the winter (Sutton et al. 2013a).

Precipitation changes in FYR Macedonia are similar to those in Albania. Yield effects are relatively heterogonous, with yield declines of up to 50 percent for maize, wheat, vegetables and grapes under 1.62°C warming in the Mediterranean and Continental parts of the country, whereas in the alpine areas of FYR Macedonia, wheat yields are projected to increase considerably by more than 50 percent (Sutton et al. 2013a). Low average temperatures and short growing seasons, both of which will be influenced by climate change, characterize the alpine region. Yield declines in grape production are especially problematic, as grapes are the most important cash crop in FYR Macedonia. Wheat, on the other hand, is the most important crop in terms of production area (World Bank 2010b).

Giannakopoulos et al. (2009b) assessed the impact of climate change on Mediterranean agriculture for the period 2030–2061 with warming above 1.5°C (reference period 1961–1990) and differentiated between the impacts on irrigated crops (C4 summer crops, tubers) and rain-fed crops (legumes, C3 summer crops, and cereals). For irrigated crops, yields in Serbia are projected to increase by 3–4 percent for C4 summer crops and by 2–5 percent for tubers. For rain-fed crops, which dominate Serbian agriculture, yields are mostly projected to decline. Cereal yields in Serbia show a variation from a 2 percent decline to a 3 percent increase depending on the climate scenario used. When introducing adaptation measures (e.g., early sowing dates, longer growing cycle cultivars), the negative impacts of climate change could be reduced or even reversed. However, the authors warned that the adaptation options they analyzed require up to 40 percent more irrigation water.

#### 5.4.2.3 Food Security

Of the 65 million people living in the five Central Asian countries, roughly five million lack reliable access to food (Peyrouse 2013). The Central Asian population is expected to increase significantly in the future (up to 95 million people by 2050), compounding the pressure induced by climate change on land and water resources (Lutz 2010). The rural population is the most exposed to food insecurity. In Tajikistan roughly 2 million people suffer from food insecurity, of which 800,000 were directly threatened by hunger in 2009. In the Kyrgyz Republic one million people are affected by food insecurity (Peyrouse, 2013). Rising food prices can have severe effects on the Central Asian population, as large percentages of household incomes are spent on food and many countries in the region are highly dependent on food imports. For example, inhabitants of Tajikistan and Uzbekistan spend 80 percent of their household incomes on food (Peyrouse, 2013). Tajikistan produces only 31 percent of the nation's food domestically. This indicates that Central Asian countries are exposed to fluctuations in international food prices (Meyers, Ziolkowska, Tothova, & Goychuk, 2012; Peyrouse, 2013). The access to international markets however is problematic due to complex regional trade linkages such as the trade blockages, exports/imports bans, and quotas (Bravi & Solbrandt, 2011; Chabot & Tondel, 2011). However, according to Headey (2013), the Central Asian region is not a hotspot of climate change induced food insecurity, even though the region is to a certain extent dependent on food imports. The country with the highest risk of food insecurity is Turkmenistan (Headey, 2013).

The various threats to food security from climate change in Central Asia and the Western Balkans are indicated in the literature as follows:

- Increasing temperatures and changes in precipitation and patterns of river runoff are serious risks for agricultural production (Meyers et al. 2012).
- The availability of suitable arable land and water resources is expected to decline simultaneously, changes in the type and intensity of pests and diseases will occur, influencing the available productive and adapted crop varieties and animal breeds (Meyers et al. 2012).
- The availability of irrigation water in Central Asia is crucial in order to maintain or expand agricultural production. As the available water is likely to decline, competition for the remaining water resources among agriculture, industry, and people (for human consumption) could increase (Hanjra and Qureshi 2010).
- Heavy rainfall events and storms may occur more often, increasing the risk of erosion from wind and water and leading to the degradation and desertification of scarce, valuable arable land (Christmann et al. 2009).
- Sensitivity thresholds of crops might be exceeded more often with rising average temperatures and the increased risk of temperature extremes (Lioubimtseva and Henebry 2012; Teixeira et al. 2013).
- Eastern Europe and parts of the Balkan region will suffer from decreasing water availability, leading to yield reductions (Meyers et al. 2012).

#### 5.4.2.4 Synthesis

Climate change will have a significant impact on agriculture in Central Asia and the Western Balkans. Central Asia's agricultural sector is highly dependent on the availability of water for irrigation. Changing precipitation patterns, reduced runoff in the major river basins, and increasing temperatures will simultaneously put additional pressure on available water resources and increase agricultural water demand (Schlüter et al. 2010; Siegfried et al. 2012; World Bank 2013r; u; v). Prolonged periods of above average temperatures will exacerbate the heat stress of agricultural crops, leading to decreasing plant productivity (Mannig et al. 2013; Teixeira et al. 2013). Increasingly frequent and intense droughts are very likely to increase desertification in the Kyrgyz Republic and Kazakhstan (World Bank 2013r; v).

Because of the high importance of irrigation agriculture in large parts of southern Central Asia and the discussed inefficiency of many irrigation systems, an improvement in irrigation techniques would be very helpful in reducing pressure on existing water resources (Lioubimtseva and Henebry 2009).

In the Western Balkans, the increasing occurrence of droughts has been identified as a major threat to agricultural production under climate change (Giannakopoulos et al. 2009b; Gocic and Trajkovic 2013, 2014; Kos et al. 2013; UNDP 2014). The risk of increasing droughts for this region was also cited in the latest IPCC publication (Kovats et al. 2014). The dominance of rain-fed agriculture in the Western Balkans makes the agricultural sector especially vulnerable to changing precipitation patterns and increasing temperatures. The increasing appearance of extreme rain and flood events also poses risks to agriculture in the region (Sutton et al. 2013a). Currently, the agricultural productivity of the Western Balkan states is comparably low—even though large parts of the region are suitable for agricultural production (Swinnen et al. 2010; Volk 2010). Recent years have seen a rise in yields, mostly based on improved production techniques (Volk 2010), and there is potential for further yield increases. While climate change could pose risks to increasing agricultural productivity, the poor execution of agricultural policy reforms, inefficient institutions, and missing infrastructure also threaten increases in productivity (Swinnen et al. 2010; Volk 2010).

While some climate impact studies on agriculture are available for the countries of Central Asia (Mannig et al. 2013; Schlüter et al. 2010; Siegfried et al. 2012; Sommer et al. 2013; Sutton et al. 2013a), the Western Balkan countries lack coverage in recent research (Meyers et al. 2012). The Western Balkan countries are at times the subjects of climate change analyses focusing on Europe or the European Union (Giannakopoulos et al. 2009b), but very few studies concentrate on the regional climate impacts on agriculture (Ruml et al. 2012).

The livestock sector is particularly underrepresented in current climate impact research on Central Asia and the Western Balkans. While the possible direct and indirect effects of climate change on agriculture are discussed in numerous studies (Fay et al. 2010; Miraglia et al. 2009; Sutton et al. 2013a; Thornton et al. 2009; UNDP 2014), there is almost no regional modeling on climate change and agriculture. For example, the effects of climate change on livestock diseases and livestock biodiversity lack coverage in the scientific literature. More research on the impact of climate change on agricultural and livestock productivity, as well as on food security in this region, is needed.

## 5.4.3 Energy Systems

### *5.4.3.1 Current Energy Access and Systems Situation in the ECA Region*

The Central Asian and Balkan countries have very different energy mixes and varying climate change vulnerabilities. Some Central Asian countries heavily rely on hydroelectricity (e.g., close to 100 percent in Tajikistan and the Kyrgyz Republic). Other countries in Central Asia, and the Balkan countries (with the exception of Albania), have access to electricity primarily via thermal electric sources and, to a lesser extent, hydroelectricity. Table 5.4 displays the shares of electricity production by source, and the total electrical power consumption per capita, in the different Central Asian countries.

### *5.4.3.2 Hydropower in Central Asia: More Conflicting Demands*

Hydropower infrastructure plays a key role in Central Asia not only for electricity generation but also for river flow regulation and irrigation. Tajikistan and the Kyrgyz Republic, which are located upstream of the Syr Darya and Amu Darya, respectively, produce 98.8 percent and 93.3 percent of their total electricity

**Table 5.4:** Electricity production from hydroelectric and thermoelectric sources, including natural gas, oil, coal, and nuclear, in 2011 in the Central Asian countries.

| COUNTRY NAME | ELECTRICITY POWER CONSUMPTION (kWh PER CAPITA) | ELECTRICITY PRODUCTION FROM HYDROELECTRIC SOURCES (% OF TOTAL) | ELECTRICITY PRODUCTION FROM THERMOELECTRIC SOURCES (% OF TOTAL) | ELECTRICITY PRODUCTION FROM OTHER SOURCES (% OF TOTAL) |
|---|---|---|---|---|
| **Kazakhstan** | 4,892 | 9 | 91 | 0 |
| **Kyrgyz Republic** | 1,642 | 93 | 7 | 0 |
| **Tajikistan** | 1,714 | 99 | 1 | 0 |
| **Turkmenistan** | 2,444 | 0 | 100 | 0 |
| **Uzbekistan** | 1,626 | 19.5 | 80.5 | 0 |

Sources: World Bank (2013e, f, g, h, i, j).

from hydropower (World Bank 2013p). By contrast, the riparian downstream countries of Kazakhstan, Uzbekistan, and Turkmenistan produce, respectively, 9.1 percent, 19.5 percent, and close to 0 percent of their electricity from hydropower (World Bank 2013p). Despite the relatively high reliance on hydroelectricity in a few countries in the region, in total only 8 percent of the regional hydropower potential has been developed (Granit et al. 2010). Taking into account the steeply growing population of Central Asian countries (World Bank 2013h) and their current and projected economic growth (World Bank 2013s), demand for energy is projected to rise. However, the impacts of climate change on river runoff and seasonality could affect hydropower generation and increase conflicting water demands for hydropower and irrigation.

A global study by Hamududu and Killingtveit (2012) projected both future river runoff and the electricity produced by hydroelectric installations at the national level, aggregated at the regional level, for Africa, Asia, Europe, North and Central America, South America, and Australasia/Oceania. The authors estimated percentage changes in hydropower generation up to 2050 under 2.3°C global warming. For Central Asia, they found that production is expected to increase by 2.29TWh, or 2.58 percent, compared to the 2005 production level. Other available projections show that the potential of installed small hydropower plants is projected to decrease by the 2050s under 2°C warming by around 13 percent in Turkmenistan and 19 percent in the Kyrgyz Republic, and to increase by nearly 7 percent in Kazakhstan (WorleyParsons 2012).

Siegfried et al. (2012) projected the impacts of climate change on Syr Darya river runoff and seasonality changes for the middle of the 21st century (2040–2049) under 1.8°C of global warming. Their projections took into account glacier melt, precipitation, and temperature at six different locations in Central Asia: the Fergana Valley (Uzbekistan, Kyrgyz Republic, and Tajikistan); the Toktogul Reservoir (Kyrgyz Republic); the Andijan Reservoir (Kyrgyz Republic); the Charvak reservoir (Uzbekistan); the Kayrakum reservoir (Tajikistan); and the Chardara reservoir (Uzbekistan). The authors concluded that the most significant consequence of climate change will be the 30–60 days seasonality shift in river runoff. This shift in seasonality is projected to have major consequences for both upstream and downstream reservoir management, and the shift could lead to a major water demand deficit. For the Fergana Valley, where approximately 22 million people depend on irrigation for their livelihoods, the water demand deficit is projected to increase due to an increase in evapotranspiration and changes in runoff seasonality. According to the projections, maximum demand deficits are projected to occur in the early growing season, which is the most sensitive for plant growth. This increased demand deficit for irrigation is projected to put more pressure on hydroelectricity, which is likely to be accentuated by a projected population growth and will contribute to a reduction in per capita water availability.

#### *5.4.3.3 Energy Systems in the Western Balkans*

The energy mix of the Western Balkans countries is very heterogeneous. Albania produces almost all of its electricity from hydropower; at the other end of the scale, Kosovo only produces two percent of its electricity from hydroelectric sources (World Bank 2013p). FYR Macedonia, Serbia, Montenegro, and Bosnia and Herzegovina produce between 20 and 45 percent of their electricity from hydroelectric sources.

As many of the Balkan countries rely on thermal electricity sources, the assessment of climate change impacts on this sector is particularly relevant. These projected impacts on southern and eastern European countries were studied by van Vliet et al. (2012); their study took into account the effects of the changes in river water temperature and river flows on thermal electricity production. They found that the capacity of nuclear and fossil-fueled power plants in Europe could face a 6–19 percent decrease in from 2031–2060 compared to the production levels observed from 1971–2000. Furthermore, due to the expected increase in the incidence of droughts and extreme river low flows, the mean number of days in which electricity production will be reduced by more than 90 percent is projected to increase threefold compared to present levels, from 0.5 days per year (at present) to 1.5 days per year from 2031–2060 under 1.5°C global warming. Table 5.5 summarizes the results of their projections.

It has also been projected that decreased production and power generation disruption induced by lower runoff and increased air and water temperatures will lead to an increase in electricity prices (McDermott and Nilsen 2014). As the majority of the countries in the region are strongly dependent on thermal electric production, climate change is projected to increase their vulnerability by affecting the supply of electricity to both households and industry. In addition, economic development and a growing population are expected to increase energy demand, thereby putting thermal electric power plants under increasing pressure. In the absence of adaptation measures, climate change, economic development, and population growth may together contribute to a rise in electricity prices and increase the risk of electricity shortages in the region.

In addition to the gradual slow-onset climate changes expected in the region, climate change may also increase the intensity and frequency of extreme weather events. The number of studies assessing the impacts of extreme weather events, such as floods, droughts and storms, on thermal electricity production plants at the regional and global level is still very limited, however; this does not allow for a comprehensive analysis of this issue.

Regarding hydropower generation, a study by Hamududu and Killingtveit (2012) found that, for Southern Europe (including the Balkan countries), overall hydropower production is expected to decrease by 1.66TWh, or 1.43 percent compared to 2005 production levels.

**Table 5.5:** Reduction in usable capacity (expressed in KWmax) of thermal power plants in Europe.

| SCENARIO / PROJECTED REDUCTION IN USABLE CAPACITY | $KW_{MAX}$ REDUCTION > 25% (IN MEAN NUMBER OF DAYS PER YEAR) | $KW_{MAX}$ REDUCTION > 50% (IN MEAN NUMBER OF DAYS PER YEAR) | $KW_{MAX}$ REDUCTION > 90% (IN MEAN NUMBER OF DAYS PER YEAR) |
|---|---|---|---|
| **Once-through or combination cooling thermal power plants** | | | |
| 1971–2000 | 64 | 31 | 0.5 |
| B1 (2031–2060)(1.4°C global warming) | 84 | 44 | 1.4 |
| A2 (2031–2060)(1.5°C global warming) | 90 | 50 | 1.5 |
| **Recirculation (tower) cooling thermal power plants** | | | |
| 1971–2000 | 14 | 9 | 0.02 |
| B1 (2031–2060)(1.4°C global warming) | 18 | 10 | 0.09 |
| A2 (2031–2060)(1.5°C global warming) | 19 | 11 | 0.08 |

Source: van Vliet et al. (2012).

Despite the limitations of this study, the projections for this region are supported by a more detailed local study in Croatia. Pasicko et al. (2012) projected that energy generation from hydropower plants could decrease by 15–35 percent in a 4°C world. The projected decrease in hydropower production in Croatia originates from the projected 35 percent reduction in future precipitation, affecting the major Croatian rivers basins in the summer months from 2080–2100 as compared to the reference period 1961–1990.

#### 5.4.3.4 Synthesis

Energy demand in the ECA region is projected to rise together with population growth and economic development. Warmer winter temperature can be expected to lead to decreased energy consumption for heating; however, this trend will be counterbalanced by higher energy consumption for cooling purposes during summers. Energy generation in the ECA region will be affected mainly by changes in the river flows and water temperatures. In Central Asia hydropower generation has a potential to play a major role in the future energy mix, however, the new pattern of intra-annual runoff distribution will mean that there will be less water available for energy generation in summer months. In the Western Balkans, hydropower generation potential could decrease due to less precipitation in the region. Furthermore, the capacity of nuclear and fossil-fuelled power plants in the sub-region could decrease due to increased water temperature.

### 5.4.4 Human Health

A number of diseases and health conditions are already present across Eastern Europe and Central Asia, some of which will be affected by climatic changes such as increased temperatures and more frequent and intense rainfall and drought events.

#### 5.4.4.1 Vector-Borne Diseases

The Balkans and parts of Kazakhstan and the Kyrgyz Republic fall into the endemic zone for tick-borne encephalitis (TBE), transmitted by the *Ixodes* genus of ticks (Lindquist and Vapalahti 2008). Although climate is only one factor among several that influence the TBE transmission, and climate change could also disrupt the conditions required for the disease transmission (Randolph and Rogers 2000), the spread of TBE appears to be a real risk associated with rising temperatures across the region.

The reemergence of malaria in Tajikistan—following its near-eradication by the end of the 1950s in the USSR (Lioubimtseva and Henebry 2009)—has happened in conjunction with an increase in mean temperatures (Ministry of Nature Protection 2003). The disease is currently endemic to Tajikistan, with the risk classified as very high in much of the Khatlon region in the southwest of the country and the Sogd region in the north, and there are currently more than 150 days of the year suitable for malaria transmission according to the Tajik meteorological agency (Ministry of Nature Protection 2003). Since the early 1990s, malaria has also reappeared in Uzbekistan, the Kyrgyz Republic, and Turkmenistan, and locally transmitted cases have also been reported in Russia and Kazakhstan (Lioubimtseva and Henebry 2009).

Dengue fever and Chikungunya fever, transmitted by *Aedes* mosquitoes, are already present in Europe (ECDC 2013). Climatic conditions in the Balkans have become more suitable over the last two decades for one of the potential vectors of dengue and Chikungunya, *A. albopictus*, also known as the Asian tiger mosquito (Caminade et al. 2012). It is currently found in most of Albania and Montenegro, and in northwestern areas of Serbia and Bosnia and Herzogovina. This is related to wetter and warmer conditions favoring the winter survival of the mosquito. A study from the European Centre for Disease Prevention and Control (2012), points to increasing climatic suitability for *A. albopictus* in the Western Balkans with climate change. Caminade et al. (2012) also projected an increased suitability from 2030–2050 in the Balkans with about 1.5°C global warming, and an associated lengthening of the mosquito's activity window.

#### *5.4.4.2 Food- and Water-Borne Diseases*

Food-borne diseases, including *salmonellosis*, display a distinct seasonal pattern that has been associated with including increased temperatures, heat waves, and flooding (Semenza et al. 2012). A time-series analysis of 10 European countries undertaken by Kovats et al. (2004) showed a clear relationship in most of the countries studied between increases in ambient temperature and increases in the incidence of sporadic *salmonella* poisoning. While the overall incidence of *salmonellosis* is in fact declining in most European countries (ECDC 2013), it is likely that, with increased temperatures, climate change will increase the risk of outbreaks.

In Central Asia, Novikov et al. (Novikov et al. 2009) noted that *salmonellosis* could become a greater problem due to warmer temperatures and the contamination of communal water sources exacerbated by either drier conditions or flooding. Contaminated water supplies are also associated with cholera, typhoid, and dysentery. The reproductive rates of flies, which often play a significant role in transmitting food and water-borne diseases, may be increased at elevated temperatures, leading to higher incidence rates and longer disease seasons (Lioubimtseva and Henebry 2009). In Tajikistan, for example, there is a risk of choleric reservoirs developing in the lower reaches of the Vakhsh, Kafirnigan, and Syrdarya rivers (Ministry of Nature Protection 2003).

#### *5.4.4.3 Impacts of Extreme Weather Events*

##### Heat Waves

Heat waves can impact human health in direct ways (e.g., heat stress) and indirectly (e.g., aggravating respiratory and cardiovascular conditions). The increased incidence and intensity of extreme heat events could cause the seasonality of temperature-related mortality across continental Europe to shift from winter to summer, with fewer cold-related deaths and more heat-related ones. While the decreasing trend in cold-related deaths is expected to initially cancel out the increasing trend in heat-related deaths, the net total number of deaths is projected to increase for the period 2050–2100 under 3˚C global warming (Ballester et al. 2011). In the Western Balkans, Albania and FYR Macedonia are considered particularly vulnerable to heat waves (ENVSEC and UNEP 2012).

Central Asia has seen an increased incidence of heat-related strokes and mortalities. For example, Tajikistan's Second National Communication to the UNFCCC reported that the number of days with extremely hot weather has doubled since 1940 (cited in BMU and WHO-Europe 2009). In addition, according to Kazakhstan's Second National Communication, most parts of that country have seen a doubling in the frequency of heat waves and a decrease in the duration of cold waves (BMU and WHO-Europe 2009).

##### Flooding

In the Western Balkans, northern Serbia is considered particularly vulnerable to flooding (ENVSEC and UNEP 2012). Further east, severe flooding has been experienced in Tajikistan in recent years. Injuries and fatalities as a result of glacial outburst flooding in the mountains of Tajikistan, Uzbekistan, and the Kyrgyz Republic have also been observed (Novikov et al. 2009); glacial lake outburst flooding poses a mounting danger as glaciers retreat with regional warming. Mudflows in Kazakhstan, meanwhile, are expected to increase tenfold with a warming of 2–3˚C (BMU and WHO-Europe 2009).

#### *5.4.4.4 Synthesis*

Little modeling of climate change impacts on human health in the Western Balkans and Central Asian regions has been undertaken. A lack of certainty about the mechanisms through which climate change affects the incidence of tick-and mosquito-borne diseases, for example, prevents strong claims about future trends. An exception, perhaps, is dengue fever: stronger indications of an increased risk of dengue in the Western Balkans have been provided by the European Centre for Disease Prevention and Control (2012) and Caminade et al. (2012). In addition, historical observations of extreme events, including glacial outburst flooding, may offer some clues as to what the increased risks of such events under climate change could mean for human health in the region.

### 5.4.5 Security and Migration

#### *5.4.5.1 Climate-related Drivers of Migration*

One of the impacts of climate change on the socioeconomic and political stability of the ECA region will be manifest from the modification and/or intensification of migratory movements within and from the Central Asian and Western Balkans countries. Concerns associated with population trends and climate change have so far been largely treated in separation (Lutz 2010). While recent research is gradually trying to bridge this gap (e.g., Drabo and Mbaye 2011; Reuveny 2007), the knowledge base remains extremely weak in terms of forecasting migratory patterns.

Frequently cited figures estimate that, globally by 2050, the number of people forced to move primarily because of climate change will be within a wide range of 200 million and one billion (Tacoli 2009, 514). It is likely that both extreme weather events and changes in mean temperatures, in precipitation, and in sea levels will contribute to increasing levels of mobility (Islami et al. 2009; Tacoli 2009). It is difficult to predict with precision, however, the extent to which these factors will impact population distributions and movements (Kniveton et al. 2008).

According to Lutz (2010), future migration within the ECA region is likely to be determined by political changes and security problems in certain countries (linked, for instance, to the presence of ethnic minorities) in addition to environmental stresses; these are all factors that are very hard to predict with certitude (Lutz 2010). The projected increase in the intensity and frequency of natural catastrophes (e.g., forest fires, heat waves, floods and landslides) (Adger et al. 2014) is likely to result in population movements that, in turn, could generate frictions in such politically sensitive countries as Albania, Bosnia and Herzegovina, and Kosovo (Maas et al. 2010). In Central Asia, the biggest potential threat is an increase in landslides and avalanches, especially in the Fergana Valley, which would impact on regional livelihoods and food security (Siegfried et al. 2012).

If it is assumed that the Western Balkans will exhibit similar reactions to those of Southeast and Eastern Europe, the increased risk of disasters will result in decreasing economic opportunities and provide incentives for migration (Maas et al. 2010). The European Union could be among the primary destinations. Migration could also take place within the region, eventually further aggravating the economic situation. In Central Asia, migratory patterns are likely to continue to flow toward more productive and secure areas (e.g., Russia, Europe, and the United States, from which the majority of remittances are currently received) (Asian Development Bank 2011; Maas et al. 2010; Schubert et al. 2007).

### 5.4.5.2 Rural-Urban Migratory Patterns as a Consequence of Climate Change

In Central Asia today, migration plays an important role in the development of the region, notably through remittances (Asian Development Bank 2011). Of the countries in the ECA region, Albania, Kazakhstan, and Georgia are among the main sending countries of migrants (Fay et al. 2010). Migration in the Western Balkans has already led to severe demographic changes; coupled with the general demographic trend toward an aging population, this is expected to cause increased regional climate change sensitivity and decreased adaptive capacity as an aging population is more sensitive to heat (EEA 2012).

According to the Asian Development Bank (2011), a large part of the region's population already lives in areas at high risk of increased water stress due to climate change. Population growth is another potential push factor contributing to both internal and external migration. For example, the population in the Aral Sea basin is expected to grow by about 20 million over the next 40 years (about a 30 percent increase relative to today), with Uzbekistan contributing about 50 percent and Tajikistan about 25 percent to the expected growth (UN World Population Database in Siegfried et al. 2010).

Population growth in climate change hotspots in the Central Asian countries indicates that, almost all of the population in the sub-region is living in areas at risk from the impacts of climate change. By 2050, a 77.2 percent increase in the population living in hotspots is expected for Tajikistan, 55.4 percent in Uzbekistan, 41.3 percent for Turkmenistan, and 31.3 percent for the Kyrgyz Republic (with respect to the values for the year 2000) (see Table 5.6).

A study commissioned by the International Organization of Migration (IOM) in 2005 found that internal displacements in Central Asia amounted to about half of the total migrant population (Kniveton et al. 2008). Among internal migrants, a significant share moved due to environmental reasons (Jaeger et al 2009). Reasons for these displacements included mudslides and landslides, floods, hazardous waste and desertification (particularly around the Aral Sea) (Asian Development Bank 2011). In Tajikistan, for example, there is a clear trend of moving out of rural areas in the period 1995–2003, with most educated employable people moving to cities, especially Dushanbe (Asian

**Table 5.6:** Central Asia: projected number of people facing multiple risks from climate change.

| COUNTY | NATIONAL POPULATION IN HOTSPOTS (%) | 2000 | 2020 | 2030 | 2050 | % CHANGE OF POPULATION IN HOTSPOTS 2000–2050 (%) |
|---|---|---|---|---|---|---|
| | | PEOPLE (MILLIONS) | | | | |
| Kazakhstan | 32.1 | 5.3 | 5.4 | 5.5 | 5.6 | 6.5 |
| Kyrgyz Republic | 99.9 | 5.0 | 6.0 | 6.3 | 6.6 | 31.3 |
| Tajikistan | 100.0 | 6.1 | 8.3 | 9.4 | 10.8 | 77.2 |
| Turkmenistan | 80.9 | 3.9 | 4.7 | 5.1 | 5.5 | 41.3 |
| Uzbekistan | 100.0 | 24.7 | 32.4 | 35.2 | 38.3 | 55.4 |

Source: Asian Development Bank (2011), page 52.

Development Bank 2011; Khakimov and Mahmadbekov 2009). This is expected to be driven by worsening agricultural conditions in the southern latitudes and improving conditions in the north, but it is unclear whether this push from southern rural areas and the pull into northern areas will translate into rural to rural migration, or will be associated with rural to urban migration into cities in the north (Lutz 2010).

According to a study by the World Bank, ISDR and CAREC under the Central Asia and Caucasus Disaster Risk Management Initiative (CAC DRMI), the urban population as a percentage of the total is expected to remain roughly constant for most countries until 2015, with the exception of Turkmenistan and Kazakhstan, where these figures are expected to increase (World Bank et al. 2012). However, between 2015 and 2020 the figures for Central Asia are expected to start increasing again, up to a rate of around 6 percent a year by 2050. Therefore, taking the overall growth patterns into account, the total urban population is expected to increase by 10 million by 2025 and by 27 million by 2050. Such an increase in the number of people living in urban areas will significantly impact the levels of vulnerability associated with high population concentrations, especially in case of disasters (World Bank et al. 2012). In fact, because urban areas have higher population densities, more concentrated infrastructure, and are key contributors to economic growth, the consequences of a catastrophic event there will generally be greater than in rural areas (World Bank et al. 2012).

#### *5.4.5.3 Other Consequences of Climate-Induced Migration*

The adverse effects of climate change will be felt most acutely by those parts of the population that are already more vulnerable owing to their gender, age, and disability. Moreover, climate change is likely to compound existing food security issues and impact heavily upon those dependent on the agricultural economy. Its distributional effects, therefore, are more likely to fall upon those involved in rain-fed subsistence agriculture or pastoralism (Government of the Republic of Tajikistan 2011).

In Tajikistan, for example, women and children, who constitute the majority of the country's poor, are especially vulnerable to the impacts of climate change as they are often charged with the responsibility to secure water, food, and fuel for cooking and heating.

According to a Climate Risk Assessment (CRA) study conducted by Camp Alatoo in the Kyrgyz Republic in 2013, the country's female population is likely to experience higher climate change risks and vulnerabilities in several situations. Women in the Talas, Chui, Naryn, and Issyk-Kul Oblasts were less impacted by landslides, but suffered more in cases of snowfall and other natural events, as well as from the impacts of climate change on crop production (Camp Alatoo 2013).

#### *5.4.5.4 Synthesis*

Projected climatic changes related to temperatures and water availability, together with an increased risk of climate extremes, will contribute to increased mobility in the ECA region. The exact migration patterns are difficult to estimate due to low data availability as well as due to the fact that the decision to migrate is usually an outcome of several processes that might be related to bio-physical environmental changes but might also be strongly influenced by the social and political context.

The projected increase in the intensity and frequency of extreme events in the ECA region is likely to lead to migration. In Central Asia almost all of the population lives in climate change hot-spot areas and the population of these areas is expected to increase in the future. In general terms, climate change may contribute to a revival of internal migration movements in Central Asia, as well as from Central Asia to Russia. Due to the projected increased urbanization, the vulnerability of cities to extreme events might rise, together with the increasing population and the concentration of infrastructure.

The adverse effects of climate change will be borne by those who are already more vulnerable: women, children and older people, disabled people, urban poor, as well as those that are dependent on rain-fed agricultural production or pastoralism. Furthermore, population movements could generate friction in politically sensitive countries such as Albania, Bosnia and Herzegovina, and Kosovo.

### 5.4.6 Russia's Forests: A Potential Tipping Point?

The forests of Russia cover 882 million ha (FAO 2012b). They have a growing stock of 79,977,200,000 $m^3$ and are of crucial relevance for the regional and global timber supply, despite the fact that only half of the annual wood increment is actually available for use (FAO 2012b).

The boreal region in Russia is characterized by markedly greater shifts to warmer temperatures and altered precipitation patterns than the global mean. In a 4°C world, for example, local temperature increases in Russian boreal forests are projected to be almost twice as high as globally (see Section 5.3.1, Projected Temperature Changes). Anthropogenic climate change is altering the Russian forest ecosystems and interacting with other changes (e.g., the abandonment of agricultural lands). This threatens the provision of such ecosystem services as carbon storage and timber production. Moreover, there is a risk that the boreal forest may cross a tipping point and shift to an alternative state (Lenton et al. 2008; Scheffer et al. 2012).

Physiological responses to changes in climate depend strongly on the limiting factors of forest growth, in particular low summer temperatures and nitrogen availability. Multiple interacting factors such as drought and heat stress, together with a changing background climate, could lead to forest diseases or insect pest outbreaks—and to increased tree mortality. If, as a response to climate change, tree mortality continues to increase more rapidly than growth, and if the permafrost is melting, the carbon balance may be substantially altered. This is significant because Russian boreal ecosystems store a massive amount of carbon, especially in soils, permafrost regions, and wetlands (Tarnocai et al. 2009). In addition, Russian forests store about 26.25 billion tons of carbon in aboveground biomass (FAO 2012b). Sharmina et al. (2013) reviewed the Russian-language climate change impact literature and found that the key climate change impacts expected to affect forest ecosystems are changes in vegetation zones, more frequent and intensive wildfires, and terrestrial $CO_2$ fertilization.

The sensitivity of the vast Russian forests to warming has significant implications for the climate system as a result of the biosphere-atmosphere exchange of water, carbon, and energy. The two dominant feedbacks are changes in carbon cycling and changes in reflectance and energy exchange (albedo) that result from the loss or gain of evergreen coniferous vegetation at high latitudes (Betts 2000; Bonan 2008; O'Halloran et al. 2012). Russian boreal ecosystems contribute strongly to the northern terrestrial carbon sink, and are estimated to represent around half of the terrestrial global sink, which was estimated at 1.3 $\pm 0.15$ PgC per year between 2000–2009 (Dolman et al. 2012; Schaphoff et al. 2013). This estimate takes into consideration emissions from land use change.

Global warming has the potential to reduce the carbon sink capacity of the boreal zone (Koven et al. 2011; Schaphoff et al. 2013). For Eurasia, climate change in interaction with vegetation shifts and fires has the potential to turn the Eurasian carbon sink into a source in a 4°C world (Kicklighter et al. 2014). In a 1.5°C world, Eurasia would remain a small carbon sink (Kicklighter et al. 2014). Observations suggest that increased temperatures could stimulate photosynthesis (Magnani et al. 2007; Myneni et al. 1997, 2001). Warszawski et al. (2013) and Ostberg et al. (2013) found that across a range of Global Vegetation Model and GCM projections the boreal forests are at particular risk of biosphere changes, including changes in the type and distribution of vegetation, carbon pool changes, and carbon and water flux changes. In combination, these changes would alter the biosphere-climate interactions.

#### *5.4.6.1 Observed Changes in Forest Productivity*

Forest growth in the northern latitudes depends on a variety of climatic and non-climatic factors. Increased radiation and atmospheric $CO_2$ concentrations as well as temperature increases leading to a lengthening of the growing season have stimulated forest growth (Berner et al. 2013; Ichii et al. 2013; Myneni et al. 1997). Berner et al. (2013) stressed that, in addition to temperature, water availability and the seasonality of precipitation also affect growth. Increased precipitation has promoted vegetation greening in some regions (Ichii et al. 2013). If water availability is sufficient, future warming could promote plant growth and forest expansion along the Russian arctic tree line (Berner et al. 2013; Devi et al. 2008; MacDonald et al. 2008). At the same time, water stress, forest fires, insect pests, and diseases have led to increased tree mortality—counteracting forest growth stimulation. Tchebakova et al. (2009) suggested that growth depends on water availability and, in the case of larch forests, on other factors potentially related to permafrost dynamics and wildfires.

Recent analyses of Normalized Differenced Vegetation Index (NDVI) data, used as a proxy for terrestrial gross primary production, explored the spatial and temporal variability of greening and browning patterns in the boreal zone (Beck et al. 2011; Bunn and Goetz 2006; Goetz et al. 2007; de Jong et al. 2011). Here, the positive trend of seasonal photosynthetic activity is mostly confined to tundra ecosystems; a number of boreal forests in the continental interior showed a negative trend (especially after 1990). Furthermore, studies of tree rings have identified complex patterns of tree growth in response to climate variability (Lloyd and Bunn 2007). Kharuk et al. (2006) found that the radial increment of larch depends strongly on summer temperatures and the amount of precipitation in both summer and winter.

##### Productivity Decline

Continuing warming may offset the benefits of an earlier spring onset and a delayed end of the growing season. Browning trends are shown to occur predominantly in the interior of the forest in late summer, despite positive trends in photosynthetic activity at the beginning of the vegetation period (Bunn and Goetz 2006). Productivity declines in the boreal forests of the continental interior appear to be related to warming-induced drought stress (Barber et al. 2000; Dulamsuren et al. 2013; McDowell 2011). Browning is associated with already-warmer areas (Berner et al. 2013). Many trees exhibited a general downward trend in basal area increment after the mid-20th century (Berner et al. 2013). Lloyd and Bunn (2007) pointed out that the highest frequency of browning occurs in the most recent time period during which greening occurs at the lowest frequency. Kharuk et al. (2013) suggest that soil moisture stress is the main factor in forest mortality in the eastern Kuznetzky Alatau Mountains of South Siberia. They found that most Siberian pine mortality was detected on steep slopes; birch and aspen trees in the same area did not, however, show drought stress. Siberian pine is an important forest species in the region and its decline has great significance for forestry.

##### Productivity Increase

Warming has increased net primary production (NPP) north of 47.5° over the past decade (2000–2009) in spite of a concurrent drying trend (Zhao and Running 2010). However, over the Siberian forest this increase was heterogeneous with an extensive negative trend over the western part (Zhao and Running 2010). A satellite imagery-based study by Jeong et al. (2011) observed an earlier onset and a delayed end of the growing season in Eurasia. The authors estimated that from 1982–1999 the growing season increased by more than 0.8 days per year in accordance with a significant warming of more than 0.25°C per year. An evaluation of satellite remote sensing data shows positive greening trends in the transition zone to tundra and wetlands during the summertime growing season since the 1990s (Beck and Goetz 2012; Bunn and Goetz 2006). Similarly, Lloyd et al. (2011) proved that warming has a more positive effect in the northern sites. Greening is more often observed in colder areas, and it was most evident in areas of low tree cover (Berner et al. 2013). Therefore, the positive trend in Normalized Difference Vegetation Index data might reflect enhanced understory growth rather than higher tree growth (Berner et al. 2011); it might also indicate a changing allocation pattern from woody parts to green plant material (Lapenis et al. 2005).

#### 5.4.6.2 Observed Forest Cover Changes and Vegetation Redistribution

Russia showed the highest forest cover loss globally from 2000–2012 (Hansen et al. 2013). Fires and subsequent recovery in Russian forests also led to large gains in forest cover over the same period; due to the slow regrowth dynamics, however, the gains typically occurred in different areas than the losses (Hansen et al. 2013). By analyzing Landsat remote-sensing data, Kharuk et al. (2006) estimated an increase in the density of larch forests of about 65 percent and an advancement of the northern treeline by 90–300 m over the period 1973–2000. Devi et al. (2008) reported an altitudinal expansion into the formerly tree-free tundra during the last century of about 20–60 m in altitude, as well as increasing tree ages and high sapling densities. At the trailing end of forest distribution, Kharuk et al. (2013) described a decline in Russian birch stands in the southeastern Siberian forest-steppe.

Vegetation redistribution affects species composition and forest structure and may also lead to biodiversity loss. Evidence from warming experiments suggests that climate change may cause a decline in biodiversity in the tundra, as warming promotes increased height and cover of deciduous shrubs and graminoids and, consequently, a decrease in mosses and lichens (and, ultimately, less species diversity) (Walker et al. 2006). An invasion of southern conifers was also reported in the zone of larch dominance (Kharuk et al. 2006).

#### 5.4.6.3 Observed Carbon Budget, Carbon Balance, and Permafrost

The forests of Russia are of great importance for the global carbon cycle. The greenhouse gas inventory approach of Pan et al. (2011) estimated a carbon sink of 0.26 PgC per year in Asian boreal forests from 1990–2010 (and 0.15 PgC per year in the 1990s and 0.20 PgC per year overall in the last century). Myneni et al. (2001) found a contribution of more than 40 percent to the Northern carbon sink in 1995–1999. Pan et al. (2011) found that Russian forests stored 34.9 PgC in live biomass in 1990 and 37.5 PgC in 2007. Thurner et al. (2013) estimated about 32 PgC per year in 2010 using modified forest inventory data and including remote sensing data. Shvidenko and Nilsson (2002, 2003) found carbon balance estimates for 1961–1998 based on forest inventories that indicated a large carbon sink ranging from 180–322 TgC per year. Dolman et al. (2012) estimated a carbon sink of 653 TgC per year from 1998–2008 that implies a substantial increase of the Russian boreal sink in the last 15 years. Tarnocai et al. (2009) have reported 331 PgC in permafrost areas of Eurasia in the first meter and another 162.8 PgC in peats. Schepaschenko et al. (2013) estimated similar amounts of soil carbon in Russia; they differentiated Asian (189 PgC) and European (42 PgC) forest areas and excluded the tundra. The large range in reported values here depends on whether vegetation and soil carbon are considered or just vegetation carbon as well as whether or not disturbances are taken into account (Balshi et al. 2007).

Northern latitude areas have a high potential to become carbon sources. Balshi et al. (2007) found conflicting estimates of mean annual changes in carbon storage for Eurasia north of 45°N for the period 1996–2002. Using a process-based ecosystem model, they simulated either a sink of 280.2 TgC per year with $CO_2$ fertilization or a source of 29.4 TgC per year without $CO_2$ fertilization.

Changes in permafrost dynamics, soil-vegetation carbon dynamics, and vegetation distribution could cause long-term changes in the biosphere at high latitudes. These could also have a large impact on the climate system. Permafrost thawing is most pronounced within the discontinuous permafrost zone but is also reported in the continuous permafrost zone (Romanovsky et al. 2010).

#### 5.4.6.4 Observed Disturbances

Disturbances play an important role in Russian forests. Fire is the single most important forest disturbance, but a larger area is also affected by various pests and diseases (FAO 2012b).

##### Pests and Diseases

About 13 million ha of East Siberian forest area, representing a loss of 2 billion m³ of growing stock, are believed to have been destroyed by the Siberian silk moth from 1880–1969 (Shvidenko et al. 2013). A single outbreak in 2001 affected an area of almost 10 million ha in a larch forest that had been thus far unaffected (Shvidenko et al. 2013). The area affected by biogenic agents in Russian forests is increasing from an average of 2.73 million ha during 1973–1987 to 5.48 million ha during 1998–2010 (Shvidenko et al. 2013). The study also pointed out that a warmer and drier climate would induce large-scale outbreaks.

Projected climate changes in the boreal zone could increase the frequency and intensity of pest outbreaks. Studies of the Canadian boreal forest show that insect disturbances can turn the forest from a carbon sink into a carbon source (Kurz et al. 2008). It is important to note that there are considerably more studies on the effects of forest fires than on pests and diseases. What is clear, however, is that climate change will lead to northward shifts, longer summer seasons, and warmer temperatures for the growth and reproduction of forest insects (Bale et al. 2002).

### Fire

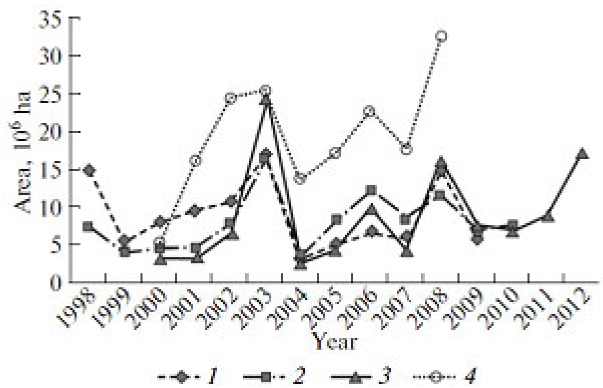
The uncertainty regarding the amount of carbon released through fires is large, and estimates from several studies compiled by Balshi et al. (2007) range from 58 TgC per year up to 520 TgC per year for boreal Russia/Siberia for different time periods within 1971–2002. A large part of the uncertainty relates to how burn severity is accounted for (Balshi et al. 2007). An estimated 59.3 percent of vegetation fires occurred in forest areas and accounted for about 82 TgC per year of emissions on average during 1998–2010 (Shvidenko et al. 2012). A later study (Shvidenko and Schepaschenko 2013) estimated the total amount of carbon burnt in 1998–2010 at 121 ± 28 TgC per year, with 76 percent (i.e., 92 ± 18 TgC per year) occurring on forest lands. Shvidenko and Schepaschenko (2013) also stressed that post-fire dieback is uncertain and may amount to 90–100 TgC per year.

Shvidenko and Schepaschenko (2013) highlighted that the types of fires have been changing, with a 1.5–2 times higher share of crown and underground fires seen of late. They found that the forest area affected by fires for 1998–2010 is 8.2 million ha per year (or 9.2 million ha per year using data from a global dataset); for 2000–2010, that number is 8.5 million ha per year. Soja et al. (2007) pointed out that 22 percent of the annual burned area is made up of severe crown fires with strong impacts on forest productivity and carbon pools (Chertov et al. 2013), and that, in severe crown fires make up 50 percent of all fires in extreme fire years. Soja et al. (2007) found an increase in fire severity during the years 1998–2006, which can be connected to warmer conditions. In addition, the area burnt in the 1990s is 29 percent greater than in the 1980s and 19 percent more than reported for a 47-year mean (Soja et al. 2007). More recent analysis of both forest statistics and remote sensing data reveal that, despite large variability, the area affected by fire seems to increase, as shown in Figure 5.19 (Shvidenko and Schepaschenko 2013).

There are important feedbacks between fire and climate. Randerson et al. (2006) found that the long-term effects of boreal forest fires on climate warming are uncertain since positive feedbacks (enhancing warming) from increasing greenhouse gas emissions may be offset by changes in surface albedo (decreasing warming due to loss of canopy and more snow exposure).

It is important to note that forest fires are also affected by socioeconomic changes. Ivanova et al. (2010) have shown that extant climate change in combination with socioeconomic changes (e.g., reduced firefighting funds) has resulted in an increase in fire intensity and area burned (but not fire frequency) in the Tuva region in southern Siberia. Moreover, Isaev and Korovin (2014) highlighted that the large forest fires that occurred in 2010 were due not only to unusual meteorological conditions but also to poor forest governance and management and an increasing area of abandoned farmlands leading to declining numbers of forest managers, forest firefighters, and less-efficient forest protection systems. Similarly, Flannigan et al. (2009) noted that, since the breakdown of the Soviet system, the effectiveness of the Russian firefighting system has decreased—which has led to larger areas being burned.

**Figure 5.19:** Dynamics of total area of wildfires in Russia's forests according to (1) GFDE3 (global fire emissions database); (2) refined data provided by the Institute of Forest, Russian Academy of Sciences; (3) Space Research Institute, Russian Academy of Sciences; and (4) Vivchar et al. (2010).



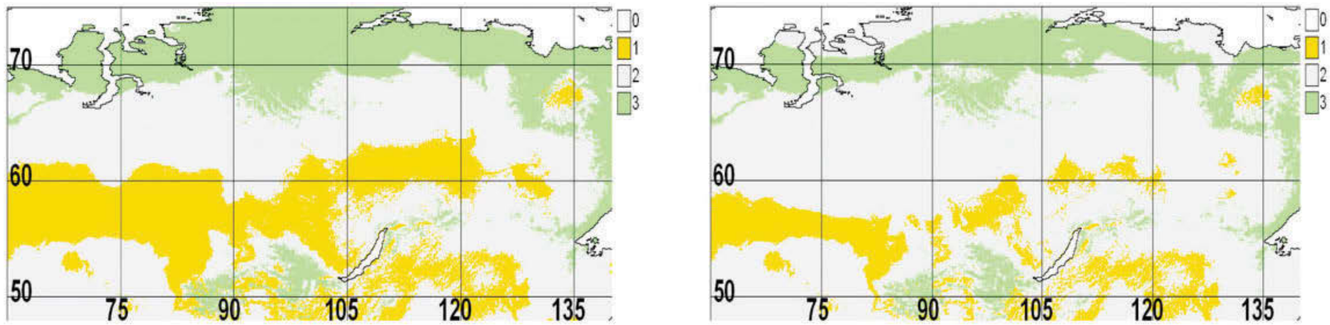

Source: Shvidenko and Schepaschenko (2013), Figure 1.

### 5.4.6.5 Projections of Vegetation Redistribution, Forest Productivity, and Carbon Budget Changes

While climate change is expected to have a great impact on vegetation distribution, changes in vegetation distribution also feed back onto the climate. Enhanced warming of the dark forest (as compared to other vegetation) results in an elevated sensible heat flux. Northward movement of the boreal forest, with its relatively low albedo and the resulting replacement of higher albedo tundra, can cause a significant increase in regional and global temperatures (Foley et al. 2003). This climate forcing could have an effect of 25.9 W per $m^2$ (Chapin et al. 2005). Such a shift could also increase carbon storage by the same magnitude (Field et al. 2007).

For the whole of the Eurasian continent, Kicklighter et al. (2014) projected that biomes will shift northward as a consequence of climate change, with boreal forest encroaching into the northern tundra zone, temperate forests encroaching into the present boreal zone, and steppes encroaching into temperate forests. In a 4°C world, this would result in a reduction in the boreal forest area of 19 percent and an increase in the temperate forest area of 258 percent; in a 1.5°C world, boreal forest area would decrease by 2 percent and temperate forest area increase by 140 percent.

**Figure 5.20:** Vegetation distribution in Siberia in 2080 from HadCM3 A1FI (leading to a 4°C world) and B1 (leading to a 3°C world) climate change scenarios.




Simulated hotspots of forest-to-steppe change (1—yellow), tundra-to-forest change (3—green), and no change in major vegetation classes (2—light gray; 0—water) in 2080. Source: Tchebakova et al. (2009).

This would lead to a 7 percent net gain in forest in a 4°C world, and a 12 percent gain in a 1.5°C world (Kicklighter et al. 2014).

Several studies using a bioclimatic model also suggest that vegetation zones will shift northward under climate change (Tchebakova et al. 2009, 2011; Tchebakova and Parfenova 2012). Tchebakova et al. (2009) showed that, for Siberia, changes in vegetation will start as early as the 2020s under all climate change scenarios. Vegetation shifts are projected to remain moderate in a 3°C world, but are expected to be substantial in a 4°C world (see Figure 5.20). Forest-steppe and steppe ecosystems are even predicted to become dominant across large areas of the Siberian tundra (Schaphoff et al. 2006; Tchebakova et al. 2009).

Study results from eastern Eurasia suggest that only a small range of climate change (with warming of no more than 2°C) is tolerable in order to maintain current forest structure and biomass, (Shuman et al. 2011; Tchebakova et al. 2009; Zhang et al. 2009b, 2011). Above this level of warming, potential changes include permafrost-thaw and changes in forest structure whereby broad-leaved deciduous trees could increase their spread over Eastern Eurasia and coniferous area could decrease (Lucht et al. 2006; Schaphoff et al. 2013; Zhang et al. 2009b). In a study of larch forests in the region, Zhang et al. (2011a) found that such forests could not be sustained under warming of more than 2°C.

For a forest area in the Kostroma region 450 km northeast of Moscow, Shanin et al. (2011) projected an increase in carbon stock in trees from 125 tons per ha to 150 tons per ha in a 4°C world; this implies strong regional warming of 7.2°C by 2100. The productivity of the stands was projected to increase as well due to the enhanced availability of nitrogen in the soil. However, soil and deadwood carbon stocks were projected to decrease under this climate change scenario (98–99 tons per ha without climate change vs. 33–35 tons per ha with climate change). It is important to note that several key climate change effects, including heat stress and $CO_2$ fertilization, were not considered in this study. Furthermore, in those simulations that included the effect of fire, the climate-change-induced increase in carbon stock was offset by higher intensity fires (Shanin et al. 2011).

Permafrost is projected to be highly vulnerable to warming, and thawing is projected to be very pronounced (Koven et al. 2011; Schaefer et al. 2011; Schaphoff et al. 2013)—but how exactly carbon stocks will be affected is still uncertain. Koven et al. (2011) and Schaphoff et al. (2013) stressed that enhanced plant productivity could increase biomass input at different soil depths which can balance out carbon release due to permafrost thawing until the late 21st century. This depends strongly, however, on the warming level. Schaefer et al. (2011) estimated a carbon stock loss of 190 ± PgC by 2200. Anisimov (2007) estimated that methane emissions from melting permafrost might increase by 20–30 percent with a global mean temperature rise of 2°C, congruent with an enhanced permafrost thawing rate of 10–15 percent over Russia for the mid-21st century. These fluxes mostly originate in the West Siberian wetlands.

Anisimov and Reneva (2006) highlighted the risk to engineered structures in regions affected by permafrost thawing. They projected a reduction in the permafrost area, down to 76–81 percent of the present day value by 2080. Furthermore, Schaphoff et al. (2013) and Schaefer et al. (2011) showed that, due to inertia in the climate system, carbon release from permafrost thawing will continue even if warming ceases.

Projections of carbon stock changes in the boreal forest ecosystems under climate change are generally uncertain. Simulations show that, as a result of vegetation shifts, the potential carbon gains from the expansion of boreal forests in the north are likely to be offset by losses in the south (Friend et al. 2014; Schaphoff et al. 2013). Furthermore, increases in tree growth from climate warming may be limited by decreased soil fertility in northern and eastern regions (Lawrence et al. 2005). In addition, model projections of forest ecosystem change in response to anthropogenic climate changes are dominated by plant physiological $CO_2$ effects (Friend et al. 2014). Moreover, the stability of ecosystems in response to such extreme events as flooding and drought is unpredictable (Bale et al. 2002). The interplay of disturbances (e.g. fire) and vegetation shifts, as well as the effects of climatic feedbacks, determine the future of the carbon stored in and the goods and services provided by boreal forests.

#### 5.4.6.6 Future Impacts on Timber Harvesting

The FAO Forest Sector Outlook Study (FAO 2012b) does not project any radical changes in Russian forests in the next 10–20 years due to climate change, but does highlight the potential for substantial impacts beyond 2030. Lutz et al. (2013b) used a forest gap model to project that, under local warming of 2°C in 2100, larch and pine forests are expected to have higher productivity and subsequent timber harvests than under the baseline climate scenario. When changing from a 2°C to a 4°C local warming scenario, however, productivity levels compared to the baseline were mostly negative (with the exception of larch forests in central Russia). Modeled spruce and fir forests showed small or negative responses to 2°C local warming; their response to 4°C local warming was consistently negative. The deciduous and more species-rich forests of the kind found in northwestern and far eastern Russia showed a projected decrease in productivity under 2°C local warming and increasing productivity and harvests under 4°C. This counterintuitive response pattern was induced by changes in the dominant species toward more heat tolerant species and constitutes a substantial shift in forest composition and forest resources. The analysis of Lutz et al. (2013b) also showed that although harvests are still profitable under 4°C local warming, this is partly due to an increased harvest in the first 50 simulation years (2010–2060) that compensates for strong declines thereafter. Moreover, the study did not include the effects of disturbances (e.g., insects or fire). The exclusion of fire may explain the somewhat contradictory results regarding increasing larch productivity (Lutz et al. 2013b) and decreasing larch productivity (Zhang et al. 2011a).

#### 5.4.6.7 Projections of Disturbances

Due to a lack of studies exploring the correlation between climate change and forest pests and diseases, this section focuses on the future risk from fire. In general, higher temperatures lead to drier fuels and hence higher fire risk (Flannigan et al. 2009). Stocks et al. (1998) projected an earlier start to and later end of the fire season as well as larger areas affected by higher fire danger in a doubled $CO_2$ scenario with 4 GCMs. Similarly, Malevsky-Malevich et al. (2008) found that the area of maximum fire risk doubles by the middle of the century and that the number of days with moderate to high fire risk increases by up to 12 days in a 3°C world. Mokhov et al. (2006) projected that, under the B2 scenario (implying a moderate global warming), fire hazard will increase in the southern latitudes and the northwestern areas of European Russia and decrease in much of the rest of Russia. The decrease in fire hazard in their projections can be explained by increasing precipitation and minor summer warming in the climate model and scenario used; the increasing fire risk is associated with precipitation decreases.

It is important to note that these studies are based on an analysis of climatic data only and do not consider current or future forest composition and structure nor interacting disturbance regimes. Shvidenko and Schepaschenko (2013) argued that a more thorough integration of such factors might show that Russian forest cover changes even more strongly. Tchebakova et al. (2009) projected an increase of an average of 10 days and 20–30 days in the annual number of high fire danger days in a 3°C and 4°C world, respectively (see Figure 5.21). They explicitly considered fire risk within a bioclimatic vegetation model and showed that climate-change-induced forest-to-steppe transitions interact with fire activity and promote the risks of large fires, especially in southern Siberia and Central Yakutia.

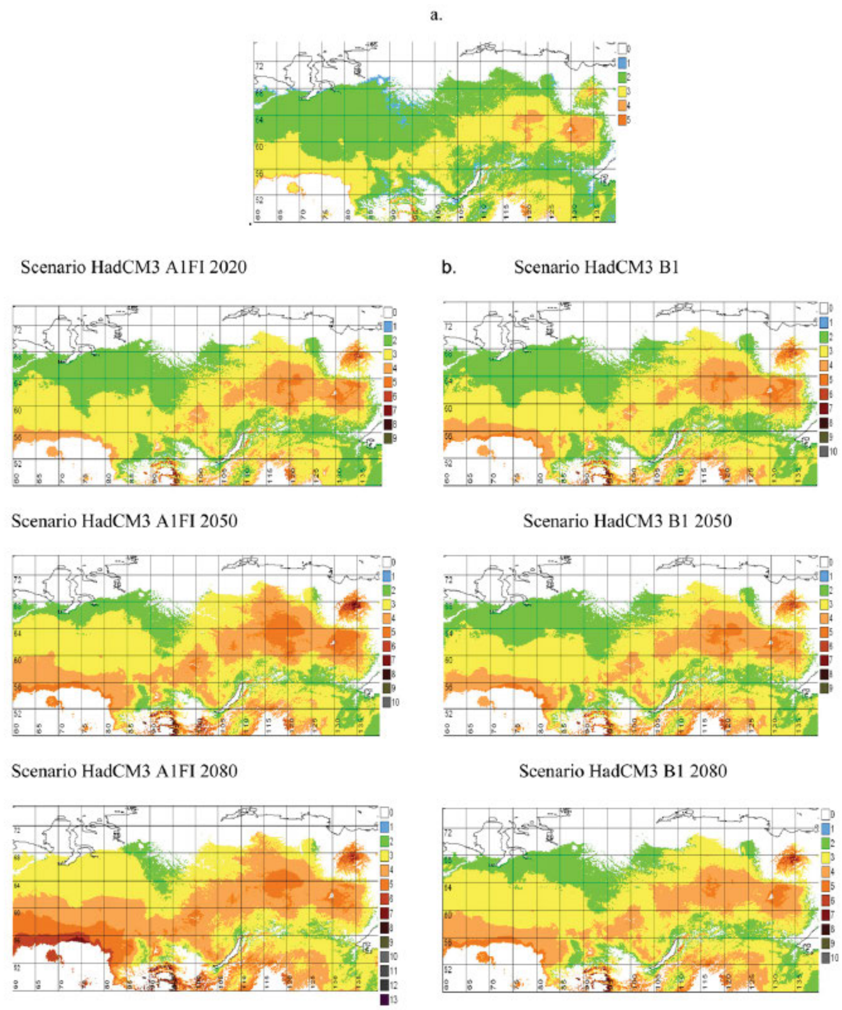
#### 5.4.6.8 Risk of a Boreal Forest Tipping Point

Lenton et al. (2008) identified the boreal forest as a tipping element in the Earth system. They argued that, under an estimated 3–5°C of global warming, water and peak summer heat stress leading to tree mortality, to increased vulnerability to diseases and fire, and to decreased reproduction rates could lead to a large-scale forest dieback and a transition to open woodlands or grasslands. Analyzing satellite data, Scheffer et al. (2012) suggested that the only possible ecosystem state at the northern edge and at the dry continental southern edge are treeless tundra and steppe. Their study also found a broad intermediate temperature range where treeless ecosystems states coexist with boreal forest (about 75 percent tree cover). Tree covers of 10 percent, 30 percent, and 60 percent are relatively rare. Scheffer et al. (2012) therefore suggest that these may represent unstable states. Such sparse tree cover occurs especially in continental permafrost-affected areas and on saturated soils. Scheffer et al. (2012) suggest that boreal forest may be less resilient than assumed (and thus potentially shift into a sparse woodland or treeless state) while tundra may shift abruptly to a more abundant tree cover state. The mechanisms which could explain such unstable states are not clear, however, and uncertainty surrounding these findings is high.

#### 5.4.6.9 Synthesis

Russia's forests cover a large area and provide important ecosystem services. Besides supplying timber, they store huge amounts of carbon in soil and vegetation. The evidence for a tipping point of the boreal forest is unclear; already, however, under current conditions

**Figure 5.21:** Modeled distributions of annual number of high fire danger days across Siberia in the current climate (a) and during the 21st century (b) for HadCM3 A1FI and B1 climate change scenarios.




Fire danger days key: 0—non-forest area; 1—<30 days; 2—40 days; 3—50 days; 4—60 days; 5—70 days; 6—80 days; 7—90 days; 8—100 days; 9—110 days; 10—120 days; and 11—>120 days. Source: Tchebakova et al. (2009), Figure 4.

the impacts of disturbances such as fire and pest outbreaks are substantial—and projected climate change impacts could be both large-scale and disastrous. Future projections highlight changes in productivity, vegetation distribution, and composition that will typically be stronger in a 4°C world than in a 2°C world—often in non-linear ways.

It is important to also highlight that change in species composition toward better adapted tree species may buffer productivity losses, although they will also lead to a strong change in the forest landscape and associated uses. Projected climate change may also induce an increase in fire danger and fire intensity. Defoliators and other pests and diseases could be stimulated by a warmer and drier climate.

Transition zones, from forest to steppe, are very vulnerable to climate change; in particular, increases in atmospheric water demand could lead to water stress and higher tree mortality. Increased occurrences of disturbances could also affect vegetation distribution in transition zones.

The impacts of climate change are often overlaid with other environmental and societal changes; this could exacerbate both existing and projected challenges. These changes may strongly affect local, regional, and global forest resource availability, ecosystem functioning, services such as carbon storage and biodiversity support, and even feedback on the global climate system.

Russia also contains an extensive area of forested permafrost. Changes here are already among the largest and they could accelerate as a result of permafrost thawing. This has the potential to affect the hydrological regimes of vast territories beyond the changes in hydrology expected from precipitation changes alone, and could affect critical carbon, water, and energy fluxes. Forest dieback and thawing of permafrost threaten to amplify global warming as stored carbon and methane are released into the atmosphere, giving rise to a self-amplifying feedback loop.

Finally, it is important to note that substantial research gaps exist, including the effect of disturbances on vegetation cover and how climate change will affect forest productivity under concomitant changes in growing conditions, disturbances, and forest management practices.

## 5.5 Regional Development Narratives

The report covers 12 countries located in the Europe and Central Asia region (ECA) that split into three sub-regions: Central Asia, Western Balkans, and Russia. The negative consequences for key development trends that may be triggered from such exposure to climatic changes that are described in the following development narratives. It is important to note that each development narratives presents only one of the many possible ways in which climate change can put key development trajectories at risk. Table 5.7 summarizes the key climate change impacts under different warming levels in the Europe and Central Asia region and Figure 5.22 summarizes the key sub-regional impacts.

### 5.5.1 Impacts on Water Resources in Central Asia Increase the Challenge of Accommodating Competing Water Demands for Agricultural Production and Hydropower Generation

The scientific basis for observed climate changes and their impacts in Central Asia is overall weak or lacking (Hijioka et al. 2014). However, as mentioned in Section 5.4.1, sub-regionally pronounced winter warming has been observed for Southern Siberia and the Tien Shan mountains, concurrent with glacier volume change by about a third from the beginning of the 20$^{th}$ century.

Five Central Asian countries (Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan) are particularly vulnerable to climate change compared to the other ECA countries (Fay et al. 2010). They face common climate challenges that affect such key resources and sectors as water, land, biodiversity and ecosystems, agriculture, energy, and health. Water resource systems in Central Asia are sensitive to climate change and variability, and climate impacts on water supplies will reverberate across the agricultural and energy sectors. Increasing temperatures are expected to increase both crop water requirements and evaporation and to reduce hydro-system storage through changes in snowpack, earlier snow melt, and glacial melt.

Expected glacier loss and reductions in snow pack pose serious threats to freshwater resources, which rely on water storage in ice and snow. Critically, as ice and snow melt earlier during the year due to rising temperatures, the timing of river flow is projected to shift within the next few decades. Peak flows are expected to shift from summer to spring, with adverse consequences for agricultural water demand during critical crop growing periods. Furthermore, an intensification of the runoff variability is expected in all river basins, increasing the risk of floods, mudslides, and droughts (Main Administration of Hydrometeorology 2009). These events already have considerable social impacts—for example, economic losses from individual mudslide events have been as high as $150 million, while over 7000 people have migrated from landslide zones in Kyrgyz Republic alone since 1992. Flooding in Tajikistan in 2005 led to notable reductions in agricultural production (e.g., 70 percent reductions in grain production and 95 percent reduction in grape production) with 71 percent of affected people stating that they had experienced a loss in income (Thurman 2011).

The impacts on water resources are distinctly different for the next few decades compared to the end of the century. In the coming decades, the contribution of melt water to river runoff is expected to increase and may lead to an increase in river runoff—increasingly high evaporation rates, however, are expected to counterbalance this effect (Davletkeldiev et al. 2009). By 2030, river runoff is expected either to remain unchanged or to increase slightly, even in the case of slightly higher precipitation rates (Main Administration of Hydrometeorology 2009). The picture changes in the second half of the century: by the end of the 21st century, runoff generation rates in the mountainous areas of Central Asia are likely to decline substantially (Main Administration of Hydrometeorology 2009).

Changes to natural water stocks are expected to severely affect irrigated agriculture. This impact will be compounded under conditions that further increase the water demands of crop production systems, as rising temperatures are expected to lead to an around 30 percent increase in potential evapotranspiration (see Section 5.3.5, Aridity). Increasing temperatures and water demand also affect rain-fed agriculture, which accounts for more than 90 percent of arable land in Kazakhstan (FAO-AQUASTAT 2012).

Uncertainties in precipitation projections translate into an uncertain future for rain-fed crop production in the region. Further, prolonged periods of above-average temperatures and heat extremes exacerbate the heat stress of agricultural crops, leading to decreased plant productivity and high climatic risks for the sector (Mannig et al. 2013; Teixeira et al. 2013). Such risks may limit a projected increase in agricultural areas or crop yields. In addition, rising temperatures and seasonally reduced water availability puts pressure on livestock directly and indirectly through limiting the regeneration potential of pastures.

Losses in agricultural productivity and employment opportunities would add pressure to the labor markets and challenge poverty reduction for affected population groups. They could further stimulate increased migration from affected areas to those with stronger economies, potentially following already established migration routes, such as from poorer areas of Central Asia to Russia, more locally to cities with better job opportunities (IOM 2011). Groups unable to migrate (older people, people with disabilities, in some cultural contexts, such as parts of Central Asia, women), are at greater risk of being trapped in poverty (Black et al. 2011) particularly if remittance flows are limited or unpredictable.

Further, decreased levels of agricultural production as well as lower levels of certainty over future yields are likely to contribute to an increase in food prices. Rising food prices may have severe effects on the Central Asian population since a large percentage of household income is spent on food; up to 80 percent in Uzbekistan and Tajikistan, and 58 percent in the Kyrgyz Republic (Bravi and Solbrandt, 2012). In addition, agricultural impacts in other large, food-producing regions, including Russia, can have negative repercussions on the Central Asian region as some countries (e.g., Tajikistan, Kyrgyz Republic, Uzbekistan, and Turkmenistan) are largely dependent on food imports and are exposed to fluctuations in food prices (Meyers et al. 2012; Peyrouse 2013).

A further risk to development stems from the energy sector, which relies on stable water supplies. Despite an expected decrease in heating loads during the winter (WorleyParsons 2012), overall energy demand is projected to rise together with population and economic growth (World Bank 2013s). Changes in climate, reduced snow accumulation, and accelerated melting of snow and glaciers increase uncertainty in the timing and amount of water available for power generation. Tajikistan and the Kyrgyz Republic, which are located upstream of the Syr Darya and Amu Darya, respectively, produce 98.8 percent and 93.3 percent of the total electricity consumed from hydropower (World Bank 2013p). Hydroelectricity can also play a major role in the future energy mix of the Central Asian countries, as only eight percent of the hydropower potential of the region has been developed (Granit et al. 2010).

Climate change impacts will result in high variability of inflows and a shift in the historical water flow patterns. Upstream countries would have to manage the impact of this change in their hydropower generation systems, which is the back bone of their electricity sector. The downstream countries would see increased demand from both the agriculture and energy generation sectors. Efficiency in water use for irrigation and for energy generation would be critical for managing this impact. Energy efficiency measures would help reduce growth in water demand for energy generation.

There are many opportunities to improve climate resilience in the region. Strengthening capacity and responsiveness of local and national disaster risk management institutions in the region could significantly boost resilience to rapid-onset effects of climate change, such as those related to more rapid spring snow-melt (UNISDR 2009). Upgrading of worn-out infrastructure and more effective poverty reduction and social protection are also priorities (Thurman 2011).

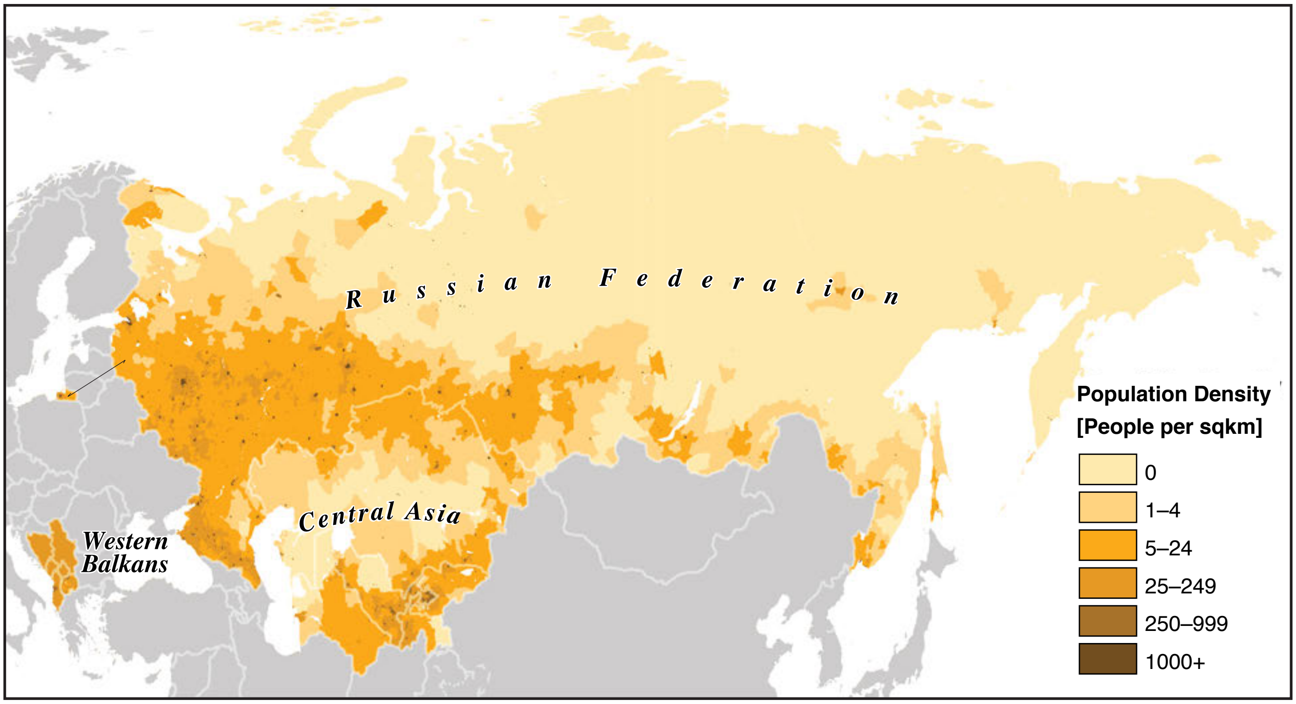
There is also room to improve water-saving irrigation techniques in the region. Approximately 87 percent of the region's extracted water is used in agriculture (FAO-AQUASTAT 2012), and in many Central Asian countries the water irrigation systems are inefficient. In Uzbekistan, for example, 70 percent of the irrigation water is lost between the river and the crop (Rakhmatullaev et al. 2012). Changes in reservoir management and the need to meet water requirements for agriculture can also have a negative impact on energy availability over the summer months (Siegfried et al. 2012).

### 5.5.2 Climate Extremes in the Western Balkans Pose Major Risks to Agricultural Systems, Energy and Human Health

For the Western Balkans, a pronounced drying trend is projected, concurrent with strongly rising temperatures and prevalence of heat extremes. Such changes pose high risks to agricultural productivity in the region. The majority of arable land in the Western Balkans is rain-fed and, therefore, highly vulnerable to changes in climatic conditions (UNDP 2014). In the Former Yugoslav Republic of Macedonia, 90 percent of the agricultural area is rain-fed; in Albania, irrigation agriculture is practiced on roughly 50 percent of arable land (World Bank 2010b, 2011c). The share of the working population of the Western Balkans that is employed in agriculture varies from 18 to 58 percent depending on the country, and agriculture is directly responsible for 17 percent of the region's GDP (Hughes 2012). Cereals and fruits (predominantly grapes) are the most important agricultural products in terms of production area and economic output, with Serbia being the biggest producer (Mizik 2010; Volk 2010).

The region is highly vulnerable to the effects of droughts, as the 2012 drought in Serbia illustrates. It led to yield declines of up to 50 percent and severe economic losses (Maslac 2012). Such events need to be expected to occur more often under climate change and absent preventive adaptation. In addition, pasture yields and grassland ecosystems for livestock grazing are expected to decline and change for large parts of Eastern Europe and the Western Balkans (Sutton et al. 2013a, b, c). Feed quality could also be negatively affected by changing climate conditions (Miraglia et al. 2009). Declines in fodder production

**Figure 5.22:** Sub-regional risks for development for Europe and Central Asia at 4°C warming in 2100 compared to pre-industrial temperatures.




**Western Balkans**

Increase in droughts, unusual heat extremes and flooding. High risks for agriculture, human health and stable hydropower generation.

*Risks for human health, food and energy security.*

**Central Asia**

Increasing glacial melt alters river runoff. Risks of glacial lake outbursts, flooding and seasonal water shortages. Increasing competition for water resources due to rising agricultural water demand and demand for energy production.

*Risks for poor through rising food prices particularly affecting women, children and the urban poor. Risks for human health due to spreading disease, heat waves and flooding.*

**Boreal Forests of the Russian Federation**

Unusual heat extremes and annual precipitation increase, rising risks of forest fires and spread of pests leading to tree mortality and decreasing forest productivity. Possible northward shift of treeline and changes in species composition. Risks of permafrost melt and methane release.

*Risk for timber production and ecosystem services, including carbon capture. Risks of substantial carbon and methane emissions.*

Data sources: Center for International Earth Science Information Network, Columbia University; United Nations Food and Agriculture Programme; and Centro Internacional de Agricultura Tropical—(2005). Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). This map was reproduced by the Map Design Unit of The World Bank. The boundaries, colors, denominations and any other information shown on this map do not imply, on the part of The World Bank Group, any judgment on the legal status of any territory, or any endorsement or acceptance of such boundaries.

could impact feed prices and potentially lead to greater price volatility (World Bank 2010b).

At the same time high vulnerability to flooding events exists. Despite large uncertainties about future precipitation extremes in the region high risks of riverine flooding are expected mostly due to more intense snow melt. The flood of 2014 illustrated the region's vulnerability to such events. The torrential rains led to floods and landslides, killing 51 people and rendering over 31,000 people temporarily homeless. According to health officials, the risk of disease outbreaks following the event was particularly high in overcrowded refugee centers and as people returned to their homes too early (Holt 2014). This flood came against the backdrop of slow-onset risks to human health as climatic conditions become increasingly suitable for vectors transmitting such diseases as dengue fever (Caminade et al. 2012). Flooding also poses high risks to agriculture, as evidenced by a 2010 event that caused damages of $450 million in Albania, Bosnia and Herzegovina, and FYR Macedonia (Hughes 2012).

A joint assessment report on the social impacts of the 2014 Floods in Serbia by the United Nations, World Bank and EU suggests that about 51,800 jobs were temporarily lost because of interruption of productive activities in the affected municipalities. Overall, the floods were estimated to reduce economic growth by 0.5 percent and to lead to a decrease in the balance of payments equivalent to 1 percent of GDP, with a further 1 percent loss related to lower tax revenue and post-disaster expenditure. Furthermore, the floods are estimated to have pushed 125,000 people below the poverty line, an increase of nearly 7 percent over the number of people living in poverty in 2013. This increase comprised not only people living close to the poverty line, but also a much better-off group that lost its productive capital as a result of the floods. The most affected people were typically those who faced specific challenges before the floods, such as access to employment, low security of tenure, and limited social support networks. About 12 percent of the 1.6 million people affected by the floods were in groups considered particularly vulnerable, such as Roma and people with disabilities. Many women were also doubly affected: in addition to sustaining livelihood losses, they have had to increase the non-paid time they devote to take care of their family (United Nations Serbia et al. 2014).

The 2014 flooding also led to a reported 40 percent cut in Serbia's electricity production and disrupted power supplies (Sito-Sucic 2014); this highlights the energy sector's vulnerability to climate impacts and extreme events. Changes in river water temperature and river flows can also impact on thermal electricity production and reduce the capacity of nuclear and fossil-fuelled power plants through changes in cooling water. Critically, reductions would be concurrent with an increase in energy-intensive cooling demand, which is projected to increase by 49 percent (Isaac and van Vuuren 2009).

### 5.5.3 Responses of Permafrost and the Boreal Forests of the Russian Federation to Climate Change Have Consequences for Timber Productivity and Global Carbon Stocks

Russia has the largest forest area in the world, representing 20 percent of the global forest area (FAO 2012b). Its forests store enormous amounts of carbon and deliver important ecosystem services, including through timber production. These services may be compromised or even lost under high levels of warming.

There is a risk that the boreal forest may cross a tipping point and shift to an alternative state (e.g., steppe grasslands) (Lenton et al. 2008; Scheffer et al. 2012). Moreover, the effects of biome shifts and damages from forest fires would not be confined to the region itself. Changes to carbon fluxes in response to rising temperatures and changing precipitation patterns, as well as interactions with disturbance regimes, would have far-reaching repercussions affecting the global carbon stock and planetary albedo across large parts of the northern hemisphere.

The boreal permafrost zones are a further potentially large source of greenhouse gases. Already, today, large formerly undisturbed permafrost zones are affected by thawing due to current warming (Romanovsky et al. 2010), leading to some subsidence of housing, disruption of infrastructure and affecting the livelihoods of indigenous minorities living in the Russian Arctic (Crate 2013). Future thawing is projected to be very pronounced.

Russian forests contributed 1.3 percent of GDP and 3.7 percent of industrial production in 2010 (FAO 2012b). The forestry sector employs one percent of Russia's population and produces 2.4 percent of export revenues (FAO 2012b). In 2010, 32 million $m^3$ of wood raw material was used for biofuels, and that number is expected to double by 2030 (FAO 2012b). Under future climate change the productivity of those forests might be at risk.

Climate projections for Russia show above-average temperature rise and an overall increase in annual precipitation. While fire outbreaks are often currently caused by anthropogenic factors rather than climate change, the risk of fire increases as higher temperatures increase the biomass potential of burning as it becomes drier (Flannigan et al. 2009). In the future, much larger areas will be exposed to forest fires (Stocks et al. 1998). The risk of fire is further enhanced by projected changes in vegetation distribution. If exposed to continuous water stress, the forest at lower latitudes may give way to steppe ecosystems if the $CO_2$ fertilization effect does not sufficiently compensate for this stress through enhanced efficiency of water use. This would likely promote larger fires, particularly in southern Siberia and Central Yakutia (Tchebakova et al. 2009).

While slow-onset changes in mean temperature and average precipitation will ultimately affect the broad patterns of future species distribution, the impacts of climate variability in terms of extremes is an important driver of tree responses and vulnerability to climate change (Reyer et al. 2013). Even under increased annual average precipitation, an increase in heat extremes may lead to strong ecosystem responses. Heat-stressed trees, for example, may be more susceptible to pest outbreaks. Such increased vulnerability would, in turn, interact with an expected but understudied expansion of areas at risk of pest outbreaks (Bale et al. 2002). In combination, these stressors could lead to increasing risks for neighboring forest stands or even a threshold behavior whereby ecosystems shift into an alternate state (Lenton et al. 2008).

Different responses and vulnerabilities of tree species to climate change could result in altered forest compositions. There are indications, however, that the largest effects on forest composition and fragmentation are due to timber harvesting (Gustafson et al. 2010). In line with this, Isaev and Korovin (2014) highlighted that the large 2010 forest fire was due not only to unusual meteorological conditions but also to poor forest governance and management—and to an increasing area of abandoned farmlands leading to declining numbers of forest managers, firefighters, and overall less efficient forest protection systems. Similarly, Flannigan et al. (2009) highlighted that, since the breakdown of the Soviet system, the effectiveness of the Russian firefighting system has decreased; this has led to larger areas being burned. Similarly, a weakening of regulatory capacities has facilitated illegal and unsustainable logging practices (Vandergert and Newell 2003) that are likely to undermine the forest's resilience to climatic stresses. For example, if logging is done in an unsustainable manner and high amounts of dead or damaged trees are left in the forest, decaying trees may trigger pest outbreaks and increase the risk of forest fires. Such negative ecosystem impacts might also undermine the livelihoods of groups dependent on the forest for timber and non-wood forest products (e.g. berries, mushrooms, medicinal plants), traditional agriculture and hunting (FAO, 2014d). It is thus the interaction of climate changes, disturbances, and unsustainable forest management and governance that will drive the vulnerability of forests, and people whose lives and livelihoods depend on them, to climate-change-related stresses.

Climate-related effects on forest productivity can lead to both an increase and a decrease in productivity. For now, it remains uncertain at what $CO_2$ concentration and temperature increase a reversal from sink to source would occur. However, if such a reversal were to occur it would affect the global carbon budget and thereby regions well beyond Russia itself.

The sustainable and farsighted management of Russian ecosystems is of global importance. If pushed beyond tolerance limits and into positive feedback mechanisms with regional and global warming, major carbon and methane stocks in the boreal forests and permafrost zones may be released into the atmosphere. Critically, carbon release would continue even if warming ceased (Schaefer et al. 2011; Schaphoff et al. 2013). Even without such threshold effects, southern boreal carbon loss as a result of ecosystem shifts is likely to offset carbon gains from potential northern boreal forest expansion (Friend et al. 2014; Schaphoff et al. 2013). Given the large uncertainties in the overall response of Russian forests to effects such as future pest outbreaks and heat stress, management practices need to be deployed that foster the resilience of forests in order both to minimize the risks for those who depend on them and to support global climate protection.

## 5.6 Synthesis Table—Europe Central Asia

**Table 5.7:** Synthesis table of climate change impacts in ECA under different warming levels. The impacts reported in several impact studies were classified into different warming levels (see Appendix for details).

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Heat Extremes** | **Highly Unusual Heat Extremes** | | 5% of land area | 10% of land area<br>Hotspot in the Balkans | 15% of land area | 50% of land area | 85% of land area |
| | **Unprecedented Heat Extremes** | | Absent | Absent | Almost absent | 10% of land area | 55% of land area |
| **Precipitation** | **Central Asia** | | | | 20% increase | | 10% decrease to 10% increase (west to east) |
| | **Western Balkans** | | | | Uncertain | | 20–30% decrease |
| | **Russian Federation** | | | Return period of maximum 1995 precipitation: 10–15 years[1] | 20–30% precipitation increase<br>Return period of maximum 1995 precipitation: 10–15 years, and 7–10 years for East Siberia[1] | | 20–60% increase<br>Return period of maximum 1995 precipitation: 5–7 years for Eastern Russia, 7–10 years for Central Russia and less than 5 years for Central and Eastern Siberia[1] |
| **Drought** | | | | Drought duration (CDD) in the Balkans: 1–5 days[2] | | Drought duration (CDD) in the Balkans: 5–10 days[2] | 20% more drought days for the Balkans, uncertain for Central Asia and Central and Eastern Russia[3]<br>Drought duration (CDD) in the Balkans: 5–15 days[2] |
| **Aridity** | **Central Asia** | | | | Uncertain | | Uncertain in the northern parts, up to 60% increase in the West and up to 60% decrease in aridity in the East |
| | **Western Balkans** | | | | 60% increase in aridity | | |
| | **Russian Federation** | | | | 10–40% decrease in aridity | | 20–60% decrease in aridity |

**Table 5.7:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Glaciers** | | 11% Central Asian volume loss between 1980 and 2011, 3–14% reduction in area since 1960s[4]<br>35.5% of glacier volume loss in Central Asia between 1901–2000[5] | | Balkan glaciers melting within decades[6]<br>31% (50 Gt = 56 $km^3$ of ice) of Tien Shan glaciers melting[7] | About 50% (31–66 percent) of Central Asian glacier volume loss[5]<br>31% mass loss in Syr Darya basin[7]<br>41% drop in the annual runoff per year[8] | 54–57% of Central Asian glacier volume loss [9] | 50–78% of glacial volume shrinkage in Central Asia[10] |
| **Water Availability** | **Runoff** | Zerafshan river: shift from summer to spring and winter[11]<br>The Aral Sea volume decrease due to climate change without anthropogenic water abstractions was ~13.7% between 1958–2002[12]<br>Strong river runoff reduction of natural rivers of the Balkans, Sava, and Danube[13] | | | In Syr Darya basin, shifts of 30–60 days from the current spring/early summer toward a late winter/early spring runoff regime[7]<br>5m Issyk-Kul lake level decrease[14]<br>15–45% reduction in water resources[15] | Increased spring and summer runoff in Central Asia; shift of peak flow from July to June; 25% discharge reduction in July and August Hagg et al. (2013). | Very significant decline of runoff formation in the mountainous areas of Central Asia[16]<br>15 m Issyk-Kul lake level decrease[14]<br>up to 40% runoff decrease in Albania[17]<br>45–75% of increased water discharge in Northeastern Russia; 15% increased in central Siberia[15]<br>More than 45% decrease in annual discharge in the Western Balkans[15] |
| | **Groundwater Recharge** | | | | | Slight increase in groundwater recharge in Central Asia[18] | |
| **Crop Growing Areas and Food Production** | | Desertification affecting 66% of Kazakhstan[19]<br>Severe droughts in 2000/2001 leading to 112,600 ha of cereal loss in Tajikistan and $50 million loss in Uzbekistan[20]<br>$2 billion lost as a consequence of 2012 drought in Serbia[21] | | | 10–15% reduced runoff in the Amu Daraya River, putting pressure on the irrigation systems and crop production; increased degradation of soils[22]<br>Water deficits during the vegetation period in the Fergana Valley[7] | | Increased desertification threatening wheat production in Kazakhstan[7]<br>Increased aridity and desertification in Kyrgyz Republic affecting up to 49% of the country's territory[23] |

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Yields** | **All Crops** | 50% yield declines following drought in 2012 in Serbia[21]<br>70% yield declines following drought in 2012 in Bosnia and Herzegovina[24] | | Up to 13% yield decline in Uzbekistan; in eastern parts of the country yield increase up to 13% possible[25]<br>Higher productivity of alfalfa and grasslands in Uzbekistan[26] | 20–50% yield loss in Uzbekistan due to heat and water stress[26]<br>10–25% lower yields in Uzbekistan due to decreasing runoff in the Syr Daraya River and increased water use competition[27]<br>Up to 21% reduced yields of olives and 20% reduced yields of grapes in Albania; up to 69% reduced yield in grapes and up to 56% reduced yield in vegetables in Macedonia, FYR, up to 50% percent yield declines for wheat in Mediterranean and Continental parts of Macedonia[25] | 20% yield loss of rain-fed grapes and olives in Albania[25] | 30% yield drops in some parts of Tajikistan[28] |
| | **Maize** | Very high concentrations of aflatoxin concentration in maize as a result of 2012 drought in Serbia[29] | | | Up to 50% percent yield declines in Mediterranean and Continental parts of Macedonia, FYR[25]<br>Up to 11% reduced yields Albania[26] | | |
| | **Cotton** | | | 0 to 6% decrease in Uzbekistan[26,30] | Up to 19% reduced yields in Uzbekistan[26] | | |

**Table 5.7:** Continued.

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| | **Wheat** | | | 12% average wheat yield increase[31] | | Kazakhstan a major hotspot of heat stress affecting wheat production [32] | |
| | | | | Up to 28% reduced yields in spring wheat in Uzbekistan[33] | Up to 57% reduced yields in spring wheat and up to 43% reduced yields in winter wheat in Uzbekistan[33]<br>Up to 24% yield increase in Albania[33] | | |
| **Livestock** | | | | | 14–33% increase of Bacillis anthracis habitat[34] | | |
| **Human Health** | | | | Most of the Balkans become suitable for *Aedes aegypti* dengue-transmitting mosquito[35] | Increased vulnerability of the Balkans to dengue and chikungunya[35] | Increase of heat-related mortality rates to 1,000 per million; very slight decline in cold-related mortality[36]<br>Tenfold increase in risk of mudflow occurrences in Kazakhstan[37] | |
| **Energy** | | | | | 2.58% increase in capacity for hydropower generation in Central Asia[38] | | |
| | | | Capacity of nuclear and fossil-fueled power plants could decrease due to changes in river water temperature and in river flows[39]<br>Mean number of days during which electricity production is possible drops due to the increase in incidence of droughts and extreme river low flow[39] | | | | |

| RISK/IMPACT | | OBSERVED VULNERABILITY OR CHANGE | AROUND 1°C (≈2010s) | AROUND 1.5°C (≈2030s) | AROUND 2.0°C (≈2040s) | AROUND 3.0°C (≈2060s) | AROUND 4°C AND ABOVE (≈2080s) |
|---|---|---|---|---|---|---|---|
| **Boreal Forests** | | Tree-line expansion in the north[40]<br>Productivity decline within interior boreal forests related to warming-induced drought stress[41] | | | Increase in timber harvest for larch and pine[42]<br>Decrease in timber harvest for spruce and fir[42]<br>Methane emissions from permafrost thawing in Russia could increase by 20–30%[43] | Moderate change in vegetation[44]<br>10 days increase in fire risk (50 to 60 days)[44] | Russian forest harvests are only profitable until 2060 under 4°C warming[42]<br>Dramatic changes in vegetation[44]<br>Large decrease in timber harvest, especially for spruce and fir; larch forest might increase productivity[42]<br>25t ha-1 in tree carbon (150t ha-1 vs. 125 t ha-1) more and ~60 t ha-1 less in soils and deadwood (33–35 t ha-1 vs. 98–99t ha-1) under climate change; harvest increased by 15% under climate change; productivity increase nullified by higher fire damage[45]<br>20–30 days increase in fire risk (60 to 80 days)[44]<br>Increasing vulnerability to diseases, fire, and decreased reproduction rates that might lead to large-scale forest dieback[46] |

Please note that 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) and 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). Exceedance with a likely chance (>66 percent) generally occurs in the second half of the decade cited. Impacts are given for warming levels irrespective of the timeframe (i.e. if a study gives impacts for 2°C warming in 2100, then the impact is given in the 2°C column). Impacts given in the observations column do not necessarily form the baseline for future impacts. Impacts for different warming levels may originate from different studies and therefore may be based on different underlying assumptions, meaning that the impacts are not always fully comparable (e.g., crop yields may decrease more in 3°C than 4°C because underlying the impact at 3°C warming is a study that features very strong precipitation decreases. Moreover, this report does not systematically review observed impacts. It highlights important observed impacts for current warming but does not conduct any formal process to attribute impacts to climate change.

## Endnotes

[1] Kharin et al. (2013)
[2] Sillmann et al. (2013b)
[3] Prudhomme et al. (2013)
[4] Giesen and Oerlemans (2013), Hijioka et al. (2014)
[5] Marzeion et al. (2012)
[6] Glaciers in Albanian Alps and Montenegrin Durmitor (Grunewald and Scheithauer 2010)
[7] Siegfried et al. (2012)
[8] Bliss et al. (2014)
[9] Giesen and Oerlemans (2013), Marzeion et al. 2012, Radić et al. (2013)
[10] Radić et al (2013), Marzeion et al. (2012)
[11] Olsson et al. (2010)
[12] Aus der Beek et al. (2011)
[13] 7 out of 8 rivers, Dimkic and Despotovic (2012)
[14] Davletkeldiev et al. (2009)
[15] Schewe et al. (2013)
[16] Main Administation of Hydrometeorology (2009)
[17] Dakova (2005)
[18] Döll (2009)
[19] World Bank 2013v
[20] Thurmann (2011)
[21] Maslac (2012)
[22] World Bank (2013f)
[23] World Bank (2013a)
[24] UNDP (2014)
[25] Sutton et al. (2013a)
[26] Without $CO_2$ fertilization; Sutton et al. (2013a,c)
[27] World Bank (2013x)
[28] World Bank (2013m)
[29] Kos et al. (2013)
[30] Sutton et al. (2013b)
[31] Without changes in irrigation water availability and with $CO_2$ fertilization effect (Sommer et al. 2013)
[32] Without $CO_2$ fertilization (Teixeira et al. 2013)
[33] Without $CO_2$ fertilization (Sutton et al. 2013b,c)
[34] Joyner et al. (2010)
[35] Caminade et al. (2012)
[36] Ballester et al. (2011)
[37] National communication of Kazakhstan (BMU and WHO-Europe 2009).
[38] Killingtveit (2012)
[39] van Vliet et al. (2012)
[40] Berner et al. (2013); Devi et al. (2008); MacDonald et al. (2008)
[41] McDowell (2011); Zhang et al. (2009b)
[42] Lutz et al. (2013b)
[43] Anisimov (2007)
[44] Tchebakova et al. (2009)
[45] Forest in Kostroma region, 450 km northeast of Moscow (Shanin et al. 2011)
[46] Lenton et al. (2012)

# Appendix

# Appendix

## A.1 Methods for Temperature, Precipitation, Heat Wave, and Aridity Projections

### A.1.1 ISI-MIP Bias Correction

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 five CMIP5 global climate models (gfdl-esm2m, hadgem2-es, ipsl-cm5a-lr, miroc-esm-chem, and 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. A regression is performed monthly on the ranked datasets. Subsequently, the derived monthly correction factors are interpolated toward daily ones. The correction factors are then applied to the projected GCM data (Warszawski 2013).

### A.1.2 Heat Extreme Analysis

For each of the ISI-MIP bias-corrected CMIP5 simulation runs, we determined the local standard deviation due to natural variability over the 20th century for each individual month (Coumou and Robinson 2013). To do so, we first used a singular spectrum analysis to extract the long-term non-linear warming trend (i.e., the climatological warming signal). Next we de-trended the 20th century monthly time series by subtracting the long-term trend, which provided the monthly year-to-year variability. From this de-trended signal, monthly standard deviations were calculated, then averaged seasonally (i.e., the seasonally averaged monthly-standard deviations). For this analysis, we employed the standard deviation calculated for the last half of 20th century (1951–2010); we found, however, that this estimate was robust with respect to different time periods. Following Coumou and Robinson (2013) and Hansen et al. (2012), we used the 1951–1980 reference period, which has the advantage of being a period of relatively stable global mean temperature prior to rapid global warming.

We defined two different extreme thresholds: one at three standard deviations warmer than the mean temperature (3-sigma events) and one at five standard deviations warmer than the mean temperature (5 sigma events). During the reference period (1951–1980), exceeding the 3-sigma threshold is extremely unlikely. Over most land regions, the monthly temperature distributions are close to a normal distribution for which 3-sigma events have a return time of 740 years. Monthly temperature will not be normally distributed everywhere and hence return times can differ. Nevertheless, for the reference period, return times for 3-sigma events will on average be at least 100 years, implying that in each year the land area expected to experience temperatures beyond 3-sigma will be one percent or less. The land area experiencing 3-sigma heat is affected by natural variability, with El Niño years seeing a larger area exceeding this threshold (Coumou and Robinson 2013). Irrespective of that, 3-sigma heat extremes are unlikely events during the reference period. Furthermore, 5-sigma events have a return time of several million years in normally distributed data. They can thus be considered to be essentially absent during the reference period.

The effect of global warming is to shift the mean temperature over almost all land regions toward warmer values. Even in the absence of a change in variability (i.e., a broadening or narrowing of the width of the distribution), this shift in the mean will cause an increase in the likelihood that the extreme thresholds are exceeded. Therefore, the observed warming since the 1980s has already strongly increased the land area experiencing 3-sigma heat—it is now about five percent (Coumou and Robinson 2013). Currently, at least on a global scale, 5-sigma heat extremes are not yet detectable. As shown in this report, future warming will strongly increase the likelihood of exceeding—and therefore the land area experiencing—the 3- and 5-sigma threshold extremes. As discussed in Coumou and Robinson (2013), this increased likelihood is on the global scale is due primarily to the projected shift in the mean toward warmer values. Regionally, changes in the variability on top of the shift in the mean might play a role as well.

Throughout this report, we analyzed the occurrence of threshold-exceeding extremes both spatially and temporally (e.g., the 2071–2100 period) aggregated. Temporal averaging is performed on an individual grid cell basis and the results are presented in probability maps globally and for the report's three focus regions. Additional spatial averaging is achieved by area-weighted averaging over the individual grid cells in the region of interest. This way, a spatial-temporal averaged number is derived that can be interpreted either spatially (e.g., 80 percent of land area covered) or temporally (e.g., 80 percent of summer months) for a given period and region of interest.

### A.1.3 Aridity Index and Potential Evaporation

The Aridity Index (*AI*) quantifies the precipitation supply over atmospheric water demand as:

$$AI = \frac{Pr}{ET0}$$

Where $Pr$ is precipitation and $ET_0$ is the reference crop evapotranspiration, sometimes also called potential evaporation. It estimates the amount of evapotranspiration from a hypothetical grass reference crop with specific characteristics at a surface which is not short of water. It thus captures the water demand of the atmosphere from meteorological conditions. We used the FAO Penman-Monteith method (Allen et al. 2006) to estimate potential evapotranspiration rate, which is a simple representation of the physical and physiological factors governing the evapotranspiration process and generally recommended for the definition and computation of the reference evapotranspiration. It requires radiation, near-surface air temperature, humidity, pressure, and wind speed data, and is given by:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

**Table A.1:** 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 |

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 2 m height [m s$^{-1}$], $e_s$ the saturation vapor pressure [kPa], $e_a$ the actual vapor pressure [kPa], Δ the slope of the vapor pressure curve [kPa °C−1], and γ the psychrometric constant [kPa °C−1].

We calculated monthly $ET_0$ values for each grid point using climatological input from the ISI-MIP database for both the historical period and future scenarios.

### A.1.4 Spatial Averaging

The time series for precipitation, temperature, heat extremes, and aridity index, as provided in this report, have been obtained by area-weighted averaging of grid-cells located in the countries of interest, as provided by the World Bank.

## A.2 Sea-Level Rise Projections: Methods for This Report

### A.2.1 Individual Contributions

We followed a process-based approach similar to the IPCC AR5 report; this is in contrast to the previously employed semi-empirical approach (Rahmstorf 2007; Schaeffer et al. 2012), which was the method employed in *Turn Down the Heat II* (in a risk-assessment perspective) and presented as the upper bound in *Turn Down the Heat I*.

The projection methods are a synthesis between a recent paper by Hinkel et al. (2014) and the references therein (we refer the reader to this publication for details) and the Chapter 13 of the IPCC AR5 WGI Report (Church et al. 2013). In particular:

- Similar methods were used for the thermal, glacier, and Greenland contributions in the two publications and in this report.
- Compared to Hinkel et al. (2014), we (1) accounted for a negative surface mass balance (SMB) contribution from Antarctica in addition to its (positive) dynamic contribution; (2) accounted for a dynamic contribution on top of Greenland surface mass balance; (3) used a larger number of CMIP5 GCMs (Taylor

et al. 2012) in our analysis—CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-ES, IPSL-CM5A-MR, MIROC-ESM, MPI-ESM-MR, MRI-CGCM3, and NorESM1-M; (4) considered the uncertainties independent when summing the various contributions; and (5) we took the cross-ensemble uncertainties as the full GCM range (minimum to maximum) to yield a range consistent with the IPCC AR5 ensemble (except for Antarctica, where the calculations are probabilistic) (Levermann et al. 2014).

- The main difference with the IPCC AR5 is the contribution from Antarctica's ice discharge, which we discuss below. Additionally, and consistent with the previous *Turn Down the Heat* reports, we did not include a contribution from groundwater mining estimated at +0.04 m (–0.01, 0.08) (Church et al. 2013, SM Table 13.5) since it is not related to climate warming. The same applies to the post-glacial rebound, which is not included here.

A novel approach is employed for Antarctica's dynamic discharge (Levermann et al. 2014), where model results from the fixed-melting SeaRISE experiments (Bindschadler et al. 2013) are "transformed" to account for scenario-dependent ocean warming and resulting melt rates. It uses the ensemble of CMIP5 models for the translation of global mean to subsurface ocean temperatures and a well-constrained parameter for the translation of warming to ice sheet melting. This new method was also used by Hinkel et al. (2014). We found this physically-based approach better suited for this report than the approach of Little et al. (2013) on which the IPCC assessment is largely based. In particular:

- The Little et al. (2013) estimate comes with a questionable assumption of linear growth rate in ice discharge, and must use subjective, rather arbitrary prior distributions of the growth rate in various basins.
- The Little et al. (2013) estimate does not include processes that are yet to start but expected as Antarctic subsurface waters warm. As such, it may underestimate the risk for enhanced ice discharge as a response to strong ocean warming toward the end of the 21st century.
- While CMIP5 projections show a clear scenario dependency for subsurface temperature in the proximity of the Antarctic ice sheet, the IPCC AR5 assumes a scenario-independent contribution to sea-level rise from Antarctica.
- Studies subsequent to the IPCC AR5 report add new evidence that oceanic melt plays an important role for mass loss in general (Rignot et al. 2013), for West Antarctica (Dutrieux et al. 2014), and potentially for East Antarctica (Mengel and Levermann 2014).

It is understandable that the "scenario-independence" null-hypothesis is agreed on in a consensus-driven report like the IPCC AR5. In light of increasing evidence for the importance of oceanic melt in Antarctica's mass balance, however, we believe that scenario dependency has to be accounted for in the sea-level rise projections for Antarctica. While our approach yields mean estimates for Antarctic sea-level rise similar to the IPCC, our estimated upper bounds are scenario-dependent. Rejecting this would undermine this report's objective to inform on the risks of different levels of global warming.

After adding surface mass balance (Church et al. 2013), we obtained a contribution of 0.04 m (–0.03 m to 0.30 m) for the RCP8.5 scenario and 0.04 m (–0.01 to 0.18 m) for the RCP2.6 scenario in 2081–2100 compared to the reference period 1986–2005. While the median projection is similar for both scenarios (and similar to the IPCC AR5), the risk of higher sea-level rise is reflected by the higher upper bound in the RCP8.5 scenario as compared to RCP2.6. Nevertheless, our upper bound only reflects model uncertainty, and can be seen as covering the likely (67 percent) range only. In particular, it does not include self-amplifying feedbacks in unstable marine ice in Antarctica. Recent literature indicates that the Thwaites Glacier may already be in a state of irreversible retreat (Joughin et al. 2014; Rignot et al. 2014), which was not clear and thus downplayed at the time IPCC AR5 was written (Parizek et al. 2013).

### A.2.2 Comparison with Previous Reports and Expert-Elicitation Studies

A detailed comparison with previous *Turn Down the Heat* reports, IPCC AR4 (Meehl et al. 2007), and IPCC AR5 (Church et al. 2013), after removal of land-water contribution for comparison purposes), is shown in Figure A.1 for RCP8.5 and other 4°C warming scenarios. While our median estimates are similar to AR5, our upper estimates of total global sea-level rise in 2081–2100 are significantly higher. This is due to the novel method for projecting Antarctica's contribution, as explained above. In a 4°C world, the 90 percent model-range of our new projections tightly encompasses the median "low" and "SEM" cases investigated in the previous *Turn Down the Heat* reports, indicating a similar level of risk. In a 2°C world (Figure A.2), the new process-based projections are more optimistic regarding the benefit of cutting emissions to limit sea-level rise.

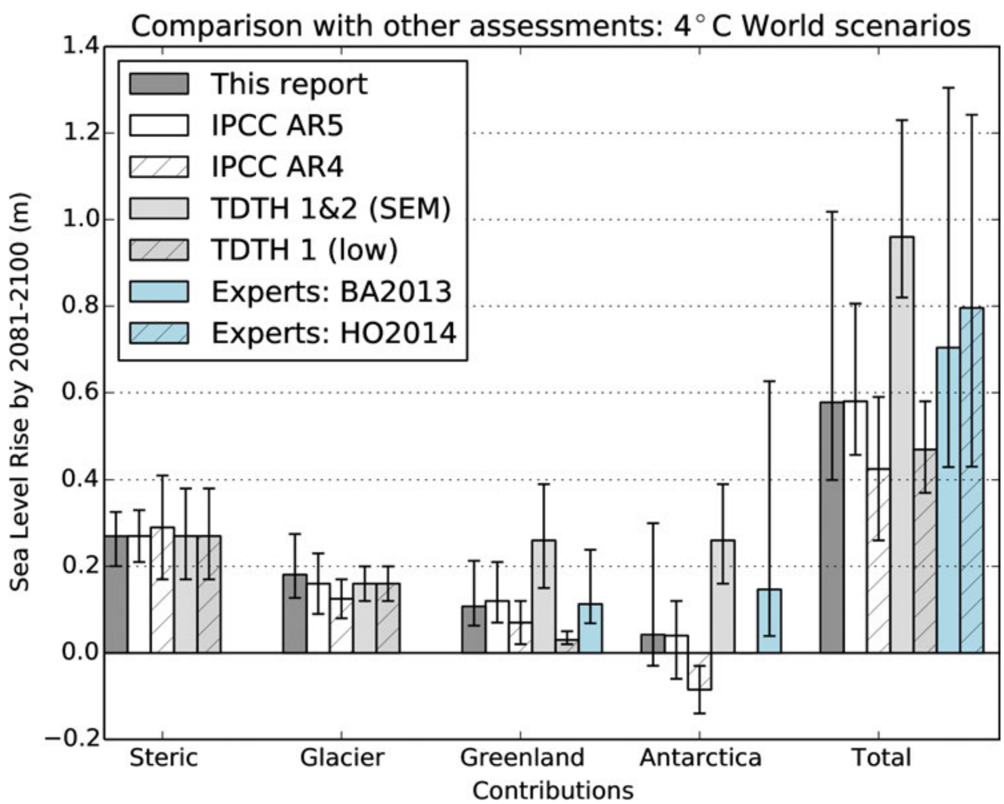
The two other projections (light blue on the figures) present results from a very different approach based on expect elicitation. Bamber and Aspinall (2013) interviewed 14 experts and estimated the sea-level contribution from the large ice sheets, taking into account both mass balance and fast ice flow processes. The median result is a 29 cm increase from ice sheets by 2100; from a risk perspective, the 95th percentile of the estimates is also highly relevant being 0.84 m by 2100.[68] Adding our estimates for RCP85

[68] Bamber and Aspinall (2013) "find an overwhelming lack of certainty about the crucial issue of the origin of recent accelerated mass loss from the ice sheets."

thermal expansion and glaciers, the maximum sea-level rise is close to 1.4 m in 2100. A broader expert elicitation based on 90 experts concluded an upper estimate (95 percent confidence) of 0.7 m sea-level rise for the low RCP2.6 scenario in contrast to 1.5 m for the high RCP8.5 scenario from 2000 to 2100 (Horton et al. 2014). An assessment by the U.S. National Research Council (2012) yielded a similar range of 0.5–1.4 m. These studies implicitly account for the risk of destabilization of the potentially unstable Antarctic marine ice, and are consistent with the latest IPCC assessment that any additional contribution from the Antarctic ice sheet would remain within a couple of tens of centimeters above the likely upper bound.

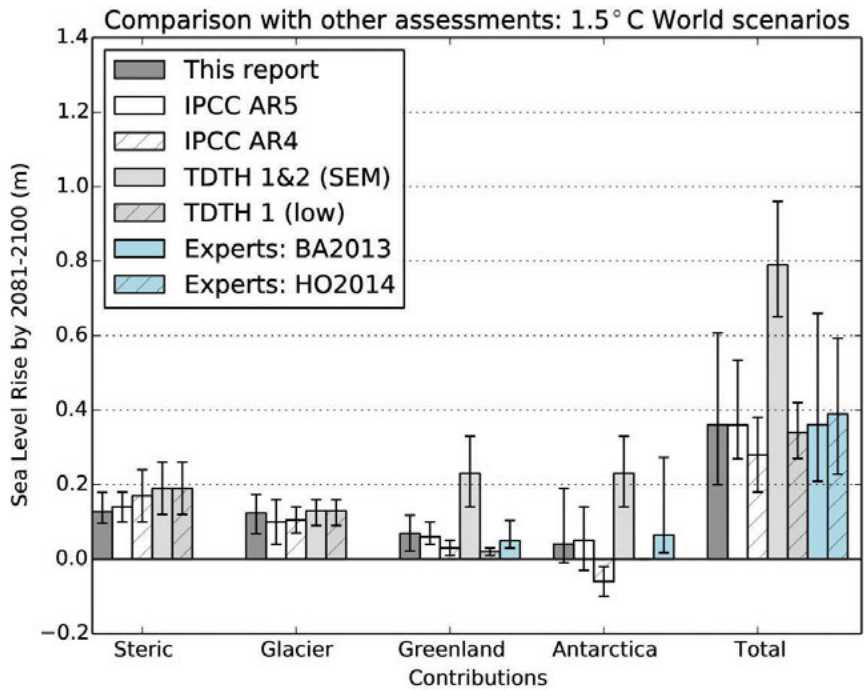
Our results include the direct effect of Southern Ocean warming on ice-shelf basal melting and related ice stream acceleration in Antarctica; as in the IPCC AR5, however, they do not include self-amplifying feedbacks responsible for marine ice sheet instability. It is still unclear at this point whether this mechanism would significantly change the picture presented in this report. We note that despite significant methodological update, our process-based upper bound of 1 m by 2080–2100 above the 1986–2005 baseline is comparable to the median projection of the semi-empirical-based "high" or "SEM" scenario investigated in the previous *Turn Down the Heat* reports (Figure A.1).

**Figure A.1:** Comparison of sea level projections by 2081–2100 above the present day, for the current report, previous *Turn Down the Heat* reports, IPCC reports, and recent subjective expert judgment assessments for a 4°C world ("Experts": Bamber and Aspinall 2013; Horton et al. 2014).




The uncertainty ranges reflect upper and lower bounds as originally reported, without distinction between likely and very likely ranges. Note that expert judgment assessments were originally reported for 2100 and subsequently adjusted by us to match the common projection horizon (2081–2100), assuming a linear increase in the rate of rise from present day to the projection horizon. Present-day baseline climate refers to 1986–2005 in the current report and may vary in other assessments (e.g. 1980–1999 for AR4, 2010 for BA2013), but no adjustment was made because results are less sensitive to the chosen baseline. Emissions scenarios vary slightly across the reports, but were selected to make the comparison at least qualitatively meaningful (e.g., A1FI for AR4, RCP8.5 for AR5 and *Turn Down the Heat*). Note that land-water storage is not included in this comparison and was removed from the IPCC AR5 estimate for consistency (estimated at 0.04 m (–0.01 m, 0.09 m) between 1986–2005 and 2081–2100, Table 13.5 in Church et al. 2013).

**Figure A.2:** Same as Figure A.1 but for a 1.5°C world.




## A.3 Meta-analysis of Crop Yield Changes with Climate Change

A meta-analysis of crop yield data was conducted separately for the three regions in this report. In addition to the regional meta-analyses presented in the main report, we present here the meta-analysis of the aggregate crop yield data for all three regions.

The data from numerous studies were analyzed with the goal of summarizing the range of projected outcomes for each of the regions and of assessing consensus. We addressed three main questions in this analysis: (1) what are the likely impacts of incremental degrees of warming on yields?; (2) what is the qualitative impact of considering adaptation measures and the effects of $CO_2$ fertilization on changes in crop yields?; and (3) what is the ability of adaptation measures and $CO_2$ fertilization to counteract the negative effects of increased temperature?

### A.3.1 Data Processing

Single studies may provide numbers for multiple countries within the region (or even multiple sites within one country) and for numerous crops, and could potentially be over-represented in the sample (i.e., having therefore a disproportionate impact on the meta-analysis). To minimize bias toward those studies, we averaged their yield results for the whole region in order to obtain a sample with a good representation of all the available studies. Moreover, whenever a study showed a range of GCMs models for a specific crop, we interpreted averages as being the expected response of aggregate production.

One quality control consisted of examining the datasets for outliers. We followed the same procedure described in Challinor et al. (2014) and examined in detail site-scaled studies that produced changes of greater than 50 percent in either direction. This led to the exclusion of four data points. The focus was on crop data only; livestock data was not included in this analysis.

Due to the small sample size for the three regions and the large variety of crop types analyzed in the different studies, an analysis per crop type was not possible. Patterns were analyzed for all crops jointly, and particular features for individual crops are described only qualitatively and with direct reference to the individual study from which they were obtained. Due to the lack of data, we were also unable to test the effect of increased precipitation on crop yield change. A small but significant correlation was found between an increase in temperature and an increase in precipitation (Challinor et al. 2014), showing that the coefficient found for effect of increase in temperature on yields captures some of the effects increased precipitation may have on crop yields.

As mentioned above, we investigated the impact of incremental degrees of global warming on crop yields. Not all studies provided all data needed and occasionally the increase in temperature associated with a projected change in yield is not explicit in the studies. Because climate change impact studies usually specify baseline conditions from which future (e.g., under one of the SRES scenario family) impacts are projected, we were able to infer the increase in temperature. This was done using the Warming Attribution Calculator (see below). We did not retain studies that did not provide this information.

The baseline periods are highly variable between studies and seem to have been selected to coincide with the baselines assumed in the climate model used in each study. In our datasets, baseline periods differed by up to 50 years between different studies; this certainly has an important impact on the projected yield (White et al. 2011). It is important to bear in mind that the different levels of temperature increase examined here are not the same in absolute terms in relation to one baseline as we focused on the crop response associated with incremental levels of warming.

This process led to a variable number of studies per region, and the meta-analysis summarized the results from a total of 10 independent studies for Latin America and the Caribbean (63 data points), 16 studies for the Middle East and North Africa (167 data points), and three studies for Europe and Central Asia (51 data points). Due to very low statistical power, we were unable to provide confident results for the ECA region.

### A.3.2 Statistical Analysis

Statistical analysis was conducted using Matlab 2013a. We fitted generalized linear models to the data to investigate the relationship between changes in crop yields and temperature increases, and to address the effect of adaptation measures and of $CO_2$. A t-test was conducted to test the relationships for significance. For the significant relationships, we present plots with best-fit lines obtained using a polynomial fit. Five hundred bootstrap replicates were carried out to derive a 95 percent confidence interval; these are presented in patches. To evaluate the relationships, we looked into the values of r-square (the amount of variability share between the two variables in question) and the slope of the regression line, which told us whether temperature increase influences crop yield change positively or negatively (all results are provided in tables).

Previous analysis (Easterling et al. 2007; World Bank 2013) showed that the influence of temperature increase on crop yield can be considerably stronger under high levels of temperature increase (higher than 2°C). Where data was available, we assessed for significance the relationship between crop yield and temperature increase below 2°C and over the whole range of temperature increases.

## A.4 Warming Level Attribution and Classification

Differentiating between impacts at different warming levels is one of the key objectives of the *Turn Down the Heat* report series. Most impact studies present their results with regard to time slices and scenarios—while not specifying global warming levels that might differ substantially due to large variations in climate sensitivity between different GCMs. Additionally, not all policy-relevant warming levels are covered by SRES (CMIP3) or RCP (CMIP5) scenarios; often the results are based on a single transient scenario only.

Wherever possible, we derived warming levels for the impact studies analyzed in the report that are based on models and scenarios from the CMIP3 or CMIP5 database. Generally, impact studies analyze changes with respect to a base period (e.g., 1986–2005). Consistent with the IPCC AR5 WGI report, the warming level for the period of interest was derived as the sum of the projected model ensemble warming in global mean temperature (GMT) relative to the base period plus warming level of the base period relative to pre-industrial levels (1850–1900) based on the HadCrut4 dataset (e.g., 0.6°C for 1986–2005).

If the impact study was based on multi-model analysis, a mean GMT time series was derived for all ensemble members equally weighted. Please note that this approach actually assumes linear scaling of the impacts with temperature in the vicinity of the warming levels, which is an approximation that might not always be appropriate. Many impact studies do not differentiate, however, among the different ensemble members underlying the projections, but give numbers only for ensemble averages.

For studies based on regional climate models, the GMT time series of the corresponding GCM is used. If no climate model was specified in the impact study, the corresponding ensemble average (either CMIP3 or CMIP5) was used. In addition, the CMIP3 data base contains not all scenarios that are analyzed in impact studies (specifically, SRES A1F1 and SRES B2 are missing). For these scenarios, GMT scenarios were emulated using MAGICC6 (Rogelj et al. 2012).

Based on this methodology, the impacts of climate change as apparent from different studies can be classified for different warming levels that comprise the following ranges of global mean warming:

| WARMING LEVEL | OBSERVED | 1°C | 1.5°C | 2°C | 3°C | 4°C |
|---|---|---|---|---|---|---|
| Range [°C] | <0.8 | 0.8–1.25 | 1.25–1.75 | 1.75–2.25 | 2.25–3.5 | >3.5 |

## A.5 Summary of Evidence Concerning Social Vulnerability

The tables below are based on extensive literature searching on social vulnerability in the three focal regions and beyond. While extensive, this was not a systematic review process and the tables make no claim to cover all relevant literature. The tables are organized by themes and primarily focus on vulnerability. They do not comprehensively review the very large literature on adaptation.

Most evidence of social vulnerability to the effects of climate change is based on and extrapolates from contemporary and historical examples. Because of the inherent difficulties of modelling changes in social systems at different degrees of global warming, given the multiple other development trends which already interact with climate change to affect social vulnerability, and will do in the future, most evidence concerns the short to medium term.

Both large-scale quantitative research and small-scale contextual research that probes social dynamics in particular locations are represented in research on social vulnerability to climate change. Most quantitative sources discuss the likely scale of vulnerability if no adaptation takes place.

Of the three focus regions, there is considerably more evidence of current and potential future social impacts of climate change in Latin America and the Caribbean and the Middle East and North Africa than there is for the parts of Europe and Central Asia studied in this report.[69] This may reflect language barriers, or the disciplinary emphases of both natural and social scientists working in Europe and Central Asia. Much of the existing evidence on social vulnerability has been funded by international organizations.

This said, compared with other regions for which there is substantially more socially disaggregated evidence (such as Sub-Saharan Africa and South Asia), evidence for the Middle East and North Africa, and to a lesser extent Latin America and the Caribbean is still relatively thin on social analysis. These tables draw on the considerably larger literature from Sub-Saharan Africa and South, South-East and East Asia and the Pacific to highlight issues that may also be of relevance in LAC, MENA and ECA.

The aspect of social vulnerability where evidence is clearest is health: there is strong evidence on vulnerability to heat waves and on access to clean, safe water, mixed but suggestive evidence on the likelihood of vector- and water-borne diseases spreading, and on the likely implications of climate change for malnutrition. The evidence is least strong for impacts on mental health, and on all forms of interpersonal violence. Thus, although there has been much research into the extent of relationship between climate change and conflict or social tensions, there is no consensus in the literature. This may reflect discrepancies between definitions or approaches—it does not, for example, reflect a qualitative/quantitative divide, as both types of studies have found evidence for and against strong relationship between climate change and violence. Though some studies have raised concerns that both extreme events and slow-onset disasters could lead to increased gender-based violence, evidence remains anecdotal.

There is also some strong evidence of likely negative impacts on agriculture- and fisheries-based livelihoods, and more limited evidence concerning pastoral livelihoods—this may reflect research priorities, or may reflect limitations of our search. The evidence concerning impacts of climate change on urban livelihoods emphasizes the destructive effects of extreme events on household assets, community infrastructure and the knock-on effects on both employed and self-employed workers. There is moderately strong evidence that negative effects on livelihoods and wellbeing of both extreme events and slow-onset climate change may lead to both short-term displacement and longer-term migration.

Evidence on the poverty implications of climate change is relatively limited, and largely based on projections of impacts on agriculture, food prices and consumption. These typically suggest a likely increase in poverty among (already poor) small-scale producers in rural areas, and among low-income urban households. Few studies discuss the implications of climate change for chronic poverty, or on social aspects of poverty, such as on social cohesion. Relatively few studies probe the linkages between climate change and coping strategies that may undermine social wellbeing, such as child labour or forced marriage, with a particular gap in evidence from the three focal regions. Systematic treatment of the gender dimensions of climate change is also weak for the three focal regions, with a particular absence in the literature on ECA.

Although evidence from other regions (and to a lesser extent from Latin America) highlights the importance of responsive institutions and opportunities for voice in building resilience to climate change, there is relatively little evidence from either MENA or ECA. Arguments for the importance of greater attention to voice, rights and institutional development are largely based on experience in other regions.

The following tables set forth the evidence on current social vulnerability, as studies examining potential impacts in scenarios of greater climate change extrapolate from contemporary evidence. As far as possible, assessments of the strength of evidence are based on discussions in the relevant chapters of the IPCC Working Group II 5th Assessment Report, Climate Change 2014: Impacts, Adaptation, and Vulnerability (IPCC 2014b). Where the strength of evidence is not specifically signaled in the relevant IPCC 5th

[69] Note that this region excludes Western Europe, for which there is a large body of evidence.

Assessment Report chapter, we made our own assessment and categorized the strength of evidence as follows:

- A **strong** evidence base denotes a consensus among studies, and/or eight or more studies with similar findings.
- A **moderate** evidence base denotes mixed findings, or 4–7 studies with similar findings.
- A **limited** evidence base indicates inconclusive findings, or fewer than three studies with similar findings.

These relatively small numbers reflect the limited evidence base on many aspects of social vulnerability.

**Table A.2:** Summary of Evidence: Food Security and Nutrition.

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Reduction of land available/ suitable for crops and ecosystems (variable by region)** | Water scarcity<br>Sea-level rise<br>Salt water intrusion<br>River flow changes<br>Desertification | Soil degradation<br>Global pressures on land, including for the production of biofuels<br>Crop diversification potential<br>Deforestation<br>Land enclosure | *Regions:*<br>MENA, especially Israel, Lebanon, Syria, Iraq and the Islamic Republic of Iran<br>*Groups:*<br>Small-scale farmers and marginalized groups most likely to be displaced by competition for land<br>Indigenous communities and small-scale farmers who lack land entitlement<br>Potential knock-on effects on food prices related to squeeze on land availability | *Adaptation:*<br>Changes in land use, such as adjusting the location of crop production in higher latitudes<br>Development of markets that reward sustainable land-use practices<br>Changes in land allocation<br>Forest conservation | Moderate | Swedish Government (2007)<br>Hazell and Wood (2008)<br>Ortiz et al. (2008)<br>Gornall et al. (2010)<br>Schroth et al. (2009)<br>Bellon et al. (2011)<br>Tacoli et al. (2013) |
| **Reduction in crop productivity (e.g., cereal production) especially for wheat and maize/ negative yields impacts for nut and fruit trees** | Temperature increases<br>Sea-level rise<br>Changes in precipitation<br>Increased frequency and severity of extreme weather events such as flooding and warm spells<br>Melting glaciers and changes in river hydrology<br>Decline of winter chill accumulation | Trade flows<br>Crop diversification potential | *Regions:*<br>Tropical and subtropical regions<br>Rain-fed agriculture in LAC<br>Western Balkans<br>*Groups:*<br>Rural food producers<br>Low-income urban consumers<br>Groups reliant on glacial melt water irrigation in Central Asia and LAC | *Adaptation:*<br>Altered cultivation techniques and sowing times<br>Improved sowing techniques (e.g., dry sowing, seedling transplanting, seed priming, double cropping or intercropping) and breeding drought-tolerant crop varieties<br>Improved climate forecasts to inform crop risk management<br>Crop insurance programs that are accessible to smallholders<br>Irrigation optimization | High confidence | Schmidhuber and Tubiello (2007)<br>Parry (2007)<br>Lobell et al. (2008)<br>Battisti and Naylor (2009)<br>Van Dingenen et al. (2009)<br>Wassmann et al. (2009)<br>Welch et al. (2010)<br>Gornall et al. (2010)<br>Thornton et al. (2011)<br>Avnery et al. (2011)<br>Okada et al. (2011)<br>Lobell et al. (2011)<br>Zwiers et al. (2011)<br>Semenov et al. (2012)<br>Teixeira et al. (2013)<br>Porter et al. (2014) |

**Table A.2:** Continued.

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Disruption to the production, storage, and transport of staple food supplies** | Temperature increases<br>Sea-level rise<br>Changes in precipitation and flooding<br>Increased frequency and severity of extreme weather events such as landslides, mudslides, hailstorms, and erosion damage | Governance<br>Political instability<br>Conflict<br>Global staple food price increases<br>Trade flows<br>Stock levels | Hazard prone countries and areas | | Moderate | Swedish Government (2007)<br>Tacoli et al. (2013)<br>Carty (2013)<br>Nelson, Rosegrant, and Palazzo et al. (2010)<br>Lobell et al. (2011)<br>Hertel et al. (2010)<br>Ziervogel and Ericksen (2010)<br>Douglas (2009) |
| **Reduction in affordability of food/variability of food prices** | Related to changes to productivity and disruption of transport<br>Increased frequency and severity of extreme weather events | Increased links between energy and agricultural markets and oil price fluctuations<br>Finance speculation<br>Increased crop demand (e.g., biofuels)<br>Increased global staple food prices<br>Trade flows<br>Conflict<br>Changing diets | Low-income countries and food-importing countries<br>*Regions:*<br>Africa, Central America, northeast Brazil, parts of the Andean region<br>Central Asia<br>MENA<br>*Groups:*<br>Low-income people in rural and urban areas<br>Children at risk of malnutrition | *Adaptation:*<br>On-farm agronomic adaptation<br>Adaptation of food systems<br>Marketing arrangements<br>Diversification of activities | Medium confidence (evidence depend on assumptions of models) | Ivanic and Martin (2008)<br>Battisti and Naylor (2009)<br>Lobell et al. (2011)<br>Roberts and Schlenker (2010)<br>Wright (2011)<br>World Bank (2012)<br>Tacoli et al. (2013)<br>FAO (2013)<br>OECD/FAO (2013)<br>Skoufias et al. (2012)<br>Porter et al. (2014) |
| **Increased livestock vulnerability and mortality** | Temperature increases<br>Increased frequency and severity of extreme weather events such as drought and flooding, affecting productivity/availability of grazing land and production of forage and feed<br>Rapid spread of livestock diseases and virus | Population pressure<br>Land ownership patterns | *Regions:*<br>Arid and semi-arid regions<br>Europe and North America<br>Groups:<br>Agro-pastoralists and pastoralists | *Adaptation:*<br>Use of more suitable livestock breeds or species<br>Migratory pastoralist activities<br>Adjusted livestock and water management to forage production<br>Use of diet supplements<br>Enhanced climate forecasts and information systems | Medium for mortality<br>Limited for livestock | Schmidhuber and Tubiello (2007)<br>Swedish Government (2007)<br>UK Government (2011)<br>Craine et al. (2010)<br>Izaurralde et al. (2011)<br>Hatfield et al. (2010)<br>Guis et al. (2012)<br>Porter et al. (2014) |

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increase in crop diseases or pests, which may reduce or increase crop yields (depending on crop type)** | Drought<br>Temperature increases<br>Heavy rainfalls | Poverty<br>Population pressures | *Groups:*<br>Food producers (especially small-scale farmers). | | Medium confidence for weeds<br>Medium confidence for insect pests | Schmidhuber and Tubiello (2007)<br>Tubiello et al. (2007)<br>Luck et al. (2011)<br>Porter et al. (2014) |
| **Disruption to fishery and shell-fishery production, including fish migrations** | Temperature increases<br>Ocean warming<br>Ocean acidification<br>Increased frequency and severity of extreme weather events | Population pressures and increased demand for seafood<br>Fish stock overexploitation<br>Pollution | *Regions:*<br>Tropical developing countries<br>Caribbean coasts, the Amazon estuaries, and the Rio de la Plata<br>Increase in fishery production in some higher-latitude areas<br>*Groups:*<br>Artisanal fishermen<br>People engaged in fish processing and trading<br>Small coastal communities | *Adaptation:*<br>Changes in water and land use (e.g., increased offtake of water to irrigate new land)<br>Increased dam building<br>International regulations to limit overfishing<br>Integrated water use planning | Strong<br><br>Limited evidence but high agreement on the socioeconomic impacts of ocean acidification | Roessig et al. (2005)<br>Perry et al. (2005)<br>Swedish Government (2007)<br>Last et al. (2011)<br>Doney et al. (2012)<br>Schmidhuber and Tubiello (2007)<br>FAO (2013)<br>Cheung et al. (2013)<br>Porter et al. (2014) |
| **Declines in coral reefs resulting in decline of fish stocks** | Temperature increases<br>Ocean warming<br>Ocean acidification | Overfishing | *Regions:*<br>Caribbean, Western Indian Ocean<br>*Groups:*<br>Small coastal communities relying on coral ecosystems<br>People engaged in fish processing and trading | | High confidence | Wilson et al. (2006)<br>Burke et al. (2004)<br>Hoegh-Guldberg et al. (2014) |

**Table A.3:** Summary of Evidence: Poverty Impacts.

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTION WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increase in poverty headcount rate and risk of chronic poverty in different warming scenarios** | Effects on food prices related to effects on productivity<br>Effects on employment and wages related to agricultural productivity | Structure of employment<br>Patterns of food production<br>Increasing food commodity prices<br>Reductions in the availability of and access to natural resources<br>Corruption | *Regions:*<br>Sub-Saharan Africa (Malawi, Mozambique, Tanzania, Zambia), Asia (Bangladesh), and Latin America (Mexico)<br>*Groups:*<br>Urban poor groups and urban wage laborers<br>Residents of informal settlements<br>Dwellers in rural hotspots where hunger is expected to become prevalent | *Adaptation:*<br>Social protection | Medium confidence (mixed findings, depending on assumptions of models) | Ruth and Ibarran (2009)<br>Jacoby et al. (2011)<br>Hertel et al. (2012)<br>Olsson et al. (2014) |
| **Increase in disaster-related impoverishment and destruction of assets. Risk of chronic poverty varies, but is compounded by often-limited access by the poorest to disaster relief** | Increased frequency and severity of extreme weather events such as flooding, drought, landslides, and cyclones | Extent of social protection and effective adaptation strategies<br>Urbanization<br>Corruption<br>Implementation of disaster risk reduction measures<br>Increasing proportion of assets and people located in areas of high exposure to hazards | *Regions:*<br>People in exposed areas (e.g., low-lying coastal areas, flood-prone land, mountain slopes)<br>*Groups:*<br>Low income rural and urban groups<br>Children and adolescents<br>Self-employed urban groups | *Adaptation:*<br>Social protection<br>Improved access to basic services<br>Development of insurance systems, particularly among vulnerable groups<br>Disaster risk reduction strategies | Limited evidence (some variation in findings by type of disaster and context) | Carter et al. (2007)<br>Shepherd et al. (2013)<br>Rossing and Rubin (2011)<br>Leichenko and Silva (2014)<br>Olsson et al. (2014) |
| **Coping strategies with negative social impacts** | Slow onset changes (e.g., drought)<br>Extreme events (e.g., flooding, cyclones) | Inadequate investment in poverty reduction<br>Increasing proportion of assets and people located in high exposure areas<br>Broader economic shocks | *Regions:*<br>Exposed areas in all regions<br>*Groups:*<br>Low-income groups<br>Children (e.g., child labors, those removal from school)<br>Girls/young women (e.g., forced marriages) | *Adaptation:*<br>Social protection<br>Improved access to basic services<br>Development of insurance systems, particularly among vulnerable groups<br>Disaster risk reduction strategies | Limited | Brown (2012)<br>ILO (2012)<br>North (2010)<br>Swarup et al. (2011) |

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTION WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Strained social cohesion and decline in reciprocity** | Slow onset changes (e.g., drought)<br>Extreme events (e.g., flooding, cyclones) | Changing social norms and expectations of reciprocity<br>Inadequate investment in poverty reduction<br>Conflict<br>Broader economic shocks | *Regions:*<br>Exposed areas in all regions<br>*Groups:*<br>Low-income groups<br>Groups experiencing sudden impoverishment and competition for resources | *Adaptation:*<br>Social protection<br>Improved access to basic services<br>Development of insurance systems, particularly among vulnerable groups<br>Disaster risk reduction strategies | Limited<br>Some counter-evidence suggesting increase in social cohesion in immediate aftermath of disasters | Afifi et al. (2012; 2011)<br>Berman et al. (2014)<br>Buechler (2014; 2009)<br>Slettebak (2012) |
| **Worsening poverty for some groups as a result of mitigation strategies** | – | Commercial pressures on land<br>Growing demand for energy | *Regions:*<br>Tropical forests and farmland<br>*Groups:*<br>Groups with limited land rights (including indigenous groups, women, smallholders without formal tenure)<br>Socially excluded groups | *Mitigation:*<br>Land alienation for forest protection (REDD+) or biofuels | Medium confidence | Olsson et al. (2014)<br>Biddulph (2012)<br>Chia et al. (2013)<br>Couto Pereira (2010)<br>Hodbod and Tomei (2013)<br>Vanwey (2009) |

**Table A.4:** Summary of Evidence: Migration.

| RISK/IMPACT | TYPE OF CLIMATE CHANGE OR SECOND-ORDER EFFECT | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Migration as a means for securing livelihoods in the face of slow-onset climatic stress** | Gradual changes in temperature and rainfall patterns<br>Drought<br>Coastal erosion<br>Increased sedimentation<br>Rising sea levels<br>Thawing permafrost | Poverty<br>Socioeconomic inequalities<br>Environmental degradation<br>Slow employment growth in relation to population pressure<br>Landholding access<br>Communications and infrastructure<br>Ability to adapt (particularly important for dry land regions)<br>Social networks<br>Employment availability in urban centers | *Regions:*<br>Coastal cities and fertile deltas which are likely to experience a large population increase<br>Small islands and coastal plains at higher levels of sea rise under 4°C warming (e.g., Caribbean and Mediterranean Coast countries)<br>Maghreb countries that serve as receiving and transit countries for Sahelian and other Sub-Saharan African migrants<br>Russian Arctic likely to experience flooding, subsidence and emigration, but also some in-migration to exploit emerging farming and extractive opportunities<br>*Groups:*<br>People with few or no land holdings<br>Men are more likely to migrate but this depends on local social norms and labour market opportunities. Women left behind face additional work burdens. | *Adaptation:*<br>Temporary migration as a risk management strategy or last resort option<br>Livelihood and sustainable development programmers have key role in reducing vulnerability | Medium | Black et al. (2008)<br>Tacoli (2009)<br>Barnett and Webber (2010)<br>Warner (2010)<br>Gemenne (2012)<br>Verner (2012)<br>Grant et al. (2014)<br>Crate (2013)<br>Adger et al. (2014) |

| RISK/IMPACT | TYPE OF CLIMATE CHANGE OR SECOND-ORDER EFFECT | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Displacement (as a result of extreme events)** | Increased frequency and severity of extreme weather events (e.g., flooding) | Poverty<br>Inequality<br>Increased movement of people and assets to areas of high exposure | *Regions:*<br>Areas prone and vulnerable to hazards<br>*Groups:*<br>Elderly and poorest are less likely to leave. However, when they leave, poor are (at greater risk of permanent displacement)<br>Displaced women sometimes find it more difficult to generate a livelihood in discriminatory labour markets. | *Adaptation:*<br>Temporary migration as a risk management strategy or last resort option<br>Disaster risk reduction strategies | Medium | Black et al. (2011)<br>Cutter (2009)<br>Barnett and Webber (2010)<br>Tacoli (2009)<br>Kartiki (2011)<br>Grant et al. (2014)<br>Adger et al. (2014) |

**Table A.5:** Summary of Evidence: Health.

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTION WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increase in malaria** | Temperature Increase (Land and sea surface temperature)<br>Humidity change<br>Water Scarcity<br>Flooding<br>El Niño effects | Globalization<br>Population displacement<br>Local patterns of behavior and settlement<br>Existing health structures<br>Land use changes | *Regions:*<br>Highland areas<br>MENA regions could be more exposed to risks of malaria<br>*Groups:*<br>People who lack immunity.<br>Poor children at greatest risk<br>Migrants<br>Low income groups most exposed | *Adaptation:*<br>Improved access to basic services and health care | Medium (Smith et al., 2014)<br>Substantial evidence with diverging conclusions<br>However, stronger evidence for highland areas | Kjellstrom and McMichael (2013)<br>Gage, Burkot, Eisen and Hayes (2008)<br>Mantilla et al. (2009)<br>Huynen et al. (2013)<br>Smith et al. (2014) |
| **Increase in dengue fever** | Temperature Increase (land and sea surface)<br>Increased precipitation<br>Increased frequency and severity of extreme weather events such as flooding and tropical cyclone activity | Globalization<br>Population Displacement<br>Local patterns of behavior (e.g., water storage) | *Regions:*<br>Tropical cities<br>*Groups:*<br>Low income groups most exposed | *Adaptation:*<br>Development of pre-seasonal treatments (spreading of insecticides)<br>Improved access to basic services and health care | Medium (Smith et al., 2014) | Patz et al. (2005)<br>BMU/WHO (2009)<br>Costello et al. (2009)<br>Smith et al. (2014) |
| **Increase in water-borne diseases (diarrheal disease and cholera)** | Increased precipitation<br>Changing rainfall patterns<br>Flooding<br>Water Scarcity<br>Increased salinization<br>El Niño effects | Local patterns of behavior<br>Population Pressure<br>Inadequate basic services such as sanitation | *Regions:*<br>Tropical cities<br>Coastal populations<br>*Groups:*<br>Children in poverty affected areas<br>Elderly populations<br>Lower socioeconomic groups | *Adaptation:*<br>Improved access to basic services and health care | Medium (Smith et al., 2014) | Few et al. (2004)<br>Azad et al. (2014)<br>Khan et al. (2011)<br>BMU/WHO (2009)<br>Smith et al. (2014) |

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTION WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increase in respiratory diseases** | Temperature increase<br>Spread of pollen and other allergens | Air pollution<br>Industrial development<br>Use of solid biomass fuels<br>Poor combustion of solid cooking fuels<br>Urbanization | *Groups:*<br>Older people and children biologically at greater risk<br>Women at risk from indoor air pollution<br>Poorer socioeconomic groups | *Mitigation:*<br>Political regulations to control and reduce air pollution<br>$CO_2$ and ozone emission controls<br>*Adaptation:*<br>Improved health services and access to health care | 'Very high confidence' in medium term (Smith et al., 2014) | Haines et al. (2006)<br>Shea et al. (2008)<br>D'Amato and Cecci (2008)<br>Smith et al. (2014) |
| **Increase in food borne infectious diseases** | Temperature increase<br>Changes in precipitation | Energy costs<br>Food storage practices | *Groups:*<br>Poorer socio-economic groups<br>Older people<br>Children | *Adaptation:*<br>Improved access to basic services and health care | 'High confidence' Smith et al. (2014) | Kovats et al. (2004)<br>Patz et al. (2005)<br>Swedish Government (2007)<br>Smith et al. (2014) |
| **Reduction in availability of clean water supply and sanitation** | Flooding<br>Drought<br>Salt water intrusion<br>Increased frequency and severity of extreme weather events | Population pressure<br>Displacement<br>Urbanization | *Regions:*<br>Coastal Zones and low lying populations (e.g. Bangladesh)<br>Cities reliant on highland or on declining ground water sources<br>*Groups:*<br>Low income groups in rural & urban areas<br>Women and children—longer distances to obtain water, affecting health. Also increased risk of violence<br>Poor children esp. vulnerable to disease | *Adaptation:*<br>Improved access to basic services and health care | Strong | Kjellstrom and McMichael (2013)<br>Black et al. (2013)<br>Barnett and Webber (2010)<br>Moser et al. (2010) |

**Table A.5:** Continued.

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTION WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increase in heat related illnesses and reduced labour productivity** | Temperature increase<br>Increased incidence of heat waves<br>Ozone ambient pollution | Population ageing<br>Urbanization | *Regions:*<br>Global<br>Particularly in densely populated large cities<br>Evidence from MENA, such as the Arabian peninsula<br>*Groups:*<br>Elderly<br>Manual laborers and those working outdoors are more exposed to heat stress<br>Overweight people<br>Displaced/people living in shelters<br>People who are not able to cool housing in the night, lost sleep<br>Residents of urban heat islands | *Adaptation:*<br>Improved access to basic services and health care | 'Very high confidence' for illnesses and 'high confidence' for reduced labour productivity (Smith et al. 2014). | Kjellstrom et al. (2009)<br>Hanna et al. (2011)<br>Berry et al. (2010)<br>Kjellstrom and McMichael (2013)<br>Costello et al. (2009)<br>Smith et al. (2014) |
| **Increased mortality rates from extreme weather events and disasters** | Flooding<br>Tropical cyclones | Lack of adequate shelter, water and sanitation services.<br>Lack of access to health services<br>Concentration of poor onto vulnerable land | *Regions:*<br>ECA esp. Western Balkans.<br>*Groups:*<br>Women and girls at increased risk if social norms prevent them acquiring survival skills<br>Men/older boys—if expected to risk their lives to rescue others<br>Children, older people more biologically vulnerable<br>Poorer households<br>People in low elevation costal zones and on land prone to flooding and landslides | *Adaptation:*<br>Improved access to basic services and health care<br>Investment in disaster management and early warning systems<br>Disaster Risk Reduction strategies | 'Very high confidence' (Smith et al. 2014) | Neumayer and Plumper (2007)<br>Pradhan et al. (2007)<br>Bartlett (2008)<br>Bradshaw and Fordham (2013)<br>Skinner (2011)<br>Smith et al. (2014) |

| RISK/IMPACT | TYPE OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTION WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increase in mental illnesses** | Temperature increase<br>Increased frequency and severity of extreme weather events | Access to health services<br>Social support systems<br>Forced displacement from familiar environments<br>Stress of livelihood failure with changing climate | Urban areas where mental disorders are more common<br>Poorer groups<br>Displaced people<br>Gender differences related to local social norms | | Limited evidence | Berry, Bowen and Kjellstrom (2010)<br>Alston (2010)<br>Smith et al. (2014) |
| **Increasing Malnutrition** | Temperature increase<br>Changing precipitation<br>Increased frequency and severity of extreme weather events | Population Pressure<br>Decline in agricultural production<br>Fluctuations of food prices<br>Lack of income and access to food<br>Discriminatory social norms<br>Existing undernutrition patterns<br>Governmental instability | *Regions:*<br>Sub-Saharan Africa, South Asia, Central America and MENA<br>*Groups:*<br>Children (esp. infants)<br>Subsistence farmers in low rainfall areas<br>Urban poor<br>Women (particularly in South Asia) | *Adaptation:*<br>Use and development of irrigation facilities<br>Improved access to markets<br>Improved social protection | 'Medium confidence' (Smith et al. 2014) | Lloyd et al. (2011)<br>Parry et al. (2009)<br>Skinner (2011)<br>Nelson et al. (2009)<br>Smith et al. (2014) |
| **Potential for increased risk of domestic and sexual violence** | Increased frequency and severity of extreme weather events<br>Longer-term climatic stress | Existing gender-based inequalities<br>Lack of supporting justice system<br>Increased stress from displacement and poverty<br>Lack of security within shelters/in post-disaster environment | *Groups:*<br>Women and children across cultures and countries are primarily affected by gender-based violence | *Adaptation:*<br>Improved targeting of awareness campaigns, particularly where illiteracy rates are high. | Limited evidence | Swarup et al. (2011)<br>Ahmad (2012)<br>Azad et al. (2014)<br>Bradshaw and Fordham (2013) |

**Table A.6:** Summary of Evidence: Conflict and Security.

| RISK/IMPACT | TYPES OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Risk of land and water scarcity (or excess of water) contributing to conflict/tensions** | Drought<br>Land degradation<br>Changes to precipitation<br>Glacial melting<br>Sea-level rise | Governance instability<br>Population pressures and high population density<br>High demand for natural resources<br>Lack of entitlements and access to key resources<br>Overexploitation of groundwater reserves<br>Storage capacities<br>Interboundary relations<br>Preexisting tensions<br>High projected urbanization rates | *Regions:*<br>Countries already affected by conflict Countries where there are tensions between the mining industry and farmers/ indigenous groups (e.g. Peruvian Andes)<br>Low-lying areas exposed to sea-level rise<br>*Groups:*<br>Land holders<br>Farmers/subsistence farmers<br>Herders<br>Indigenous groups | *Adaptation:*<br>Diversification of income-generating activities in agriculture and fishing<br>Temporary migration as a risk management strategy or last resort option<br>Transboundary water cooperation and flood management | Medium<br>Lack of conclusive findings on the relationship between climatic changes and conflict | Rayleigh and Urdal (2007)<br>Hendrix and Saleyhan (2012)<br>Harris et al. (2013)<br>Kallis and Zografos (2012)<br>Adano et al. (2012)<br>Theisen (2012)<br>Kloos et al. (2013)<br>Benjaminsen et al. (2012)<br>Adger et al. (2014) |
| **Extreme weather events or sudden disasters leading to conflict/social unrest** | Floods<br>Tropical cyclones | Preexisting tensions<br>Grievances (e.g., related to distribution of relief supplies and other resources)<br>Food price fluctuations<br>Weak governance | *Regions:*<br>Countries where governance is weak or visibly inequitable<br>*Groups:*<br>Poor people<br>Children | *Adaptation:*<br>Disaster risk reduction strategies | Limited (inconclusive evidence) | Nel and Righarts (2008)<br>Harris et al. (2013)<br>Bergholt and Lujala (2012)<br>Adger et al. (2014) |
| **Protests related to increased food or fuel prices** | | Poverty and inequality<br>Financial speculation over food stocks and energy prices<br>Carbon subsidies | *Regions:*<br>More common where governance is weak or visibly inequitable<br>*Groups:*<br>Low income urban groups | | Limited (much speculation but few studies) | Ortiz et al. (2013)<br>Hoffman and Jamal (2012) |

| RISK/IMPACT | TYPES OF BIOPHYSICAL CHANGE | INTERACTION WITH OTHER TRENDS | WHO IS PARTICULARLY AFFECTED AND WHERE | INTERACTIONS WITH ADAPTATION AND MITIGATION PROCESSES | EVIDENCE BASE | KEY REFERENCES |
|---|---|---|---|---|---|---|
| **Increased risk of conflict through climate/extreme event-induced displacement** | Increased frequency and severity of extreme weather events | Population pressures<br>Reduction of and competition over natural resources<br>Visible inequalities<br>Cultural clashes<br>Political instability | *Regions:*<br>Countries where resources are scarce/or physically vulnerable to climate change with inequalities on ethnic/ regional lines<br>*Groups:*<br>Low-income groups<br>People who lack political recognition | *Adaptation:*<br>Diversification of income-generating activities in agriculture and fishing<br>Temporary migration as a risk management strategy<br>Transboundary water cooperation and flood management | Risk of increased conflict cannot be ruled out | Buhaug et al. (2010)<br>Stern (2013)<br>Bernauer et al. (2012)<br>Koubi et al. (2012)<br>Scheffran et al. (2011)<br>Theisen et al. (2012)<br>Adger et al. (2014) |

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