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Emergent Risks and Key Vulnerabilities

Coordinating Lead Authors:
Michael Oppenheimer (USA), Maximiliano Campos (Costa Rica), Rachel Warren (UK)

Lead Authors:
Joern Birkmann (Germany), George Luber (USA), Brian O'Neill (USA), Kiyoshi Takahashi (Japan)

Contributing Authors:
Franz Berkhout (Netherlands), Pauline Dube (Botswana), Wendy Foden (South Africa), Stefan Greiving (Germany), Solomon Hsiang (USA), Matt Johnston (USA), Klaus Keller (USA), Joan Kleypas (USA), Robert Kopp (USA), Rachel Licker (USA), Carlos Peres (UK), Jeff Price (UK), Alan Robock (USA), Wolfram Schlenker (USA), John Richard Stepp (USA), Richard Tol (UK), Detlef van Vuuren (Netherlands)

Review Editors:
Mike Brklacich (Canada), Sergey Semenov (Russian Federation)

Volunteer Chapter Scientists:
Rachel Licker (USA), Solomon Hsiang (USA)

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Executive Summary

This chapter assesses climate-related risks in the context of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC). {Box 19.1} Such risks arise from the interaction of the evolving exposure and vulnerability of human, socioeconomic, and biological systems with changing physical characteristics of the climate system. {19.2} Alternative development paths influence risk by changing the likelihood of climatic events and trends (through their effects on greenhouse gases (GHGs) and other emissions) and by altering vulnerability and exposure. {19.2.4, Figure 19-1, Box 19-2}

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, as well as adaptation and mitigation actions affecting the same or a different sector are generally not included or well integrated into projections of risk. However, their consideration leads to the identification of a variety of emergent risks {Box 19-2} that were not previously assessed or recognized (*high confidence*). {19.3} This chapter identifies several such complex system interactions that increase vulnerability and risk synergistically. For example:

- **The risk of climate change to human systems (e.g., agriculture and water supply) is increased by the loss of ecosystem services that are supported by biodiversity** (e.g., water purification, protection from extreme weather events, preservation of soils, recycling of nutrients, and pollination of crops) (*high confidence*). Studies since the Fourth Assessment Report (AR4) broadly confirm that a large proportion of species are at increased risk of extinction at all but the lowest levels of warming. {19.3.2.1, 19.5.1, 19.6.3.5}
- **Risks result from the management of water, land, and energy in the context of climate change.** For example, in some water stressed regions, as groundwater stores that have historically acted as buffers against impacts of climate variations and change are depleted, adverse consequences arise for human systems and ecosystems simultaneously undergoing alteration of regional groundwater resources due to climate change. The production of bioenergy crops to mitigate climate change leads to land conversion (e.g., from food crops and unmanaged ecosystems to energy crops; *high confidence*) and in some scenarios, reduced food security as well as additional GHG emissions over the course of decades or centuries. {19.3.2.2}
- **Climate change has the potential to adversely affect human health by increasing exposure and vulnerability to a variety of stresses.** For example, the interaction of climate change with food security can exacerbate malnutrition, increasing vulnerability of individuals to a range of diseases (*high confidence*). {19.3.2.3}
- **The risk of severe harm and loss due to climate change-related hazards and various vulnerabilities is particularly high in large urban and rural areas in low-lying coastal zones (*high confidence*).** These areas, many characterized by increasing populations, are exposed to multiple hazards and potential failures of critical infrastructure, generating new systemic risks. Cities in Asian megadeltas, where populations are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding, provide an example. {19.2.3, 19.3.2.4, 19.4.2.1, 19.6.1.3.1, 19.6.2.1, 19.7.5, Table 19-4}
- **Spatial convergence of impacts in different sectors creates compound risk in many areas (*medium confidence*).** Examples include the Arctic (where thawing and sea ice loss disrupt land transportation, buildings, other infrastructure, and are projected to disrupt indigenous culture); and the environs of Micronesia, Mariana Island, and Papua New Guinea (where coral reefs are highly threatened due to exposure to concomitant sea surface temperature rise and ocean acidification). {19.3.2.4}

Emergent risks also arise from indirect, trans-boundary, and long-distance impacts of climate change. Adaptive responses and mitigation measures sometimes increase such risks (*high confidence*). {19.4} Human or ecological responses to local impacts of climate change can generate harm at distant places.

- Increasing prices of food commodities on the global market due to local climate impacts, in conjunction with other stressors, decrease food security and exacerbate food insecurity at distant locations. {19.4.1}
- Climate change will bear significant consequences for human migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). {19.4.2.1}
- The effect of climate change on conflict and insecurity is an emergent risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change. In numerous statistical studies, the influence of climate variability on violent conflict is large in magnitude (*medium confidence*). {19.4.2.2}
- Many species shift their ranges in response to climate change, adversely affecting ecosystem function and services while presenting new challenges to conservation efforts (*medium confidence*). {19.4.2.3}

- Mitigation measures taken in one location can have long-distance or indirect impacts on biodiversity and/or human systems. For example, the development of biofuels as energy sources can increase food prices (*high confidence*) and affect distant land use practices. {19.4.1, 19.4.3}

Additional risks related to particular biophysical impacts of climate change have arisen recently in the literature in sufficient detail to permit assessment (*high confidence*). {19.5}

- **Risks associated with global temperature rise in excess of 4°C relative to preindustrial levels[1] arise** from severe and widespread impacts on unique and threatened systems, substantial species extinction, extensive loss of ecosystem functioning, large risks to global and regional food security, and the combination of high temperature and humidity compromising normal human activities, including growing food or working outdoors in some areas for parts of the year (*high confidence*) and the potential for traversing thresholds that lead to disproportionately large Earth systems responses (*medium confidence*). {19.5.1}
- **Ocean acidification poses risks to marine ecosystems and the societies that depend on them.** For example, ocean acidification is *very likely* to lead to changes in coral calcification rates. Reduced coral calcification is projected to have impacts of medium to high magnitude on some ecosystem services, including tourism and the provisioning of fishing. {19.5.2}
- **There is increasing evidence in the literature that high ambient carbon dioxide (CO_2) concentrations in the atmosphere will affect human health by increasing the production and allergenicity of pollen and allergenic compounds and by decreasing nutritional quality of important food crops. {19.5.3}**
- **In addition to providing potential climate change abatement benefits, geoengineering poses widespread risks to society and ecosystems.** For example, in some model experiments the implementation of Solar Radiation Management (SRM) for the purpose of limiting global warming leads to ozone depletion and reduces precipitation. In addition, the failure or abrupt halting of SRM risks rapid climate change. {19.5.4}

Global, regional, and local socioeconomic, environmental, and governance trends indicate that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic and thus vary across temporal and spatial scales (*high confidence*). Effective risk reduction and adaptation strategies consider these dynamics and the inter-linkages between socioeconomic development pathways and the vulnerability and exposure of people. Changes in poverty or socioeconomic status, ethnic composition, age structure, and governance had a significant influence on the outcome of past crises associated with climatic hazards. {19.6.1}

Challenges for vulnerability reduction and adaptation actions are particularly high in regions that have shown severe difficulties in governance. Studies confirm that countries that are classified as failed states and afflicted by violence are often not able to reduce vulnerability effectively. Unless governance improves in countries with severe governance failure, risk will increase as a result of climate changes interacting with increased human vulnerability (*high confidence*). {19.6.1.3.3}

***Key risks* inform evaluation of "dangerous anthropogenic interference with the climate system," in the terminology of UNFCCC Article 2. These are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of hazards linked to climate change and the vulnerability of exposed societies and systems. Key risks were identified in this assessment based on expert judgments made by authors of the various chapters of this report in light of criteria described here {19.2.2.2} and consolidated into the following representative list (*high confidence*).** {19.2.2.2, 19.6.2.1, Table 19-4, Boxes 19-2 and CC-KR} (Roman numerals indicate corresponding entries in Table 19-4; notation at end of each entry indicates corresponding Reasons for Concern (RFCs), discussed below.)

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[1] Levels of global mean temperature change are variously presented in the literature with respect to "preindustrial" temperatures in a specified year or period, e.g., 1850–1900. Alternatively, the average temperature within a recent period, e.g., 1986–2005, is used as a baseline. In this chapter, we use both, depending on the literature being assessed. The increase above preindustrial (1850–1900) levels for the period 1986–2005 is estimated at 0.61°C (WGI AR5 Section 11.3.6.3). For example, using these baselines, a 2°C increase above preindustrial levels corresponds to a 1.39°C increase above 1986–2005 levels. We use other baselines on occasion depending on the literature cited and explicitly indicate where this is the case. Climate impact studies often report outcomes as a function of regional temperature change, which can differ significantly from changes in global mean temperature. In most land areas, regional warming is larger than global warming (WGI AR5 Section 10.3.1.1.2). However, given the many conventions in the literature for baseline periods, readers are advised to check carefully and to adjust baseline levels for consistency when comparing outcomes.

i) Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise. [RFC 1-5]
ii) Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions. [RFC 2 and 3]
iii) Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services. [RFC 2-4]
iv) Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas. [RFC 2 and 3]
v) Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings. [RFC 2-4]
vi) Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions. [RFC 2 and 3]
vii) Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic. [RFC 1, 2, and 4]
viii) Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods. [RFC 1, 3, and 4]

Climate change risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region, and time period; both are important to understanding possible outcomes (*high confidence*). In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a key role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services. {19.6.2.2}

Assessment of the RFC framework pertinent to Article 2 of the UNFCCC has led to evaluations of risk being updated in light of the advances since the AR4. {19.6.3} (All temperature changes are relative to 1986–2005, i.e., "recent." Numbers are indicative of RFC designation in key risk enumeration, above.)

1. **Unique and threatened systems**: Some unique and threatened systems, including ecosystems and cultures, are already at risk from climate change (*high confidence*). The number of such systems at risk of severe consequences is higher with additional warming of around 1°C. Many species and systems with limited adaptive capacity are subject to very high risks with additional warming of 2°C, particularly Arctic-sea-ice and coral-reef systems. {19.6.3.2}
2. **Extreme weather events**: Climate-change-related risks from extreme events, such as heat waves, extreme precipitation, and coastal flooding, are already moderate (*high confidence*) and high with 1°C additional warming (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*). {19.6.3.3}
3. **Distribution of impacts**: Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Risks are already moderate because of regionally differentiated climate-change impacts on crop production in particular (*medium* to *high confidence*). Based on projected decreases in regional crop yields and water availability, risks of unevenly distributed impacts are high for additional warming above 2°C (*medium confidence*). {19.6.3.4}
4. **Global aggregate impacts**: Risks of global aggregate impacts are moderate for additional warming between 1-2°C, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*), but few quantitative estimates have been completed for additional warming around 3°C or above. {19.3.2.1, 19.5.1, 19.6.3.5}
5. **Large-scale singular events**: With increasing warming, some physical systems or ecosystems may be at risk of abrupt and irreversible changes. Risks associated with such tipping points become moderate between 0-1°C additional warming, due to early warning signs that both warm-water coral reef and Arctic ecosystems are already experiencing irreversible regime shifts (*medium confidence*). Risks increase disproportionately as temperature increases between 1-2°C additional warming and become high above 3°C, due to the potential for a large and irreversible sea level rise from ice sheet loss. For sustained warming greater than some threshold, near-complete loss of the Greenland ice sheet would occur over a millennium or more, contributing up to 7 m of global mean sea level rise. {19.6.3.6}

Impacts of climate change avoided under a range of scenarios for mitigation of GHG emissions are potentially large and increasing over the 21st century (*high confidence*). {19.7.1} Among the impacts assessed here, benefits from mitigation are most immediate for surface ocean acidification and least immediate for impacts related to sea level rise. Because mitigation reduces the rate as well as the magnitude of warming, it also increases the time available for adaptation to a particular level of climate change, potentially by several decades.

Only mitigation scenarios in the most stringent category (i.e., with 2100 CO_2-eq concentrations of 430 to 480 ppm) maintain moderately healthy coral reefs (*medium confidence*). With respect to the RFCs, only the most stringent of scenarios in this category constrain overall risks to unique and threatened systems, and those associated with extreme weather events to a moderate level, while the other scenarios in this category create risk in the high range for these two RFCs. The most stringent among these scenarios constrain the level of risk associated with all other RFCs to the moderate level (*high confidence*). {19.6.3.2-3, 19.7.1}

The higher part of the range of GHG emission scenarios in the literature, that is, those with 2100 CO_2-eq concentrations above 720 ppm create risks associated with extreme weather events and large-scale singular events that are in the high range, and very high range (reflecting inability to adapt) for unique and threatened systems. Risks associated with the distribution of impacts increase toward the very high range (*high confidence*). Risks of global aggregate impacts transition from moderate to high as CO_2-eq concentrations increase from 720 ppm. {19.6.3.2, 19.6.3.4, 19.7.1}

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). For example, very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood. {19.7.1-2}

The risk of crossing tipping points (critical thresholds) in the Earth system or socio-ecological systems is projected to decrease with reduced GHG emissions {19.7.3}, and the risk of crossing tipping points in socio-ecological systems can also be reduced by reducing human vulnerability or by preserving ecosystem services, or both (*medium confidence*). {19.7.4} The risk of crossing tipping points is reduced by limiting the level of climate change and/or removing concomitant stresses such as overgrazing, overfishing, and pollution, but there is *low confidence* in the level of climate change associated with such tipping points and measures to avoid them.

19.1. Purpose, Scope, and Structure of this Chapter

The objective of this chapter is to assess new literature published since the Fourth Assessment Report (AR4) on emergent risks and key vulnerabilities to climate change from the perspective of the distribution of risk over geographic location, economic sector, time period, and socioeconomic characteristics of individuals and societies. Frameworks used in previous IPCC reports to assess risk in the context of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) are updated and extended in light of new literature, and additional frameworks arising in recent literature are examined. A focal point of this chapter is the interaction of the changing physical characteristics of the climate system with evolving characteristics of socioeconomic and biological systems (exposure and vulnerability) to produce risk (see Figure 19-1). Given the centrality of Article 2 to this chapter, the greater emphasis is on harmful outcomes of climate change rather than potential benefits.

19.1.1. Historical Development of this Chapter

The Third and Fourth Assessment Reports (TAR and AR4, respectively) each devoted chapters to evaluating the state of knowledge relevant to Article 2 of the UNFCCC (Smith et al., 2001; Schneider et al., 2007; see Box 19-1). The TAR sorted and aggregated impacts discussed in the literature according to a framework called Reasons for Concern (RFCs), and assessed the level of risk associated with individual impacts of climate change as well as each category or "reason" as a whole, generally as a function of global mean warming. This assessment took account of the distribution of vulnerability across particular regions, countries, and sectors.

AR4 furthered the discussion relevant to Article 2 by assessing new literature and developing criteria potentially useful for policy makers in the determination of key impacts and vulnerabilities, that is, those meriting particular attention in respect to Article 2. See Box 19-2 for definitions of Reasons for Concern, Key Vulnerabilities (KVs), and related terms. Some definitions go beyond those in the Glossary to provide details especially pertinent to this chapter.

AR4 emphasized the differences in vulnerability between developed and developing countries but also assessed new literature describing vulnerability pertaining to various aggregations of people (such as by ethnic, cultural, age, gender, or income status) and response strategies for avoiding key impacts. The RFCs were updated and the Synthesis Report (IPCC, 2007a) noted that they "remain a viable framework to consider key vulnerabilities" (IPCC, 2007a, Section 5.2). However, their

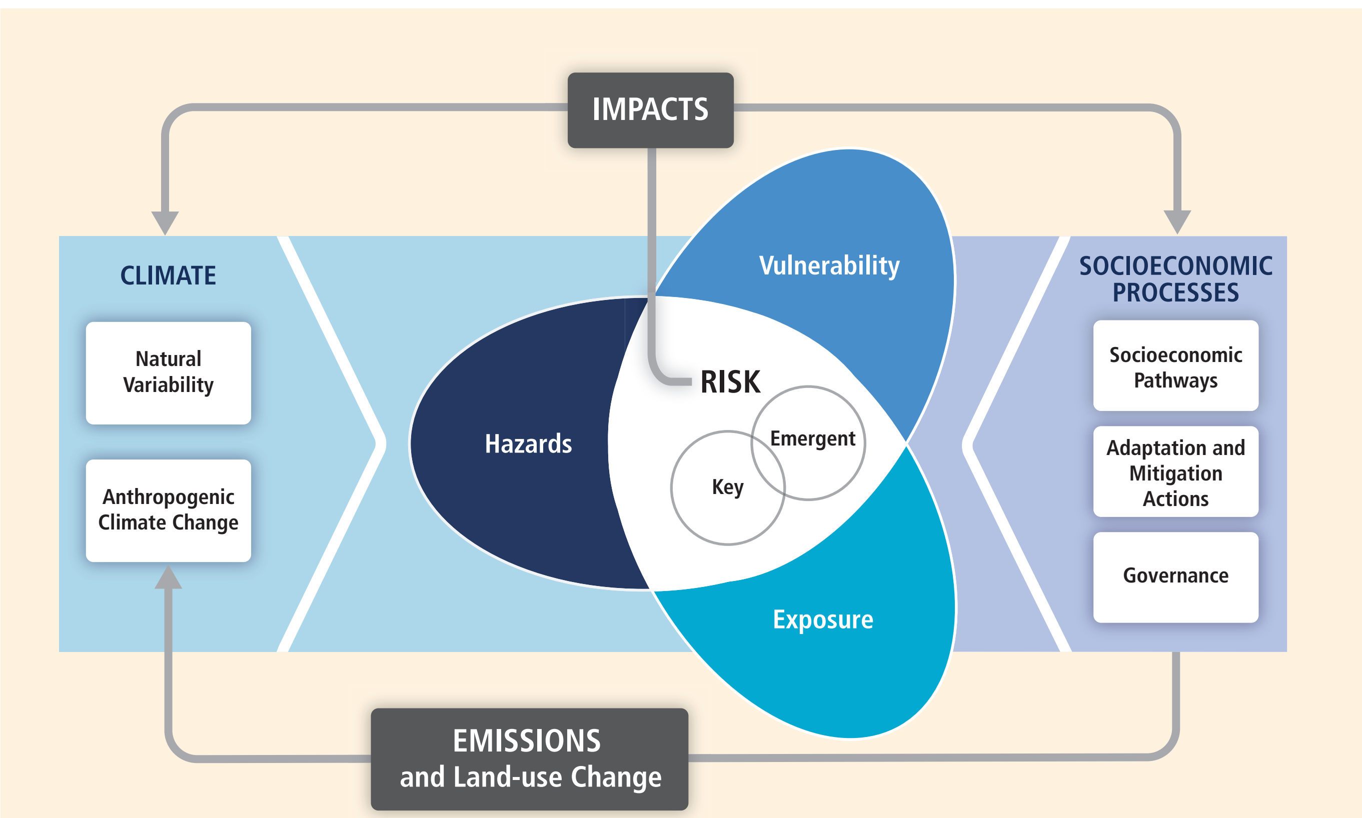

Figure 19-1 | Schematic of the interaction among the physical climate system, exposure, and vulnerability producing risk. The figure visualizes the different terms and concepts discussed in this chapter. Risk of climate-related impacts results from the interaction of climate-related hazards (including hazardous events and trends) with the vulnerability and exposure of human and natural systems. The definition and use of "key" and "emergent" are indicated in Box 19-2 and the Glossary. Vulnerability and exposure are, as the figure shows, largely the result of socioeconomic pathways and societal conditions (although changing hazard patterns also play a role; see Section 19.6.1.1). Changes in both the climate system (left side) and socioeconomic processes (right side) are central drivers of the different core components (vulnerability, exposure, and hazards) that constitute risk (modified version of SREX Figure SPM.1 (IPCC, 2012a)).

utility was limited by several factors: the lack of a time dimension (i.e., representation of impacts arising from timing and rates of climate change and climate forcing); the focus on risk only as a function of global mean temperature; lack of a clear distinction between impacts and vulnerability; and, importantly, incomplete incorporation of the evolving socioeconomic context, particularly adaptation capacity, in representing impacts and vulnerability.

19.1.2. The Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation

The IPCC *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; IPCC, 2012a) provides additional insights with respect to two RFCs (risks associated with extreme weather events and the distribution of impacts) and particularly the distribution of capacities to adapt to extreme events across countries, communities, and other groups, and the limitations on implementation of these capacities. SREX emphasized the role of the socioeconomic setting and development pathway (expressed through exposure and vulnerability) in determining, on the one hand, the circumstances where extreme events do or do not result in extreme

Box 19-1 | Article 2 of the United Nations Framework Convention on Climate Change

Article 2

OBJECTIVE: The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Frequently Asked Questions

FAQ 19.1 | Does science provide an answer to the question of how much warming is unacceptable?

No. Careful, critical scientific research and assessment can provide information to help society consider what levels of warming or climate change impacts are unacceptable. However, the answer is ultimately a subjective judgment that depends on values and culture, as well as socioeconomic and psychological factors, all of which influence how people perceive risk in general and the risk of climate change in particular. The question of what level of climate change impacts is unacceptable is ultimately not just a matter of the facts, but of how we feel about those facts.

This question is raised in Article 2 of the UNFCCC. The criterion, in the words of Article 2, is "dangerous anthropogenic interference with the climate system"—a framing that invokes both scientific analysis and human values.

Agreements reached by governments since 2009, meeting under the auspices of the UNFCCC, have recognized "the scientific view that the increase in global temperature should be below 2 degrees Celsius" (Section 19.1, UNFCCC, Copenhagen Accord). Still, as informed on the subject as the scientists referred to in this statement may be, theirs is just one valuable perspective. How each country or community will define acceptable or unacceptable levels, essentially deciding what is "dangerous," is a societal judgment.

Science can certainly help society think about what is unacceptable. For example, science can identify how much monetary loss might occur if tropical cyclones grow more intense or heat waves more frequent, or identify the land that might be lost in coastal communities for various levels of higher seas. But "acceptability" depends on how each community values those losses. This question is more complex when loss of life is involved and yet more so when damage to future generations is involved. These are highly emotional and controversial value propositions that science can only inform, not decide.

The purpose of this chapter is to highlight key vulnerabilities and key risks that science has identified; however, it is up to people and governments to determine how the associated impacts should be valued, and whether and how the risks should be acted upon.

Box 19-2 | Definitions

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

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

A broad set of factors such as wealth, social status, and gender determine vulnerability and exposure to climate-related risk.

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

Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term *hazard* usually refers to climate-related physical events or trends or their physical impacts.

Stressors: Events and trends, often not climate-related, that have an important effect on the system exposed and can increase vulnerability to climate-related risk.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.

$$\text{Risk} = (\text{Probability of Events or Trends}) \times \text{Consequences}$$

Risk results from the interaction of vulnerability, exposure, and hazard (see Figure 19-1). In this report, the term *risk* is used primarily to refer to the risks of climate-change impacts.

Key vulnerability, key risk, key impact: A vulnerability, risk, or impact relevant to the definition and elaboration of "dangerous anthropogenic interference (DAI) with the climate system," in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2, meriting particular attention by policymakers in that context.

Key risks are potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate-related hazards with vulnerabilities of societies and systems exposed. Risks are considered "key" due to high hazard or high vulnerability of societies and systems exposed, or both.

Vulnerabilities are considered "key" if they have the potential to combine with hazardous events or trends to result in key risks. Vulnerabilities that have little influence on climate-related risk, for instance, due to lack of exposure to hazards, would not be considered key.

Key impacts are severe consequences for humans and social-ecological systems.

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Box 19-2 (continued)

Extract from WGII AR4 Chapter 19:

Many impacts, vulnerabilities and risks merit particular attention by policy-makers due to characteristics that might make them 'key'. The identification of potential key vulnerabilities is intended to provide guidance to decision-makers for identifying levels and rates of climate change that may be associated with 'dangerous anthropogenic interference' (DAI) with the climate system, in the terminology of United Nations Framework Convention on Climate Change (UNFCCC) Article 2 (see Box 19-1). Ultimately, the definition of DAI cannot be based on scientific arguments alone, but involves other judgments informed by the state of scientific knowledge.

Emergent Risk: A risk that arises from the interaction of phenomena in a complex system, for example, the risk caused when geographic shifts in human population in response to climate change lead to increased vulnerability and exposure of populations in the receiving region. Many of the emergent risks discussed in this report have only recently been analyzed in the scientific literature in sufficient detail to permit assessment. In this chapter, the only emergent risks discussed are those that have the potential to become key risks once sufficient understanding accumulates.

Reasons for Concern: Elements of a classification framework, first developed in the IPCC Third Assessment Report, which aims to facilitate judgments about what level of climate change may be "dangerous" (in the language of Article 2 of the UNFCCC) by aggregating impacts, risks, and vulnerabilities.

Summary of Reasons for Concern (revised from WGII TAR Chapter 19; see also Sections 1.2.3, 18.6.4):

"Reasons for Concern" may aid readers in making their own determination about what is a "dangerous" climate change. Each Reason for Concern is consistent with a paradigm that can be used by itself or in combination with other paradigms to help determine what level of climate change is dangerous. The reasons for concern are the relations between global mean temperature increase and:

1. *Risks to unique and threatened systems*
2. *Risks associated with extreme weather events*
3. *Risks associated with the distribution of impacts*
4. *Risks associated with global aggregate impacts*
5. *Risks associated with large-scale singular events*

impacts and disasters, and on the other hand, when non-extreme events may also result in extreme impacts and disasters.

19.1.3. New Developments in this Chapter

With these frameworks already established, and a long list of impacts and key vulnerabilities enumerated and categorized in previous assessments, the current chapter has three goals: first, to recognize and assess risks that arise out of complex interactions involving climate and socio-ecological systems, called *emergent risks* (see Boxes 19-2, CC-KR; Table 19-4). In many cases, scientific literature sufficient to permit assessment of such risks has become available largely since AR4. In this chapter, we consider only those emergent risks that are relevant to interpreting Article 2 or have the potential to become relevant (see criteria in Section 19.2.2) as additional understanding accumulates. For example, since AR4, sufficient literature has emerged to allow initial assessment of the potential relationship between climate change and conflict. The second goal is to reassess and reorganize the existing frameworks (based on RFCs and KVs) for evaluating the literature pertinent to Article 2 of the UNFCCC to address the deficiencies cited in Section 19.1.1, particularly in light of the advances in SREX and the current report's discussions of vulnerability and human security (Chapters 12 and 13) and adaptation (Chapters 14 to 17 and 20). From this perspective, the objective stated in Article 2 may be viewed as aiming in part to ensure human security in the face of climate change. Third, this chapter assesses recent literature pertinent to additional frameworks for categorizing risk and vulnerability, focusing on indirect impacts and interaction and concatenation of risk, including geographic areas of compound risk (Section 19.3).

To clarify the relative roles of characteristics of the physical climate system, such as increases in temperature, precipitation, or storm frequency, and characteristics of the socioeconomic and biological systems with which these interact (vulnerability and exposure) to produce risks of particular consequences (the latter term used interchangeably here with "impacts" and "outcomes"), we rely heavily on a concept used sparingly in the TAR and AR4, *key risks* (see Box 19-2). Furthermore, we emphasize recent literature pointing to the *dynamic* character of vulnerability and exposure based on their intimate relationship to development.

Section 19.2 describes the framework used here for identifying key vulnerabilities, key risks, and emergent risks. We consider a variety of types of emergent risks, including in Section 19.3 those arising from multiple interacting systems and stresses, and in Section 19.4, those arising from indirect impacts, trans-boundary impacts, and impacts occurring at a long distance from the location of the climate change that causes them. One example that illustrates all of these properties is the extent to which climate change impacts on agriculture, water resources, and sea level affect human migration flows. These shifts entail both risks of harm and potential benefits for the migrants, for the regions where they originate, and for the destination regions (see Sections 12.4, 19.4.2.1). Associated risks include indirect impacts, like the effect of land use changes on ecosystems occurring at the new locations of settlement, which may be near the location of the original climate impact or quite distant. Such distant, indirect effects would compound the direct consequences of climate change at the locations receiving the incoming migrants. In Section 19.5, we discuss other risks newly assessed here, including those arising from ocean acidification. Section 19.6 assesses key risks and vulnerabilities in light of the criteria discussed here (Section 19.2.2) and in the context of the RFCs, and Section 19.7 assesses response strategies aimed at avoiding key risks.

19.2. Framework for Identifying Key Vulnerabilities, Key Risks, and Emergent Risks

19.2.1. Risk and Vulnerability

Definitions and frameworks that systematize hazards, exposure, vulnerability, risk, and adaptation in the context of climate change are multiple, overlapping, and often contested (see, e.g., Burton et al., 1983; Blaikie et al., 1994; Twigg, 2001; Turner et al., 2003a,b; UNISDR, 2004; Schröter, 2005; Adger, 2006; Birkmann, 2006b; Füssel and Klein, 2006; Thomalla et al., 2006; Tol and Yohe, 2006; Villagrán de León, 2006; IPCC, 2007a; Cutter and Finch, 2008; Cutter et al., 2008; ICSU-LAC, 2010a,b; Cardona, 2011; DEFRA, 2012; IPCC, 2012a; Kienberger, 2012; Birkmann et al., 2013a; Costa and Kropp, 2013). Today, key reports and most authors differentiate among hazards, vulnerability, risk, and impacts (see, e.g., Hutton et al., 2011; IPCC, 2012a; Birkmann et al., 2013a). The recent literature underscores that risks from climate change are not solely externally generated circumstances or changes in the climate system to which societies respond, but rather the result of complex interactions among societies or communities, ecosystems, and hazards arising from climate change (Susman et al., 1983; Comfort et al., 1999; Birkmann et al., 2011a, 2013a; UNISDR, 2011; IPCC, 2012a). The differentiation of the various aspects of these interactions is an important improvement since AR4 because it exhibits the social construction of risk through the concept of vulnerability (IPCC, 2012a). This new framework, growing out of SREX, translates information more easily into a risk management approach that facilitates policy making (de Sherbinin, 2013). The following section advances this framework in the context of Article 2 of the UNFCCC.

We refer to the characteristics of climate change and its effects on geophysical systems, such as floods, droughts, deglaciation, sea level rise, increasing temperature, and frequency of heat waves, as *hazards*. In contrast, *vulnerability* refers primarily to characteristics of human or social-ecological systems exposed to hazardous climatic (droughts, floods, etc.) or non-climatic events and trends (increasing temperature, sea level rise) (UNDRO, 1980; Cardona, 1986, 1990; Liverman, 1990; Cannon, 1994, 2006; Blaikie et al., 1996; UNISDR, 2004, 2009; Birkmann, 2006a; Füssel and Klein, 2006; Thywissen, 2006; IPCC, 2012a). Ecosystems or geographic areas can be classified as vulnerable, which is of particular concern if human vulnerability increases as a result of potential impairment of the related ecosystem services. The Millennium Ecosystem Assessment (MEA), for example, identified ecosystem services that affect the vulnerability of societies and communities, such as provision of freshwater resources and air quality (Millennium Ecosystem Assessment, 2005a,b). Examples in this chapter and other chapters in this report include the vulnerability of warmwater coral reefs and respective ecosystem services for coastal communities (see Table 19-4; Box CC-KR).

The new framework used here also underscores that the development process of a society has significant implications for exposure, vulnerability, and risk. Climate change is not a risk per se; rather climate changes and related hazards interact with the evolving vulnerability and exposure of systems and therewith determine the changing level of risk (see Figure 19-1; Table 19-4). Identifying key vulnerabilities facilitates estimating key risks when coupled with information about evolving hazards associated with climate change. This approach provides the basis for criteria developed in the following sections.

19.2.2. Criteria for Identifying Key Vulnerabilities and Key Risks

Vulnerability is dynamic and context specific, determined by human behavior and societal organization, which influences for example the susceptibility of people (e.g., by marginalization) and their coping and adaptive capacities to hazards (see IPCC, 2012a). In this regard coping mainly refers to capacities that allow a system to protect itself in the face of adverse consequences, while adaptation—by contrast—denotes a longer term process that also involves adjustments in the system itself and refers to learning, experimentation, and change (Yohe and Tol, 2002; Pelling, 2010; Birkmann et al., 2013a). Perceptions and cognitive constructs about risks and adaptation options as well as cultural contexts influence adaptive capacities and thus vulnerability (Grothmann and Patt, 2005; Rhomberg, 2009; Kuruppu and Liverman, 2011; see Section 19.6.1.4). SREX stressed that the consideration of multiple dimensions (e.g., social, economic, environmental, institutional, cultural), as well as different causal factors of vulnerability, can improve strategies to reduce risks to climate change (see IPCC 2012c, p. 17; Cardona et al., 2012, pp. 17, 67–106).

Key vulnerability and key risk are defined in Box 19-2. Vulnerabilities that have little influence on overall risk are not considered key. Similarly, the magnitude or other characteristics of climate change-related hazards, such as glacier melting, sea level rise, or heat waves, are not by themselves adequate to determine key risks, as the consequences of climate change also will be determined by the vulnerability of the exposed society or social-ecological system. Key vulnerabilities and key risks embody a normative component because different societies might rank the various vulnerability and risk factors and actual or potential types of loss and damage differently (see Schneider et al., 2007, p. 785; Lavell et al., 2012, p. 45). Generally, vulnerability merits particular attention when the survival of societies, communities, or ecosystems is threatened (see UNISDR, 2011, 2013; Birkmann et al., 2011a). Climate change will influence the nature of the climatic hazards people and ecosystems are exposed to and also contribute to deterioration or improvement of coping and adaptive capacities of those exposed to these changes. Consequently, many studies (Wisner et al., 2004; Cardona, 2010; Birkmann et al., 2011a) focus with a priority on the vulnerability of humans and societies as a central feature, rather than solely on the level of climatic change and respective hazards.

19.2.2.1. Criteria for Identifying Key Vulnerabilities

We reorganize and further develop criteria for identifying vulnerabilities as "key" used in AR4 based on the literature (Blaikie et al., 1994; Bohle, 2001; Turner et al., 2003a,b; Birkmann, 2006a, 2011a; Villagrán de León, 2006; Cutter et al., 2008; Cutter and Finch, 2008; ICSU-LAC, 2010a,b; Cardona, 2011; UNISDR, 2011; IPCC, 2012a; Birkmann et al., 2013a) and the differentiation of hazard, exposure, and vulnerability presented here. The criteria in this and succeeding sections were used to identify key vulnerabilities, key risks, and emergent risks in Sections 19.4 and 19.6.1-2, and in Table 19-4. Not all of the criteria need to be fulfilled to characterize a vulnerability or risk as key but the characterization of a phenomenon as a KV or key risk is usually supported by more than one criterion.

The following five criteria are used to judge whether vulnerabilities are key:

1) *Exposure of a society, community, or social-ecological system to climatic stressors*. While exposure is distinct from vulnerability, exposure is an important precondition for considering a specific vulnerability as key. If a system is neither at present nor in the future exposed to hazardous climatic trends or events, its vulnerability to such hazards is not relevant in the current context. Exposure can be assessed based on spatial and temporal dimensions.
2) *Importance of the vulnerable system(s). Views on the importance of different aspects of societies or ecosystems can vary across regions and cultures* (see Kienberger, 2012). However, the identification of KVs is less subjective when it involves characteristics that are crucial for the survival of societies or communities or social-ecological systems exposed to climatic hazards. Defining key vulnerabilities in the context of particular societal groups or ecosystem services also takes into account the conditions that make these population groups or ecosystems highly vulnerable, such as processes of social marginalization or the degradation of ecosystems (Leichenko and O'Brien, 2008; O'Brien et al., 2008; IPCC, 2012a).
3) *Limited ability of societies, communities, or social-ecological systems to cope with and to build adaptive capacities to reduce or limit the adverse consequences of climate-related hazard.* Coping and adaptive capacities are part of the formula that determines vulnerability (see IPCC, 2012a; Birkmann et al., 2013a). While coping describes actions taken within existing constraints to protect the current system and institutional settings, adaptation is a continuous process that encompasses learning and change of the system exposed, including changes of rule systems or modes of governance (Smithers and Smit, 1997; Pielke Jr., 1998; Frankhauser et al., 1999; Smit et al., 1999; Kelly and Adger, 2000; Yohe and Tol, 2002; Adger et al., 2005; Smit and Wandel, 2006; Pelling et al., 2008; Pelling, 2010; Tschakert and Dietrich; 2010; IPCC, 2012a; Birkmann et al., 2013a; Garschagen, 2013). Severe limits of coping and adaptation provide criteria for defining a vulnerability as key, as they are core factors that increase vulnerability to climatic hazards (see, e.g., Warner et al., 2012).
4) *Persistence of vulnerable conditions and degree of irreversibility of consequences.* Vulnerabilities are considered key when they are persistent and difficult to alter. This is particularly the case when the susceptibility is high and coping and adaptive capacities are very low as a result of conditions that are hard to change. Irreversible degradation of ecosystems (e.g., warmwater coral reefs), chronic poverty and marginalization, and insecure land tenure arrangements are drivers of vulnerability that in combination with climatic hazards determine risks that often persist over decades (see Box CC-KR), for example, as observed in the Sahel Zone. In this way, communities or social-ecological systems (e.g., coastal communities dependent on fishing or mountain communities dependent on specific soil conditions) may reach a tipping point (or critical threshold) that would cause a partial or full collapse of the system, including displacement (see Renaud et al., 2010; Section 19.4.2.1). Inability to replace such a system or compensate for potential and actual losses and damages (i.e., irreversibility) is a critical criterion for determining what is "key."
5) *Presence of conditions that make societies highly susceptible to cumulative stressors in complex and multiple-interacting systems*. Conditions that make communities or social-ecological systems highly susceptible to the imposition of additional climatic hazards or that impinge on their ability to cope and adapt, such as violent conflicts (e.g., during drought disaster in Somalia (see Menkhaus, 2010)) are considered under this criterion. Also, the critical dependence of societies on highly interdependent infrastructures (e.g., energy/power supply, transport, and health care) (see Rinaldi et al., 2001; Wang, S. et al., 2012; Atzl and Keller, 2013) leads to key vulnerabilities regarding multiple-interacting systems where capacity to cope or adapt to their failure is low (see Copeland, 2005; Reed et al., 2010; Section 19.6.2.1; Table 19-4).

19.2.2.2. Criteria for Identifying Key Risks

Risks are considered "key" due to high hazard or high vulnerability ("key vulnerability") of societies and systems exposed, or both. Criteria for determining key risks build on the criteria for key vulnerabilities, as vulnerability is a component of risk. As such, risk is strongly determined by coping and adaptive capacities. However, the criteria for identifying key risks also take into account the magnitude, frequency, and intensity of hazardous events and trends linked to climate change to which vulnerable systems are exposed. Accordingly, the following four additional criteria are used to judge whether risks are key:

1) *Magnitude*. Risks are key if associated harmful consequences have a large magnitude, determined by a variety of metrics including human mortality and morbidity, economic loss, losses of cultural importance, and distributional consequences (see Schneider et al., 2007; IPCC, 2012a). Magnitude and frequency of the hazard as well as socioeconomic factors that determine vulnerability and exposure contribute.
2) *Probability that significant risks will materialize and their timing*. Risks are considered key when there is a high probability that the hazard due to climate change will occur under circumstances where societies or social-ecological systems exposed are highly susceptible and have very limited capacities to cope or adapt and consequently potential consequences are severe. Both the timing of the hazard and the dynamics of vulnerability and exposure contribute. Risks that materialize in the near term may be evaluated differently than risks that materialize in the distant future, as the time available for building up adaptive capacities is different (Oppenheimer, 2005; Schneider et al., 2007; see also Section 19.6.3.6).
3) *Irreversibility and persistence of conditions that determine risks*. Persistence of risks refers to the fact that underlying drivers and root causes of these risks, either socioeconomic (e.g., chronic poverty; see Chapter 13) or physical, cannot be rapidly reduced. The criteria for assessing key vulnerabilities include the persistence of socioeconomic conditions contributing to vulnerability that also apply here (Section 19.2.2.1, point 4). In addition, some hazards are associated with the potential for persistent physical impacts, such as loss of an ice sheet causing irreversible sea level rise or release of methane (CH_4) clathrates from the seabed.
4) *Limited ability to reduce the magnitude and frequency or other characteristics of hazardous climatic events and trends and the vulnerability of societies and social-ecological systems exposed*. Criterion 3 pertaining to key vulnerabilities (Section 19.2.2.1) discusses limited ability of societies to improve coping and adaptive capacities in order to manage risk. This criterion also applies here. In addition, risks are also considered to be key when societies together have very limited prospects for reducing the magnitude, frequency, or intensity of the associated climate hazards. For example, risks that may be reduced or limited by greenhouse gas (GHG) reductions that reduce the probability of the associated hazard are less threatening than those for which the likelihood of the hazard cannot be effectively altered (see also Section 19.7.1). For example, risks that are already projected to be large during the next few decades under a range of Representative Concentration Pathways (RCPs) are much more difficult to influence by reducing emissions than those projected to become large late in this century (e.g., see discussion of risk from extreme heat in Section 19.6.3.3).

19.2.3. Criteria for Identifying Emergent Risks

A risk that arises from the interaction of phenomena in a complex system is defined here as an *emergent risk*. For example, feedback processes between climatic change, human interventions involving mitigation and adaptation, and processes in natural systems can be classified as emergent risks if they pose a threat to human security. Emergent risks could arise from unprecedented situations, such as the increasing urbanization of low-lying coastal areas that are exposed to sea level rise or where new pluvial flooding risk emerges due to urbanization of vulnerable areas not historically populated. Some emergent risks have been identified or discussed only recently in the scientific literature, and as a result our ability to assess whether they are key risks is limited. In this chapter, the only emergent risks discussed are those that have the potential to become key risks once sufficient understanding accumulates.

19.2.4. Identifying Key and Emergent Risks under Alternative Development Pathways

Key risks are determined by the interaction of climate-related hazards with exposure and vulnerabilities of societies or ecosystems. Development pathways describing possible trends in demographic, economic, technological, environmental, social, and cultural conditions (Hallegatte et al., 2011) will affect key risks because they influence both the likelihood and nature of climate-related hazards, and the societal and ecological conditions determining exposure and vulnerability. Therefore some risks could be judged to be key under some development pathways but not others. Emergent risks can depend on development pathways as well, because whether or not they become key risks may be contingent on future socioeconomic conditions.

The effect of development pathways on climate-related hazards occurs through their effects on emissions and other radiative forcing factors such as land use change (see WGI AR5 Chapter 12). Components of development pathways such as economic growth, technical change, and policy will influence the rates and spatial distributions of emissions of GHGs and aerosols, and of land use change, and therefore influence the magnitude, timing, and heterogeneity of hazards (see WGIII AR5 Chapter 5).

Development pathways will also influence the factors determining key vulnerabilities of human and ecological systems, including exposure, susceptibility, or sensitivity to impacts, and adaptive capacity (Yohe and Tol, 2002; Füssel and Klein, 2006; Hallegatte et al., 2011; Birkmann et al., 2013a; O'Neill et al., 2014). The magnitude of the aggregate exposure and sensitivity of socio-ecological systems will depend on population growth and spatial distribution, economic development patterns, and social systems. The particular elements of the social-ecological system that are most exposed and sensitive to climate hazards, and that are considered most important, will depend on spatial development patterns as well as on cultural preferences, attitudes toward nature/biodiversity, and reliance on climate-sensitive resources or services, among other factors (Adger, 2006; Füssel, 2009). The degree to which persistent or difficult to reverse vulnerabilities are built into social systems, as well as the degree of inequality in exposure and vulnerability across social groups or regions, also depend on characteristics of development pathways (Adger et al., 2009).

19.2.5. Assessing Key Vulnerabilities and Emergent Risks

The criteria above for assessing vulnerability and risk provide a sequence of potential assessment steps. While the initial assessment phase would explore whether and how a society or social-ecological system is exposed to climate-related hazards, the assessment would subsequently focus on the predisposition of societies or ecosystems to be adversely affected (vulnerability) and the potential occurrence of severe adverse consequences for humans and social-ecological systems once the hazard interacts with the vulnerability of societies and systems exposed. In addition, the importance of the system at risk and the ability of a society or system to cope and to adapt to these stressors would be assessed. Finally, the application of the criteria would also require the assessment of the irreversibility of the consequences and the persistence of vulnerable conditions. Hence, the assessment criteria for risks focus on the internal conditions of a person, a community (e.g., age structure, poverty), or a social-ecological system and the contextual conditions that influence their vulnerability (e.g., governance conditions and systems of norms), in addition to the assessment of hazards, such as storm intensity, heat waves, and sea level rise, which are directly influenced by climate change. Examples of such KVs and key risks drawn from other chapters of this assessment are provided in Section 19.6 and particularly in Table 19-4 and Box CC-KR.

19.3. Emergent Risk: Multiple Interacting Systems and Stresses

19.3.1. Limitations of Previous Approaches Imply Key Risks Overlooked

Interactions of climate change impacts on one sector with changes in exposure and vulnerability, or with adaptation and mitigation actions affecting the same or a different sector, are generally not included or well integrated into projections of risk (Warren, 2011). However, their consideration leads to the identification of a variety of *emergent risks* that were not previously assessed or recognized. This chapter identifies several such complex system interactions that increase vulnerability and risk synergistically (*high confidence*; Section 19.3). There are a very large number of potential interactions, and many important ones have not yet been quantified, meaning that some key risks have been overlooked (*high confidence*). In some cases, literature analyzing these risks is very recent. The six interaction processes listed below, though not exclusive, are systemic and may lead to further key vulnerabilities as well as a larger number of less significant impacts. Several of these are discussed in more detail in the following sections:

- Biodiversity loss induced by climate change that erodes ecosystem services, in turn increasing vulnerability and exposure of human systems dependent on those services (Section 19.3.2.1).
- Alterations in extreme weather events induced by climate change that affect human systems and ecosystems, increasing vulnerability and exposure to the effects of mean climate change. Most impacts projections are based only on changes in mean climate (Rosenzweig and Hillel, 2008; IPCC, 2012a, Box 3-1).
- The interaction between non-climate stressors such as those related to land management, water management, air pollution (which has drivers in common with climate change), and energy production and climate change (Section 19.3.2.2). Heretofore, mainly climate interactions with population/economic growth were assessed.
- Climate changes that increase human exposure and vulnerability to disease (Section 19.3.2.3).
- Locations where risks in different sectors are compounded because impacts, hazards, vulnerability, and exposure interact non-additively (Section 19.3.2.4).
- Mitigation or sectoral adaptation that has unintended consequences for the functioning of another sector (Section 14.6).

19.3.2. Examples of Emergent Risks

19.3.2.1. Emergent Risks Arising from the Effects of Degradation of Ecosystem Services by Climate Change

Biodiversity loss is linked to disruption of ecosystem structure, function, and services (Díaz et al., 2006; Gaston and Fuller, 2008; Cardinale et al., 2012; Maestre et al., 2012; Midgley, 2012). Terrestrial and freshwater species face increased extinction risks under projected climate change during and beyond the 21st century, especially as climate change interacts with other pressures (*high confidence*; Section 4.3.2.5). A large number of modelling studies project that species ranges decline in size as mean climate changes (Section 4.3.2.5); for example, a global scale study of 50,000 species found that the range sizes of 57 ± 6% of widespread and common plants and 34 ± 7% of widespread and common animals are projected to decline by more than 50% by the 2080s if global temperatures increase by 3.5°C relative to preindustrial times, when allowing for species to disperse at observed rates to areas that become newly climatically suitable (Warren et al., 2013a). AR4 (Fischlin et al., 2007, p. 213) estimated that "Approximately 20 to 30% of plant and animal species assessed so far (in an unbiased sample) are likely to be at increasingly high risk of extinction as global mean temperatures exceed a warming of 2 to 3°C above preindustrial levels (*medium confidence*)." Evaluation of various lines of evidence including a range of modeling approaches and, since AR4, new and/or improved techniques (e.g., multifactorial driven species distribution models, species specific population dynamics, tree- and trait-based modeling (for an overview see Bellard et al., 2012, Table 1; also Murray et al., 2011; Dullinger et al., 2012; Staudinger et al., 2012; Foden et al., 2013) imply similar levels of risk as in AR4 with some new estimates indicating higher fractions of species at risk. However, there is *low agreement* on the completeness of these lines of evidence for assigning specific numerical values for fraction of species at risk (see Sections 4.3.2.5, 19.5.1).

These extinction risks and possible declines in species richness are associated with change in mean climate, but ecosystems and species are also expected to be affected by projected climate change-induced increases in short-term extreme weather events and increased fire frequency in some locations (see IPCC, 2012a; WGI AR5 Table SPM.1; WGI AR5 Sections 6.4.8.1, 12.4.3, 12.4.5). Accordingly, despite the recognition of additional uncertainties in numerical estimates since AR4 (Section 4.3.2.5), the evidence for risk to a substantial fraction of species associated with increasing global mean temperature (GMT) is *robust*.

In both terrestrial and marine environments, the potential for the disruption of ecosystem functionality as a result of climate change translates into a key risk of large-scale loss of ecosystem services (Mooney et al., 2009; Midgley, 2012; Table 19-4). At-risk services include water purification by wetlands, removal and sequestration of carbon dioxide (CO_2) by forests, crop pollination by insects, coastal protection by mangroves and coral reefs, regulation of pests and disease, and recycling of waste nutrients (Sections 4.3.4, 22.4.5.6, 27.3.2.1; Box 23-1; Chivian and Bernstein, 2008). Biodiversity loss can lead to an increase in the transmission of infectious diseases such as Lyme, schistosomiasis, and hantavirus in humans, and West Nile virus in birds, creating a newly identified dimension to the emergent risks resulting from biodiversity loss (Keesing et al., 2010).

There are a number of examples of projected yield losses in the agricultural sector due to increased prevalence of pest species under climate change including *Fusarium graminearum* (a fungal disease of wheat), the European corn borer, the Colorado beetle, bakanae disease and leaf blights of rice, and Western corn root worm (Petzoldt and Seaman, 2006; Huang et al., 2010; Kocmánková et al., 2010; Chakraborty and Newton, 2011; Magan et al., 2011; Aragón and Lobo, 2012); or declines in pollinators (Rosenzweig and Hillel, 2008; Abrol, 2012; Bedford et al., 2012; Giannini et al., 2012; Kuhlmann et al., 2012; see also Section 4.3.4). Climate change impacts on pollinators places these valuable services at risk, and affects animals that are dependent on the plants (see Chapter 4). Although the impacts of CO_2 fertilization on plant-pathogen systems is not well understood (Section 7.3.2.3), these processes operate simultaneously with climate change's direct effects on yields through changing temperature, precipitation, and CO_2 concentrations, creating an emergent risk. Climate change has caused, or is projected to cause, range expansion in weeds that have the potential to become invasive (Bradley et al., 2010; Clements and Ditommaso, 2011). These can damage agriculture and threaten other species with extinction, with costs to economies being extremely high (e.g., US$120 billion annually in the USA; Pimentel et al., 2005; Crowl et al., 2008). Although there are also examples of projected decreases in insect damage to crops, there is a tendency for risk of insect damage to plants to increase with climate change (Section 7.3.2.3). Any one of the above mechanisms could result in harmful outcomes that act in synergy with existing climate change impacts on agriculture. Hence, these various susceptibilities to loss of ecosystem services comprise a KV and, in interaction with climate change, imply a potential key risk that global scale yields of a number of crops will be reduced by such interactions.

Severe decline of coral reefs (Section 19.3.2.4) would result in widespread loss of income for many countries, for example, AU$5.4 billion to the Australian economy from tourism (Box CC-CR). More generally, for many small island developing states (SIDS), increases in vulnerability due to loss of such ecosystem services interact with physical impacts of climate change such as sea level rise to create an emergent risk (*high confidence*).

Various studies of ecosystem services, nationally or globally, illustrate the very large values that are attributed to these services (Table 19-1). Such costs are represented only very crudely in aggregate global models of the economic impacts of climate change where "non-market impacts" are estimated very broadly if at all (Section 19.6.3.5). These costs contribute to the large magnitude of risks to human systems resulting from loss of ecosystem services, which in some cases would be irreversible. Hence the increase in vulnerability due to loss of ecosystem services interacting with climate change hazards comprises a key risk (*high confidence*). In some regions (e.g., South America) payment for ecosystem services (PES) has been implemented to support landowners to maintain the provision of services over time (Section 27.6.2; Table 27-7). Studies on degraded ecosystems examine the cost of restoring ecosystem services. Willingness to pay to restore degraded services along the Platte River (USA) (Loomis et al., 2000) greatly exceeded estimated costs of restoration. A meta-analysis of 89 studies looking at the restoration of ecosystem services measured using 526 different metrics found that restoration increased the amount of biodiversity and ecosystem services by 44 and 25% respectively, but restored services were still lower than in intact ecosystems (Benayas et al., 2009). Restoration of damaged ecosystems may be cost-effective, but only partially compensates for loss of services.

Concomitant stress from land use change adds to the extinction risk from climate change, increasing the projected extinction rate (e.g., Şekercioğlu et al., 2012) and contributing to the emergent risk of ecosystem service loss (see also Chapter 4). A synthesis of empirical studies across the globe reveals that ecosystem impacts due to land use change correlate locally with current maximum temperature and recent precipitation decline, indicating a potential for climate change to exacerbate the impacts of land use change (Mantyka-Pringle et al., 2012).

Land clearing releases carbon to the atmosphere and removes carbon sinks (WGI AR5 Section 6.3.2.2) such as old growth forests which would otherwise accumulate carbon (Luyssaert et al., 2008). Studies that value ecosystem services have tended to underestimate the importance of carbon sinks in ecosystems, owing to a tendency to consider only the carbon currently stored in the systems and not the fluxes (Anderson-Teixeira and DeLucia, 2011) and overlooking other aspects such as changes in albedo (e.g., Betts et al., 2012).

19.3.2.2. Emergent Risk Involving Non-Climate Stressors: The Management of Water, Land, and Energy

Human management of water, land, and energy interacts with climate change and its impacts, to profoundly affect risks to the amount of

Table 19-1 | Examples of global and national ecosystem service valuation studies. This table is not intended to be comprehensive. Furthermore, it encompasses studies based on a wide range of methodologies.

Ecosystem service	Region	Value	Currency	Citation
Pollination of crops	Globe	153 billion	Euro	Gallai et al. (2009)
Pollination of crops and wild plants	UK	430 million	£	UK NEA (2011)
Woodland cover increase from 6 to 12%	UK	680 million	£	UK NEA (2011)
CO_2 fixation, O_2 release, nutrient recycling, soil protection, water holding capacity, and environmental purification	Chinese terrestrial ecosystems	6.6 trillion	Yuan RMB	Shi et al. (2012)
Climate regulation provided by forests	USA	1–6 billion	US$ per year	Krieger (2001)
Recreation provided by forests	USA	1.3–110 billion	US$ per year	Krieger (2001)
Biodiversity supported by forests	USA	554 billion	US$ per year	Krieger (2001)
Coral reef services	Australia	5.4 billion	Au$	Section 19.3.2.1; Box CC-CR

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carbon that can be stored in terrestrial ecosystems, the amount of water available for use by humans and ecosystems, and the viability of adaptation plans for cities or protected areas. Failure to manage land, water, and energy in a synergistic fashion can exacerbate climate change impacts globally (Searchinger et al., 2008; Wise et al., 2009; Lotze-Campen et al., 2010; Warren et al., 2011) producing emergent risks which are also potential key risks. For example, the use of water by the energy sector, by thermo-electric power generation, hydropower, and geothermal energy, or biofuel production, can contribute to water stress in arid regions (Kelic et al., 2009; Pittock, 2011). Some energy technologies (biofuels, hydropower, thermal power plants), transportation fuels and modes, and food products (from irrigated crops, in particular animal protein produced by feeding irrigated crops) require more water than others (Box CC-WE; Sections 3.7.2, 7.3.2, 10.2, 10.3.5; McMahon and Price, 2011; Macknick et al., 2012; Ackerman and Fisher, 2013). In irrigated agriculture, climate, crop choice, and yields determine water requirements per unit of produced crop, and in areas where water must be pumped or treated, energy must be provided (Box CC-WE; Gerten et al., 2011). Recent studies address the energy, water, and land "nexus" to explore risks to the agricultural and energy sectors (Box CC-WE; Tidwell et al., 2011; Skaggs et al., 2012; Smith et al., 2013).

Biofuels can potentially mitigate GHG emissions when used in place of fossil fuels such as gasoline, diesel, and more carbon-intensive fuels from tar sands and heavy oil (Cherubini et al., 2009). One simulation of stringent mitigation (e.g., RCP2.6, which constrains radiative forcing to 2.6 W m^{-2} and therefore limits global mean temperature increase to 2°C over preindustrial levels during the 21st century) shows an increased reliance on biofuels (van Vuuren et al., 2011). However, due to the potential negative consequences of its use as a mitigation strategy, bioenergy development leads to several emergent risks, which are summarized in Table 19-2. Systems that may be vulnerable to bioenergy development are food systems (*high confidence*, due to bioenergy feedstocks replacing food crops; see Table 19-2.iii; Section 19.4.1) and ecosystems (*high confidence*), where biofuel cropping can directly or indirectly induce land use change, displacing terrestrial ecosystems such as forests, which can otherwise also act as carbon sinks (see Table 19-2.i).

While *direct* land use change (LUC) from impacts of biofuel development (from crop substitution and/or biofuel feedstock crop expansion) are a concern, *indirect* land use change (iLUC) has received more attention in the literature—both due to the magnitude of its potential impact (twice as great as direct LUC; Melillo et al., 2009a) and controversy over the uncertainty in accurately quantifying it. iLUC connotes land use change resulting from biofuel impacts on agricultural commodity markets (Fargione et al., 2008; Searchinger et al., 2008). Reductions of GHG emissions from biofuel production and use (compared to fossil fuels) may be offset partly or entirely for decades or centuries from iLUC-induced CO_2 emissions from deforestation and the draining of peatlands (*medium confidence*; Bringezu et al., 2009; van Vuuren et al., 2010; IPCC, 2011, Chapter 2; Miettinen et al., 2012; Smith et al. 2013). In Brazil, further biofuel expansion would be expected to impinge upon the Cerrado, the Amazon, and the Atlantic rainforest—all three of which have high levels of biodiversity (Table 19-2.v) and high levels of endemism (Lapola et al., 2010). Another study of biofuel production in Brazil (Barr et al., 2011) found that when pasture is accounted for, direct expansion into unexploited forest land is minor, that is, most of additional cropland is predicted to come from conversion of pastureland. However, unless the density of livestock operations is increased in tandem, the latter can also lead to iLUC. To the extent that biofuel feedstock crops are grown on areas that were previously fallow or degraded, the iLUC effects might be minimized and CO_2 potentially sequestered (Fargione et al., 2010; IPCC, 2011)—although the amount, alternative uses, and potential productivity of so-called degraded lands are still contested (Dauber et al., 2012). (For more information on the effects of biofuel production on terrestrial ecosystems, see Section 4.4.4; for more information on the effects of land acquisition for biofuel production on the poor, see Section 13.3.1.4.)

Whether such land management dynamics confound or contribute to mitigation depends on important interactions with global emissions mitigation policies (Table 19-2.ii; Van Vuuren et al., 2011). A failure to include land use change emissions within a carbon mitigation regime—for example, by applying a carbon price to fossil fuel and industrial emissions only—has been projected to lead to large-scale deforestation of natural forests and conversion of many other natural ecosystems by the end of the 21st century in 450 ppmv CO_2-eq and 550 ppmv CO_2-eq scenarios (Melillo et al. 2009b; Wise et al., 2009). This dynamic is due primarily to enhanced bioenergy production without a corresponding incentive to limit the resulting land use change emissions. If, instead, an equal carbon price is applied to terrestrial carbon (which, however, presents monitoring difficulties) along with fossil and industrial carbon, deforestation could slow down or even reverse.

That said, there are many equally compelling reasons for a country to encourage biofuel production including a means to produce downward pressure on oil prices, rural development, and reduced oil imports—all of which could be prioritized over biofuels as a GHG mitigation strategy depending on the country (Cherubini et al., 2009). Per-liter GHG emissions from biofuels decrease as agriculture is further intensified through row cropping, fertilizer and pesticide use, and irrigation, while other per-liter environmental impacts such as eutrophication increase (Burney et al., 2010; Grassini and Cassman, 2012). This creates an implicit conflict between alternative development priorities. Second-generation biofuels, such as those based on non-food crops (grasses, algae, timber) and agricultural residues, are expected to offer reduced emissions of GHGs and other air pollutants compared to most first-generation biofuels. This is due primarily to their having a smaller adverse interaction with food systems resulting in less LUC and iLUC (Plevin, 2009; Cherubini and Ulgiati, 2010; Fargione, 2010; Sander and Murthy, 2010). Further, bioelectricity and biogas both may be more effective at mitigating GHG emissions than liquid biofuels (Campbell et al., 2009; Power and Murphy, 2009).

Other emergent risks from bioenergy development are summarized in Table 19-2. Nearly all of the risks presented here are driven by the increased need for raw agricultural feedstocks. Competition for cultivable lands, irrigation resources (Box CC-WE), and other inputs are not unique to biofuel-related issues. The approximate doubling of agricultural demand projected between 2005 and 2050 (Tilman et al., 2011) similarly increases competition for land and water, and would be expected to exacerbate GHG emissions from agriculture (see also WGI AR5 Sections 6.4.3.2, 8.3.5).

Table 19-2 | Emergent risks related to biofuel production as a mitigation strategy.

No.	Issue	Issue description	Nature of emergent risk	Reference
i	Direct and/or indirect land use change	Potential for enhancement of greenhouse gas emissions	Mitigation benefit of biofuels reduced or negated	Melillo et al. (2009a,b); Wise et al. (2009); Khanna et al. (2011)
ii	Policies targeting only fossil carbon	Biofuel cropping competes with agricultural systems and ecosystems for land and water.	Mitigation benefit of policies reduced; harmful interactions with other key systems	Searchinger et al. (2008); Mellilo et al. (2009a,b); Wise et al. (2009); Fargione et al. (2008)
iii	Food/fuel competition for land	Competition for land driving up food prices	Emergent risk of food insecurity due to mitigation-driven land use change	Searchinger et al. (2008); Pimentel et al. (2009); Hertel et al. (2010)
iv	Biofuel production affects water resources.	Competition for water affects biodiversity and food cropping.	Emergent risk of biodiversity loss and food insecurity due to mitigation-driven water stress	Fargione (2010); Fingerman et al. (2010); Poudel et al. (2012); Yang et al. (2012)
v	Biofuel production affects biodiversity.	Competition for land reduces natural forest and biodiversity.	Emerging risk of biodiversity loss due to mitigation-driven land use change	Fizherbert et al. (2008); Koh et al. (2009); Lapola et al. (2010); Fletcher et al. (2011)
vi	Land conversion causes air pollution.	Potential for increased production of tropospheric ozone from palm/sugarcane-induced land use change	Emergent risk of greenhouse gas-mitigation-driven plant and human health damage caused by tropospheric ozone	Cançado et al. (2006); Hewitt et al. (2009)
vii	Fertilizer application	Potential for increased emissions of N_2O	Offsets some benefits of other mitigation measures	Donner and Kucharik (2008); Searchinger et al. (2008); Fargione (2010)
viii	Invasive properties of biofuel crops	Potential to become an invasive species	Unintended consequences that damage agriculture and/or biodiversity	Raghu et al. (2006); DiTomaso et al. (2007); Barney and Ditomaso (2008)

Projected changes in the hydrological cycle due to climate change (WGI AR5 Section 12.4.5) combined with increasing water demand leads to an emergent, potentially key risk of water stress exacerbated by the reduction of groundwater which serves as "an historical buffer against climate variability" (Green et al., 2011), and potentially further exacerbated by existing governance constraints that can act as barriers to reduce vulnerability. Climate change and increasing food demand are expected to drive expansion of irrigated cropland (Wada et al., 2013), increasing the demand for energy intensive extraction and conveyance of (ground or desalinated sea) water for irrigation (see Box CC-WE). If water is provided through groundwater extraction, pumping, or construction and use of de-salinization plants, local energy demand (and GHG emissions) will increase, although advanced irrigation systems are available that minimize enhancement of emissions (Rothausen and Conway, 2011).

A further potential key risk arises from increased water stress due to unsustainable groundwater extraction, which is expected to increase as an adaptation to climate change. Groundwater extraction is generally increasing globally with particularly large extraction in India and China (Wang, J. et al., 2012). The effects of climate change on groundwater are varied with some areas expecting decreased recharge while others are projected to experience increased recharge (Green et al., 2011; Portmann et al., 2013). Where extraction rates increase or recharge decreases, water tables will be depleted with potential key risks to local ecosystems and human systems (such as agriculture, tourism, and recreation), while water quality will decrease. One projection shows insufficient water availability in Africa, Latin America, and the Caribbean to satisfy both agricultural demands and ideal environmental flow regulations for rivers by 2050, a situation that is exacerbated by climate change (Strzepek and Boehlert, 2010).

19.3.2.3. Emergent Risks Involving Health Effects

Climate change will act through numerous direct and indirect pathways to alter the prevalence and distribution of diseases that are climate and weather sensitive. These effects will differ substantially depending on baseline epidemiologic profiles, reflecting the level of development and access to clean and plentiful water, food, and adequate sanitation and health care resources. Furthermore, the impact of climate change will differ within and between regions, depending on the adaptive capacity of public health and medical services and key infrastructure that ensures access to clean food and water.

A principal emergent global public health risk is malnutrition secondary to ecological changes and disruptions in food production as a result of changing rainfall patterns, increases in extreme temperatures (*high confidence*; IPCC, 2012a; see also Section 11.6.1), and increased atmospheric CO_2 (Taub et al., 2008; Burke and Lobell, 2010; Section 7.3.2.5). Modeling of the magnitude of the effect of climate change on future under-nutrition in five regions in South Asia and sub-Saharan Africa in 2050 (using *Special Report on Emissions Scenarios* (SRES) A2 emissions scenario) suggests an increase in moderate nutritional stunting, an indicator linked to increased risk of death and poor health (Black et al., 2008), of 1 to 29%, depending of the region assessed, compared to a future without climate change, and a much greater impact on severe stunting for particular regions, such as 23% for central sub-Saharan Africa and 62% for south Asia (Lloyd et al., 2011). The impact of climate-induced drought and precipitation changes in Mali include the southward movement of drought-prone areas which would result in a loss of critical agriculturally productive land by 2025 and increase food insecurity (Jankowska et al., 2012).

In densely populated megacities, especially those with a pronounced urban heat island effect, a principal emergent health risk results from the synergistic interaction between increased exposure to extreme heat and degraded air quality with the convergence of increasing vulnerability of an aging population and a global shift to urbanization (*high confidence*; Sections 8.2.3.5, 8.2.4.6, 11.5.3; Box CC-HS). These trends will increase the risk of relatively higher mortality from exposure to excessive heat (Knowlton et al., 2007; Kovats and Hajat, 2008; Luber and McGeehin, 2008). The health risks of such interactions include increased injuries and fatalities as a result of severe weather events including heat waves (see Section 19.6.3.3); increased aeroallergen production in urban areas leading to increases in allergic airway diseases (see Section 19.5.3); and respiratory and cardiovascular morbidity and mortality secondary to degraded air quality and ozone formation (see Section 19.6.3.3). While the association between ambient air quality and health is well established, there is an increasingly *robust* body of evidence linking spikes in respiratory diseases to weather events and to climate change. In New York City, for example, each single degree (Celsius) increase in summertime surface temperature has been associated with a 2.7–3.1% increase in same-day hospitalizations due to respiratory diseases, and an increase of 1.4–3.6% in hospitalizations due to cardiovascular diseases (Lin et al., 2009). Respiratory health outcomes will be exacerbated by climate change through increased production and exposure to ground-level ozone (particularly in urban areas), wildfire smoke, and increased production of pollen (D'Amato et al., 2010).

19.3.2.4. Spatial Convergence of Multiple Impacts: Areas of Compound Risk

In this chapter, we define an area of compound risk as a region where climate change-induced impacts in one sector affects other sectors in the same region, or a region where climate change impacts in different sectors are compounded, resulting in extreme or high-risk consequences. The frequent and ongoing spatial and temporal coincidence of impacts in different sectors in the same region has consequences that are more serious than simple summation of the sectoral impacts indicates (*medium confidence*). Such synergistic processes are difficult to identify through sectoral assessment and are apt to be overlooked in spite of their potential importance in considering key vulnerabilities and risks. For example, a large flood in a rural area may damage crop fields severely, causing food shortages (Stover and Vinck, 2008). The flood may simultaneously cause a deterioration of hygiene in the region and the spread of water-borne diseases (Schnitzler et al., 2007; Hashizume et al., 2008; Kovats and Akhtar, 2008). The coincidence of disease and malnutrition can thus create an area of compound risk for health impacts, with the elderly and children most at risk.

As a systematic approach, identification of areas of compound risk could be achieved by overlaying spatial data of impacts in multiple sectors, but this cannot indicate synergistic influences and dynamic changes in these influences quantitatively. For global analysis, certain types of integrated assessment models that allow spatial analysis of climate change impacts have been used to identify regions that are affected disproportionately by climate change (MNP, 2006; Kainuma et al., 2007; Warren et al., 2008; Füssel, 2010). Recent efforts attempt to collect and archive spatial data on impact projections and facilitate their public use. These have created overlays for identifying areas of compound risk with Web-Geographic Information Systems (GIS) technology (Adaptation Atlas; Resources for the Future, 2009). There are also efforts to coordinate impacts assessments adopting identical future climatic and/or socioeconomic scenarios at various spatial scales (Parry et al., 2004; Piontek et al., 2014). Areas of compound risk identified by overlaying spatial data of impacts in multiple sectors can be used as a starting point for regional case studies on vulnerability and multifaceted adaptation strategies (Piontek et al., 2014).

Frequently Asked Questions

FAQ 19.2 | How does climate change interact with and amplify preexisting risks?

There are two components of risk: the probability of adverse events occurring and the impact or consequences of those events. Climate change increases the probability of several types of harmful events that societies and ecosystems already face, as well as the associated risks. For example, people in many regions have long faced threats associated with weather-related events such as extreme temperatures and heavy precipitation (which can trigger flooding). Climate change will increase the likelihood of these two types of extremes as well as others. Climate change means that impacts already affecting coastal areas, such as erosion and loss of property in damaging storms, will become more extensive due to sea level rise. In many areas, climate change increases the already high risks to people living in poverty or to people suffering from food insecurity or inadequate water supplies. Finally, climate and weather already pose risks for a wide range of economic sectors, including agriculture, fisheries, and forestry: climate change increases these risks for much of the world.

Climate change can amplify risks in many ways, including through indirect interactions with other risks. These are often not considered in projections of climate change impacts. For example, hotter weather contributes to increased amounts of ground level ozone (smog) in polluted areas, exacerbating an existing threat to human health, particularly for the elderly and the very young and those already in poor health. Also, efforts to mitigate or adapt to climate change can have negative as well as positive effects. For example, government policies encouraging expansion of biofuel production from maize have recently contributed to higher food prices for many, increasing food insecurity for populations already at risk, and threatening the livelihoods of those like the urban poor who are struggling with the inherent risks of poverty. Increased tapping of water resources for crop irrigation in one region in response to water shortages related to climate change can increase risks to adjacent areas that share those water resources. Climate change impacts can also reverberate by damaging critical infrastructure such as power generation, transportation, or health care systems.

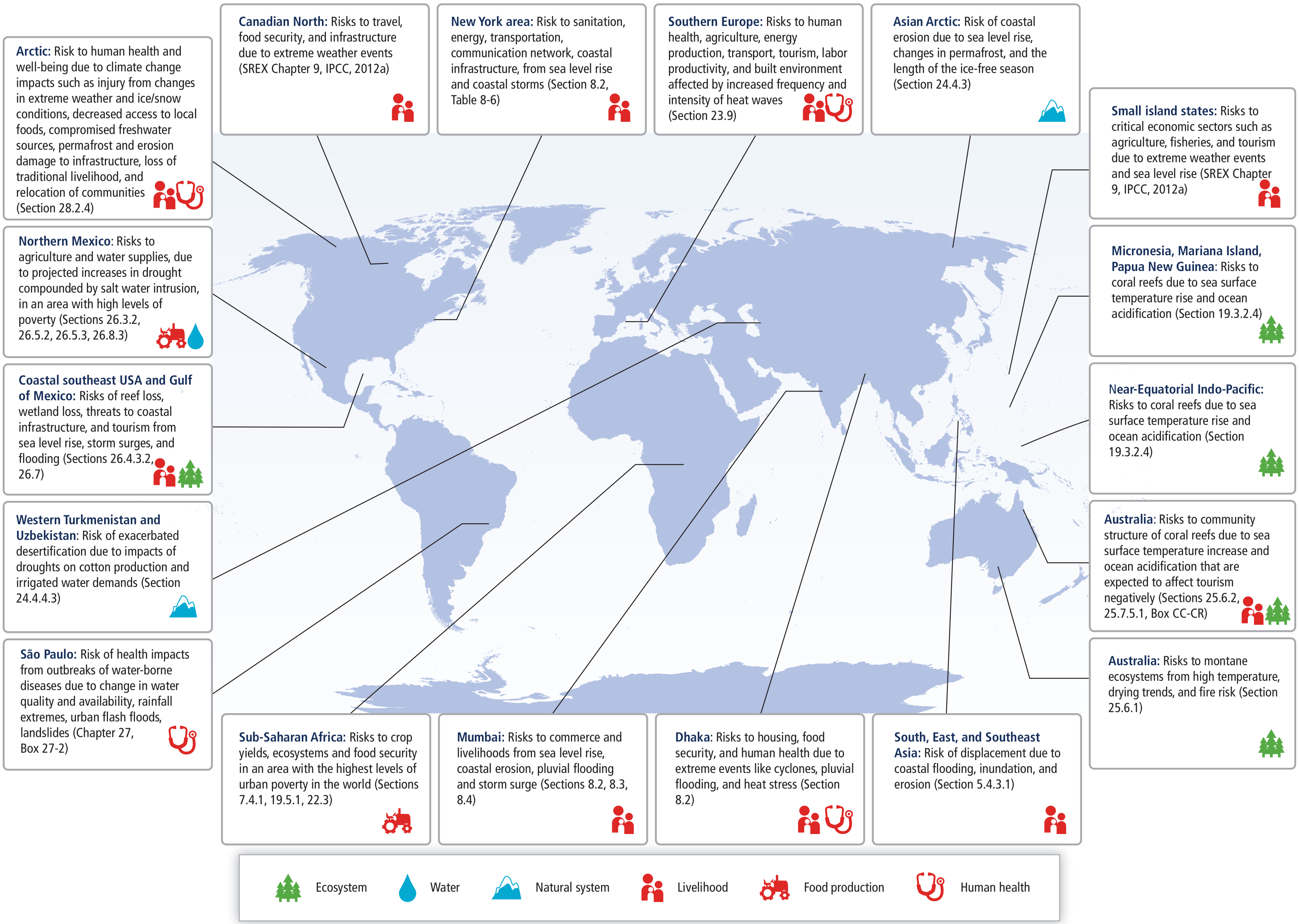

Figure 19-2 | Some examples of areas of compound risk identified in this assessment. Symbols indicate one or two of the main sectors or systems subject to compound risk, but in each case additional sectors and systems are at risk.

General equilibrium economic models (see Chapter 10) may facilitate quantitative evaluation of synergistic influences. An analysis of the EU by the PESETA project (Projections of economic impacts of climate change in sectors of Europe based on bottom-up analysis) showed sub-regional welfare loss by considering impacts on agriculture, coastal system, river floods, and tourism together in the Computable General Equilibrium (CGE) model, which is designed to represent interrelationships among economic activities of sectors. The result indicated the largest percentage loss in southern Europe (Ciscar et al., 2011).

The following examples illustrate different types of areas of compound risk where climate change impacts coincide and interact:

1) *Cities in deltas*, which are subject to sea level rise, storm surge, coastal erosion, saline intrusion, and flooding. Extreme weather events can also disrupt access to food supplies, enhancing malnutrition risk (Ahmed et al., 2009; see also Section 19.3.2.3). Based on national population projections, if contemporary rates of effective sea level rise (a net rate, defined by the combination of eustatic sea level rise and local contributions from fluvial sediment deposition and subsidence and subsidence due to groundwater and hydrocarbon extraction) continue through 2050, more than 6 million people would be at risk of enhanced inundation and increased coastal erosion in three megadeltas and 8.7 million in 40 deltas, absent measures to adapt (Ericson et al., 2006). Examples of urbanized delta areas at risk include, for example, those where Mumbai and Dhaka are located (see Chapters 8, 24; Section 19.6.3.4; Table 19-4).
2) *The Arctic*, where indigenous people (Crowley, 2011) are projected to be exposed to the disruption, and possible destruction of, their hunting and food sharing culture (see Chapter 28). Risk arises from a combination of sea ice loss and the concomitant local extinctions of the animals dependent on the ice (Johannessen and Miles, 2011). Thawing ground also disrupts land transportation, buildings, and infrastructure while exposure of coastal settlements to storms also increases due to loss of sea ice. Arctic ecosystems are broadly at risk (Kittel et al., 2011).
3) *Coral reefs*, which are highly threatened due to the synergistic effects of sea surface temperature rise and perturbed ocean chemistry, reducing calcification and also increasing sensitivity to other impacts such as the loss of coral symbionts (Chapter 6). The importance of reef sensitivity to climate change was recently highlighted in the near-equatorial Indo Pacific, the area of greatest reef diversity worldwide (Lough, 2012). A second highly diverse reef system at risk for warming was identified around Micronesia, Mariana Island, and Papua New Guinea (Meissner et al., 2012).

In Figure 19-2, these and other examples of areas of compound risk identified in this assessment are indicated on a world map. The map focuses on the key role that exposure plays in determining risk, particularly compound risk, rather than vulnerabilities per se.

19.4. Emergent Risk: Indirect, Trans-boundary, and Long-Distance Impacts

Climate change impacts can have consequences beyond the regions in which they occur. Global trade systems transmit and mediate a variety of impacts—the most prominent example of this is the global food trade system. The competitive market forces which dominate trade do not account for considerations of justice, and thus can incidentally diminish or enhance inequality in the distribution of impacts (see Section 19.6.3.4). Where prices on food, land, and other resources increase, vulnerability increases, *ceteris paribus*, for those most in need and least able to pay (see Section 19.6.1.2 on differential vulnerability). In addition, both mitigation and other adaptation responses have unintended consequences beyond the locations in which they are implemented (Oppenheimer, 2013). All of these mechanisms can create emergent risks (*high confidence*).

19.4.1. Crop Production, Prices, and Risk of Increased Food Insecurity

Recent literature indicates that climate trends have already influenced the yield trends of important crops (e.g., Kucharik and Serbin, 2008; Tao et al., 2008; Brisson et al., 2010; Lobell et al., 2011). Chapters 7 and 18 provide a detailed overview of these impacts, and have assessed with *medium confidence* that the effects of climate trends on maize and wheat yield trends have been negative in many regions over the past several decades, and have been small for major rice and soybean production areas (see Sections 7.2.1.1, 18.4.1.1.). For projected impacts, "Without adaptation, local temperature increases in excess of about 1°C above preindustrial is projected to have negative effects on yields for the major crops (wheat, rice, and maize) in both tropical and temperate regions, although individual locations may benefit (*medium confidence*)" (Section 7.4; Figures 7-4, 7-5, 7-7; Chapter 7 ES). Across all studies projecting crop yield impacts (some of which include both CO_2 fertilization and adaptation, and some which account for only one or neither of these), negative impacts on average yields become *likely* from the 2030s (Figure 7-5). Median yield impacts of 0 to –2% per decade are projected for the rest of the century (compared to yields without climate change) (Figure 7-7), and after 2050 the risk of more severe impacts increases (*medium confidence*) (Chapter 7 ES; Figure 7-5). Among the smaller number of studies that have projected global yield and price impacts, negative net effects of climate change, CO_2 increases, and agronomic adaptation on global yields are *about as likely as not* by 2050 and *likely* later in the 21st century (Section 7.4.4).

Climate impacts on crop production influence food prices directly and through complex interactions with a variety of factors, including biofuel crop production and mandates, as well as other domestic policies such as crop export bans (Sections 7.1.2, 7.2.2, 7.4.4). If climate changes reduce crop yields, international food prices and the number of food-insecure people are expected to increase globally (*limited evidence*, *high agreement*; Section 7.4.4). For example, global rice prices exhibit sensitivity both to yield impacts from climate changes as well as the loss of arable land to sea level rise (Chen et al., 2012). While the evidence base of how climate change will affect future food consumption patterns is limited (Section 7.3.3.2), there are large numbers of households that would be especially vulnerable to a loss of food access if food prices were to increase, for example, agricultural producers in low-income countries who are net food buyers (Section 7.3.3.2; Table 7-1).

In addition to the direct impacts of climate change, biofuel production in service of climate change mitigation may also affect food prices.

Accurately tracking and quantifying the direct and indirect impacts of biofuel production on the food system has become an intense area of study since AR4. U.S. ethanol production (for which maize is the primary feedstock) increased around 720% since 2000, with maize commodity prices nearly tripling and harvested land growing by more than 10%, mainly at the expense of soy (Wallander et al., 2011; EIA, 2013). Ethanol recently consumed one-quarter of U.S. maize production, even after accounting for feed by-products returned to the market (USDA, 2013). However, isolating biofuels' exact contribution to food system changes from other factors such as extreme weather events, climate change, changing diets, and increasing population have proven difficult (Zilberman et al., 2011). Still, estimates of the supply and demand elasticity of basic grain commodities lead to a prediction that the 2009 U.S. Renewable Fuel standard could increase commodity prices of maize, wheat, rice, and soybeans by roughly 20%, *ceteris paribus*, assuming one-third of the calories used in ethanol production can be recycled as animal feed (Roberts and Schlenker, 2013). More generally, there is *high confidence* that pressure on land use for biofuels will further increase food prices (see Table 19-2.iii).

In summary, through the global food trade system, climate change impacts on agriculture can have consequences beyond the regions in which those impacts are directly felt. Food access can be inhibited by rising food price levels and volatility (Sections 7.3.3.1-2), as demonstrated during the recent 2007–2008 price rise episode that resulted from the combination of poor weather in certain world regions combined with a demand for biofuel feedstocks, increased demand for grain-fed meat, and historically low levels of food stocks (Abbot and Borot de Battisti, 2011; Adam and Ajakaiye, 2011; Figure 7-3). These episodes provide an analog elucidating how reduced crop yields due to impacts of climate variability and biofuel cropping work synergistically to create a risk of increased food insecurity: hence this interaction of climate change and mitigation actions with the food system via markets comprises an *emergent risk* of the impacts of climate change acting at a distance, affecting the food security of vulnerable households (Section 7.3.3.2).

19.4.2. Indirect, Trans-boundary, and Long-Distance Impacts of Adaptation

Risk can also arise from unintended consequences of adaptation (see Section 14.6), and this can act across distance, if for example, there is migration of people or species from one region to another. Adaptation responses in human systems can include land use change, which can have both trans-boundary and long-distance effects, and changes in water management, which often has downstream consequences.

19.4.2.1. Risks Associated with Human Migration and Displacement

Human migration is one of many possible adaptive strategies or responses to climate change (Reuveny, 2007; Tacoli, 2009; Piguet, 2010; McLeman, 2011), assessed in detail in Chapter 12 in the context of the many other causes of migration. Displacement refers to situations where choices are limited and movement is more or less compelled by land loss due to sea level rise or extreme drought, for example (see Section 12.4). A number of studies have linked past climate variability to both local and long-distance migration (see review by Lilleør and Van den Broeck, 2011). In addition to yielding positive and negative outcomes for the migrants, migration indirectly transmits consequences of climate variability and change at one location to people and states in the regions receiving migrants, sometimes at long distances. Consequences for receiving regions, which can be assessed by a variety of metrics, could be both positive and negative, as may also be the case for sending regions (Foresight, 2011; McLeman, 2011; see Chapter 12). A rapidly growing literature examines potential changes in migration patterns due to future climate changes, but projections of specific positive or negative outcomes are not available. Furthermore, recent literature underscores risks previously ignored: risks arising from the lack of mobility in face of a changing climate, and risks entailed by those migrating into areas of direct climate-related risk, such as low-lying coastal deltas (Foresight, 2011; see Section 12.4.1.2).

Climate change-induced sea level rise, in conjunction with storm surges and flooding, creates a threat of temporary and eventually permanent displacement from low-lying coastal areas, the latter particularly the case for small island developing states (SIDS) and other small islands (Pelling and Uitto 2001; see Chapter 12). The distance and permanence of the displacement will depend on whether governments develop strategies such as relocating people from highly vulnerable to less vulnerable areas nearby, and conserving ecosystem services which provide storm surge protection in addition to so-called "hardening" including building sea walls and surge barriers (Perch-Nielsen, 2004; Box CC-EA). Numbers of people at risk from coastal land loss have been estimated on a regional basis (Ericson et al., 2006; Nicholls and Tol, 2006; Nicholls et al., 2011) yet projections of resulting anticipatory migration or permanent versus temporary displacement are not available.

Taken together, these studies indicate that climate change will bear significant consequences for migration flows at particular times and places, creating risks as well as benefits for migrants and for sending and receiving regions and states (*high confidence*). Urbanization is a pervasive aspect of recent migration which brings benefits but, in the climate change context, also significant risks (see Sections 8.2.2.4, 19.2.3, 19.6.1-2, 19.6.3.3). While the literature projecting climate-driven migration has grown recently (Section 12.4), there is as of yet insufficient literature to permit assessment of projected region-specific consequences of such migration. Nevertheless, the potential for negative outcomes from migration in such complex, interactive situations is an emergent risk of climate change, with the potential to become a key risk (Box CC-KR).

19.4.2.2. Risk of Conflict and Insecurity

Violent conflict between individuals or groups arises for a variety of reasons (Section 12.5). Factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change and variability (*high confidence*; Sections 12.5.1, 12.5.3, 13.2). In this section, we focus on evidence for the magnitude of a climate effect on violent conflict to assess its potential to become a key risk.

The only meta-analysis of the literature (Hsiang et al., 2013), examining 60 quantitative empirical studies generally published since AR4, implicates climatic events as a contributing factor to the onset or intensification of several types of personal violence, group conflict, and social instability in contexts around the world, at temporal scales ranging from a climatologically anomalous hour to an anomalous millennium and at spatial scales ranging from the individual level (Vrij et al., 1994; Ranson, 2012) to the communal level (Hidalgo et al., 2010; O'Loughlin et al., 2012) to the national level (Burke et al., 2009; Dell et al., 2012) to the global level (Hsiang et al., 2011). Nevertheless, some individual studies have been unable to obtain evidence that violence has a statistically significant association with climate (Buhaug, 2010; Theisen et al., 2011). In detection and attribution of their impact on human conflict, there is *low confidence* that climate change has an effect (Section 18.4.5) and *medium confidence* that climate variability has an effect.

Evidence suggests that climatic events over a large range of time and spatial scales contribute to the likelihood of violence through multiple pathways discussed in Section 12.5 (Bernauer et al., 2012; Scheffran et al., 2012; Hsiang and Burke, 2014). Results from modern contexts (1950–2010) indicate that the frequency of violence between individuals rises 2.3% and the frequency of intergroup conflict rises 13.2% for each standard deviation change toward warmer temperatures (Hsiang et al., 2013). Because annual temperatures around the world are expected to rise 2 to 4 standard deviations (as measured over 1950–2008) above temperatures in 2000 by 2050 (A1B scenario) (Hsiang et al., 2013), there is potential *ceteris paribus* for large relative changes to global patterns of personal violence, group conflict, and social instability in the future.

Social, economic, technological, and political changes that might exacerbate or mitigate this potential impact are discussed in Chapter 12. These changes may cause future populations to respond to their climate differently than modern populations; however, the influence of climate variability on rates of conflict is sufficiently large in magnitude that such advances may need to be dramatic to offset the potential influence of future climate changes.

The effect of climate change on conflict and insecurity has the potential to become a key risk because factors such as poverty and economic shocks that are associated with a higher risk of violent conflict are themselves sensitive to climate change (*medium confidence*; Sections 12.5.1, 12.5.3, 13.2), and in numerous statistical studies the influence of climate variability on human conflict is large in magnitude (*medium confidence*).

19.4.2.3. Risks Associated with Species Range Shifts

One of the primary ways species adapt to climate change is by moving to more climatically suitable areas (range shifts). These shifts will affect ecosystem functioning, potentially posing risks to ecosystem services (*medium confidence*; Millennium Ecosystem Assessment, 2005a,b; Dossena et al., 2012), including those related to climate regulation and carbon storage (Wardle et al., 2011). One example of a key impact is the warming-driven expansion and intensification of Mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in North American pine forests and its current and projected impacts on carbon regulation and economies (Sections 26.4.2.1, 26.8.3). Risks also arise from projected range shifts of important resource species (e.g., marine fishes; Sections 6.5.2-3), as well as from potential introductions of diseases to people, livestock, crops, and native species (see Sections 5.4.3.5, 7.3.2.3, 22.3.5, 23.4.2, 26.6.1.6, 28.2.3). Many newly arrived species prey on, outcompete, or hybridize with existing biota (e.g., by becoming weeds or pests in agricultural systems) (Section 4.2.4.6) . The ecological implications of species reshuffling into novel, no-analog communities largely remain unknown and pose additional risks that cannot yet be assessed (Root and Schneider, 2006; Sections 6.5.3, 19.5.1, 21.4.3).

Current legal frameworks and conservation strategies face the challenge of untangling desirable species range shifts from undesirable invasions (Webber and Scott, 2012), and identifying circumstances when movement should be facilitated versus inhibited. New agreements may be needed recognizing climate change impacts on existing, new, or altered trans-boundary migration (e.g., under the Convention on the Conservation of Migratory Species of Wild Animals). As target species and ecosystems move, protected area networks may become less effective, necessitating re-evaluation and adaptation, including possible addition of sites, particularly those important as either "refugia" or migration corridors (Warren et al., 2013a; Sections 9.4.3.3, 24.4.2.5, 24.5.1). Assisted colonization—moving individuals or populations from currently occupied areas to locations with higher probability of future persistence—is arising as a potential conservation tool for species unable to track changing climates (Sections 4.4.2.4, 21.4.3). The value of these approaches, however, is contested and implementation is very limited giving *low confidence* that this would be an effective technique (Loss et al., 2011). *Ex situ* collections (Section 4.4.2.5) have often been put forward as fallback resources for conserving threatened species, yet the expense and the relatively low representation of global species and genetic diversity (Balmford et al., 2011; Conde et al., 2011) minimize the effectiveness of this technique.

19.4.3. Indirect, Trans-boundary, and Long-Distance Impacts of Mitigation Measures

Mitigation, too, can have unintended consequences beyond its boundaries, which may affect natural systems and/or human systems. If mitigation involves a form of land use change, then regional implications can ensue in the same way as they can for adaptation (see Section 14.7).

Mitigation can potentially reduce direct climate change impacts on biodiversity (Warren et al., 2013a). However, impacts on biodiversity as a result of land use change induced by biofuel production can offset benefits associated with biofuels (see Boxes 4-1, 25-10; Sections 4.2.4.1, 4.4.4, 9.3.3.4, 19.3.2.2, 22.6.3, 24.6, 27.2.2.1). Climate change mitigation through "clean energy" substitution can also have negative impacts on biodiversity. However, attention to siting and monitoring can decrease some negative ecological and socioeconomic impacts (*medium confidence*) while maximizing positive ones (Section 4.4.4). For example, the U.S. Government performed an intensive study of suitable sites for solar power on public lands in the western USA. The end result opened 285,000 acres of public land for large-scale solar deployment while blocking development on 78 million acres to protect "natural and cultural" resources (US DOE and BLM, 2012). The construction of large hydroelectric dams can affect both terrestrial and aquatic ecosystems

Frequently Asked Questions

FAQ 19.3 | How can climate change impacts on one region cause impacts on other distant areas?

People and societies are interconnected in many ways. Changes in one area can have ripple effects around the world through globally linked systems such as the economy. Globalized food trade means that changed crop productivity as a result of extreme weather events or adverse climate trends in one area can shift food prices and food availability for a given commodity worldwide. Depletion of fish stocks in one region due to ocean temperature rise can cause impacts on the price of fish everywhere. Severe weather in one area that interferes with transportation or shipping of raw or finished goods, such as refined oil, can have wider economic impacts.

In addition to triggering impacts via globally linked systems like markets, climate change can alter the movement of people, other species, and physical materials across the landscape, generating secondary impacts in places far removed from where these particular direct impacts of climate change occur. For example, climate change can create stresses in one area that prompt some human populations to migrate to adjacent or distant areas. Migration can affect many aspects of the regions people leave, as well as many aspects of their destination points, including income levels, land use, and the availability of natural resources, and the health and security of the affected populations—these effects can be positive or negative. In addition to these indirect impacts, all regions experience the direct impacts of climate change.

along river systems (World Commission on Dams, 2000; see also Sections 3.7.2.1, 4.4.4, 24.4.2.3, 24.9.1).

Mitigation strategies will have a range of effects on human systems. Reforestation that properly mimics existing forest ecosystems in structure and composition would potentially benefit human systems by stabilizing micro-climatic variation (Canadell and Raupach, 2008) and allowing benefits from the sustainable harvest of non-timber forest products for food, medicine, and other marketable commodities (Guariguata et al., 2010). However, there is a generally longer time frame and greater expense involved in recreating a diverse forest system. Afforestation creates a similar set of costs and benefits (Sections 3.7.2.1, 4.4.3, 17.2.7.1, 22.4.5.6-7; Box CC-WE). Mitigation strategies designed to reduce dependence on carbon-intensive fuels present a very different set of circumstances in relation to human systems. The development of bioresources for energy use may have significant economic and market effects potentially influencing food prices (see also Section 19.4.1). This would especially affect populations that already devote a considerable portion of their household income to food (Hymans and Shapiro, 1976).

19.5. Newly Assessed Risks

Newly assessed risks are those for which the evidence base in the scientific literature has only recently become sufficient to allow for assessment. Furthermore, these risks have at least the potential to become key based on the criteria in Section 19.2.2. Several of the emergent risks discussed in Sections 19.3 and 19.4, including those associated with human migration (Section 19.4.2.1) and mitigation measures (Section 19.4. 3), can be considered newly assessed. Others are related to diverse aspects of climate change, including the impacts of a large temperature rise, ocean acidification and other direct consequences of $CO2$ increases, and the potential impacts of geoengineering implemented as a climate change response strategy.

19.5.1. Risks from Large Global Temperature Rise >4°C above Preindustrial Levels

Most climate change impact studies focus on climate change scenarios corresponding to global mean temperature rises of up to 3.5°C relative to 1990 (slightly more than 4°C above preindustrial levels), with only a few examples of assessments of temperature rise significantly above that level (Parry et al., 2004; Hare, 2006; Warren et al., 2006; Easterling et al., 2007; Fischlin et al., 2007). Recently the potential for larger amounts of warming has received increasing attention and preliminary assessment of impacts above that level of warming is possible for agriculture, ecosystems, water, health, and large-scale singular events. In this section, all temperature changes are global and relative to preindustrial levels. Relevant climate scenarios include those based on RCP8.5, which in 2081–2100 is projected to result in a temperature rise of 4.3°C ± 0.7°C with temperature above 4°C *as likely as not* (WGI AR5 Section 12.4.1, Table 12.3), and some simulations using SRES A2 and A1FI, which can reach 5.9°C and 6.9°C warming, respectively, by 2100 (WGI AR4 SPM). Literature that uses these scenarios but assumes low climate sensitivity and hence less than 4°C of warming is excluded.

Relatively few studies have considered impacts on cropping systems for scenarios where global mean temperatures increase by 4°C or more (Section 7.4.1). Among these, one indicates substantial reductions in yields in sub-Saharan Africa (Thornton et al., 2011) and another indicates reversal of gains in yields and substantial reductions for Finland (Rötter et al., 2011). Other studies at or below 4 °C anticipate yield losses, particularly in tropical regions, even when taking agronomic adaptations into account (Section 7.5.1.1.1). The possibility of compensation for

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these losses due to other responses of the food system to impacts on production, such as land use change and adjustment of trade patterns, cannot yet be adequately assessed for a world with GMT >4°C (Sections 19.4.1, 19.6.3.4).

Assessments of ecological impacts at and above 4°C warming imply a high risk of extensive loss of biodiversity with concomitant loss of ecosystem services (*high confidence*; Section 4.3.2.5; Table 4-3). AR4 estimated that 20 to 30% of species were likely at increasingly high risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above preindustrial levels (*medium confidence*; Fischlin et al., 2007); hence 4°C warming implies further increases to extinction risks for an even larger fraction of species. However, there is *low agreement* on the numerical assessment because as more realistic details have been considered in models, it has been shown that extinction risks may be either under- or overestimated when using the simpler models (Section 4.3.2.5), among other reasons due to the existence of microrefugias or to delay in population decline leading to extinction debts (e.g., Dullinger et al., 2012). Additional risks include biome shifts of 400 km (Gonzalez et al., 2010), the disappearance of analogs of current climates in regions of exceptional biodiversity in the Himalayas, Mesoamerica, East and South Africa, the Philippines, and Indonesia (Beaumont et al., 2011), and loss of more than half of the climatically determined geographic ranges of 57 ± 6% of plants and 34 ± 7% of animals studied (Warren et al., 2013a). Widespread coral reef mortality is expected at 4°C due to the concomitant effects of warming and a projected decline of ocean pH of 0.43 since preindustrial times (*high confidence*; WGI AR5 Figure TS.20; Section 5.4.2.4; Boxes CC-CR, CC-OA). The corresponding CO_2 concentration in such a scenario is about 900 ppm (WGI AR5 Figure 12.36) whereas the onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.2.4, 26.4.3.2).

A number of studies project increases in water stress, flood, and drought in a number of regions with >4°C warming, and decreases in others (Li et al., 2009; Arnell, 2011; Fung et al., 2011; Dankers et al., 2013; Gerten et al., 2013; Gosling and Arnell, 2013). For example, projections of the proportion of global population exposed to water stress due to climate change range from 5 to 50% (Gosling and Arnell, 2013) by 2100. The proportion of cropland exposed to drought disaster (one or more months with Palmer Drought Severity Index (PDSI) drought indicator below –3) is projected to increase from 15% today to 44 ± 6% by 2100, based on a range of projections including some that reach or exceed 4°C global warming (Li et al., 2009). Concurrently irrigation water demand in currently cultivated areas in the North Hemisphere is projected to rise by 20% in the summer by 2100 under RCP8.5 due to climate change alone (Wada et al. 2013), although this could be partly buffered by decreasing evapotranspiration due to plant physiological responses to increased atmospheric CO_2 (Konzmann et al., 2013; Box CC-VW). One study (Portmann et al., 2013) projects that, by the 2080s under the RCP8.5 scenario, 27 to 50% (mean 38%) of the global population would experience at least a 10% decrease in groundwater resources, mostly in drier areas with high population density where water stress is more likely to occur. Concurrently, 20 to 45% of the population is projected to experience at least a 10% increase in groundwater resources under RCP8.5 in the 2080s. This is projected to occur mostly in wetter areas or those with low population density where it is less probable that water stress will be an issue. Another study projects that annual runoff will fall by up to 75% across the Danube and Mississippi river basins, and by up to 90% in the Amazon; while runoff is projected to either fall (by up to 75%) or to rise (by up to 30%) in the Murray Darling, and increase by up to 150% in the Ganges basin, and up to 80% in the Nile basin (Fung et al., 2011) with 4°C warming. Both studies are based on an ensemble of climate model projections. Under RCP8.5 in 2100, nine global hydrological models driven by five global circulation models project increases in flood frequency in over half of the land surface, and decreases in roughly a third of the land surface (Dankers et al., 2013). According to one study, even if the human population remained constant in Europe, without adaptation, 3.5°C to 4.8°C global warming by the 2080s would expose an additional 250,000 to 400,00 people to river flooding, doubling economic damages since 1961 to 1990, and expose an additional 850,000 to 5,550,000 to coastal flooding (Ciscar et al., 2011), compared to 36,000 in 1995.

Under 4°C warming most of the world land area will be experiencing 4°C to 7°C higher temperatures than in the recent past, which means that important tipping points for health impacts may be exceeded in many areas of the world during this century, including coping mechanisms for daily temperature/humidity, seasonally compromising normal human activities, including growing food or working outdoors (Chapter 11 ES). Exceedance of human physiological limits is projected in some areas for a global warming of 7°C, and in most areas for global warming of 11°C to 12°C (*low confidence*; Sherwood and Huber, 2010), a temperature increase that is possible by 2300 (WGI AR5 Figure 12.5).

The risk of large-scale singular events such as ice sheet disintegration, CH_4 release from clathrates, and regime shifts in ecosystems (including Amazon dieback), is higher with increased warming (and therefore higher above 4°C than below it) although there is *low confidence* in the temperature changes at which thresholds might exist for these processes (Section 19.6.3.6; WGI AR5 Sections 12.5.5, 13.4). There are also more gradual changes that become large with global temperature rise of 4°C or more, such as decline in the Atlantic Meridional Overturning Circulation (AMOC) and release of carbon from thawed permafrost (CTP). The AMOC is considered *very likely* to weaken for such warming, with best estimates of loss over the 21st century under RCP8.5 ranging from 12 to 54% (WGI AR5 Sections 12.4.7.2, 12.5.5.2). The best estimated range for CTP by 2100 is from 50 to 250 PgC for RCP8.5 (WGI AR5 Section 6.4.3.4) although there are large uncertainties. Larger decreases in AMOC and increases in CTP are thus implied for a global warming of above 4°C. Similarly, because a nearly ice-free Arctic Ocean in September before mid-century is likely under RCP8.5, by which time projected GMT rise amounts to 2.0 ± 0.4°C above the 1986–2005 baseline (*medium confidence*; WGI AR5 Section 12.4.6.1), the likelihood is even higher for global warming of above 4°C. Regions of the boreal forest could witness widespread forest dieback (*low confidence*), putting at risk the boreal carbon sink (Section 4.3.3.1.1; WGI AR5 Section 12.5.5). Forest susceptibility to fire is projected to increase substantially in many areas for the high emissions scenario (RCP 8.5; Section 4.3.3.1; Figure 4-6) and hence larger changes are implied for global warming above 4°C.

Based on the assessment in this section, we conclude that climate change impacts at 4°C and above would be of greater magnitude and more widespread than at lower levels of global temperature rise (*medium evidence*, *high agreement*; *high confidence*), extending to higher temperature levels previous findings that risks increase with increasing global average temperature (WGII AR4 SPM.2; National Research Council, 2011). Few studies yet consider the interactions between these effects, which could create significant additional risks (Warren et al., 2011; Sections 19.3-4).

19.5.2. Risks from Ocean Acidification

Ocean acidification is defined as "a reduction in pH of the ocean over an extended period, typically decades or longer, caused primarily by the uptake of carbon dioxide (CO_2) from the atmosphere" (WGI AR5 Section 3.3.2, Box 3.2; Box CC-OA; see also Glossary). Acidification is a physical and biogeochemical impact resulting from CO_2 emissions that poses risks to marine ecosystems and the societies that depend on them. Research on impacts on organisms, ecological responses, and consequences for ecosystem services is relatively new; the potential for associated risks to become key is magnified by the fact that acidification is a global phenomenon and, without a decrease in atmospheric CO_2 concentration, it is irreversible on century time scales.

It is *virtually certain* that ocean acidification is occurring now (WGI AR5 Section 3.9) and will continue to increase in magnitude as long as the atmospheric CO_2 concentration increases (National Research Council, 2010). Risks to society and ecosystems result from a chain of consequences beginning with direct effects on biogeochemical processes and organisms and extending to indirect effects on ecosystems, ecosystem services, and society (Figure 19-3). The degree of confidence in assessing risks decreases along this chain owing to the complexity of interactions across these scales and the relatively small number of studies available for quantitative risk assessment.

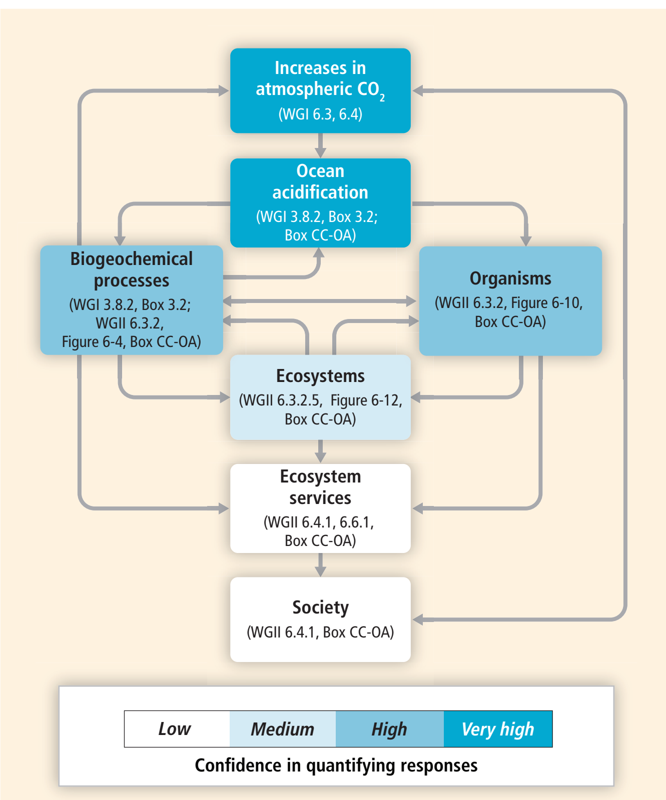

Figure 19-3 | The pathways by which ocean acidification affects marine processes, organisms, ecosystems, and society. The confidence in quantifying the impacts decreases along the pathway.

Most studies have focused on the direct effects of ocean acidification on marine organisms and biogeochemical processes. The overall effects on organisms can be assessed with *medium confidence* (Section 6.3.2; Box CC-OA), but the effects vary widely across processes (e.g., photosynthesis, growth, calcification; Section 6.3.2) and across organisms and their life stages (Section 6.3.2; Box CC-OA).

Far fewer studies have assessed the impacts on ecosystems (Section 6.3.2.5) and ecosystem services (Section 6.4.1), and most of these studies have focused on the economic impacts on fisheries (Section 6.4.1.1). For example, changes in overall availability and nutritional value of desired mollusk species could affect economies (Narita et al., 2012) and food availability (Section 6.4.1.1). In Table 19-3, we assess the risks to ecosystem services through the impact of acidification on two key marine processes, calcification in warmwater corals and nitrogen fixation, using the criteria for key risks (Section 19.2.2.2).

Based on Table 19-3, the response of coral calcification to ocean acidification and the resulting consequences for coral reefs constitute a key risk to important ecosystem services (*high confidence*). The effect of ocean acidification on marine N_2-fixation could potentially become a key risk, given that it could have potentially large consequences for marine ecosystems, but currently there is *limited evidence* on the likelihood of this risk materializing.

19.5.3. Risks from Carbon Dioxide Health Effects

There is increasing evidence that the impacts of elevated atmospheric CO_2 on plant species will affect health via two distinct pathways: the increased production and allergenicity of pollen and allergenic compounds, and the nutritional quality of key food crops. The evidence for these impacts on plant species is increasingly *robust* and recent evidence in the public health literature points to a *medium* to *high confidence* in the potential for these risks to be sufficiently widespread in geographical scope and large in *magnitude* of their impact on human health to be considered key risks.

Climate change is expected to alter the spatial and temporal distribution of several key allergen-producing plant species (Shea et al., 2008), and increased atmospheric CO_2 concentration, independent of climate effects, has been shown to stimulate pollen production (Rasmussen, 2002; Clot, 2003; Galán et al., 2005; Garcia-Mozo et al., 2006; Ladeau and Clark, 2006; Damialis et al., 2007; Frei and Gassner, 2008). A series of studies (Ziska and Caulfield, 2000; Ziska et al., 2003; Ziska and Beggs, 2012) found an association of elevated CO_2 concentrations and temperature with faster growing and earlier flowering ragweed species (*Ambrosia artemisiifolia*) along with greater production of ragweed pollen (Wayne et al., 2002; Singer et al., 2005; Rogers et al., 2006), leading, in some areas, to a measurable increase in hospital visits for allergic rhinitis

Table 19-3 | An assessment of the risks to ecosystem services posed by the impacts of ocean acidification on warm-water coral calcification and nitrogen fixation, based on the four criteria for key risks (Section 19.2.2.2).

Criterion for key risk	Coral calcification	Nitrogen fixation
1. Magnitude of consequences for ecosystem services	Ecosystem services include supporting habitats, provisioning of fish, regulating shoreline erosion, and tourism. Potential magnitude of consequences is medium to high (Box CC-CR).	Ecosystem services include nitrogen cycling, which supports ecosystem structure and food chains (Hutchins et al., 2009). Potential magnitude of consequences has not been investigated.
2. Likelihood that risks will materialize and their timing	A reduction in coral calcification rate and an increase in reef dissolution rates are *very likely* (Section 6.1.2), so that reefs will progressively shift toward net dissolution (*medium confidence*; Section 5.4.2.4; Boxes CC-CR and CC-OA).	Both increases and decreases in nitrogen fixation have been observed in various N_2-fixing organisms (Section 6.3.2.2) but there is *limited* in situ *evidence* and *medium agreement* on how N_2-fixation rates will change in response to ocean acidification.
3. Irreversibility and persistence of ocean acidification impacts	Decreases in ocean pH will persist as long as atmospheric CO_2 levels remain elevated (WGI AR5 Section 3.8.2). Reductions in coral calcification will persist unless corals can physiologically adapt to maintain calcification rates. Reversibility of impacts on ecosystem services of coral reefs is unknown and depends on ecological factors such as hysteresis.	Decreases in ocean pH will persist as long as atmospheric CO_2 levels remain elevated (WGI AR5 Section 3.8.2). Reversibility and persistence of impacts on nitrogen fixation are unknown.
4. Limited ability to reduce the magnitude and frequency or nature of ocean acidification impacts	Reduction of ocean acidification will require global reductions in atmospheric CO_2. Feasibility of mitigating ocean acidification at the local scale is unknown.	Reduction of ocean acidification will require global reductions in atmospheric CO_2.

(Breton et al., 2006). Experimental studies have shown that poison ivy, another common allergenic species, responds to atmospheric CO_2 enrichment through increased photosynthesis, water use efficiency, growth, and biomass. This stimulation, exceeding that of most other woody species, also produces a more potent form of the primary allergenic compound, urushiol (Mohan et al., 2006).

While climate change and variability are expected to affect crop production (see Chapter 7), emerging evidence suggests an additional stressor on the food system: the impact of elevated levels of CO_2 on the nutritional quality of important foods. A prominent example of the effect of elevated atmospheric CO_2 is the decrease in the nitrogen concentration in vegetative plant parts as well as in seeds and grains and, related to this, the decrease in the protein concentrations (Cotrufo et al., 1998; Taub et al., 2008; Wieser et al., 2008). Experimental studies of increasing CO_2 to 550 ppm demonstrated effects on crude protein, starch, total and soluble beta-amylase, and single kernel hardiness, leading to a reduction in crude protein by 4 to 13% in wheat and 11 to 13% in barley (Erbs et al., 2010). Other CO_2 enrichment studies have shown changes in the composition of other macro- and micronutrients (calcium, potassium, magnesium, iron, and zinc) and in concentrations of other nutritionally important components such as vitamins and sugars (Idso and Idso, 2001). Declining nutritional quality of important global crops is a potential risk that would broadly affect rates of protein-energy and micronutrient malnutrition in vulnerable populations. While there is *medium confidence* that this risk has the potential to become key when judged by its *magnitude* and other criteria (Sections 19.2.2.1-2) there is currently insufficient information to assess under what ambient CO_2 concentrations this would occur.

19.5.4. Risks from Geoengineering (Solar Radiation Management)

Geoengineering refers to a set of proposed methods and technologies that aim to alter the climate system at a large scale to alleviate the impacts of climate change (see Glossary; IPCC, 2012b; WGI AR5 Sections 6.5, 7.7; WGIII AR5 Chapter 6). The main intended benefit of geoengineering would be the reduction of climate change that would otherwise occur, and the associated reduction in impacts (Shepherd et al., 2009). Here we focus on risks, consistent with the goal of this chapter. Although geoengineering is not a new idea (e.g., Rusin and Flit, 1960; Budyko and Miller, 1974; Enarson and Morrow, 1998; and a long history of geoengineering proposals as detailed by Fleming, 2010), it has received increasing attention in the recent scientific literature.

Geoengineering has come to refer to both carbon dioxide removal (CDR; discussed in detail in WGI AR5 Section 6.5, FAQ 7.3) and Solar Radiation Management (SRM; Izrael et al., 2009; Lenton and Vaughan, 2009; Shepherd et al., 2009; discussed in detail in WGI AR5 Section 7.7, FAQ 7.3). These distinct approaches to climate control raise very different scientific (e.g., Shepherd et al., 2009), ethical (Morrow et al., 2009; Preston, 2013), and governance (Lloyd and Oppenheimer, 2014) issues. Many approaches to CDR are considered to more closely resemble mitigation rather than other geoengineering methods (IPCC, 2012b). In addition, CDR is thought to produce fewer risks than SRM if the CO_2 can be stored safely (Shepherd et al., 2009) and unintended consequences for land use, the food system, and biodiversity can be avoided (Section 19.4.3). For these reasons, in addition to the more substantial recent literature on SRM's potential impacts, we address only SRM in this section. SRM is a potential key risk because it is associated with impacts to society and ecosystems that could be large in magnitude and widespread. Current knowledge on SRM is limited and our confidence in the conclusions in this section is *low*.

Studies of impacts on society and ecosystems have been based on two of the various SRM schemes that have been suggested: stratospheric aerosols and marine cloud brightening. These approaches in theory could produce large-scale cooling (Salter et al., 2008; Lenton and Vaughan, 2009), although it is not clear that it is even possible to produce a stratospheric sulfate aerosol layer sufficiently optically thick to be effective (Heckendorn et al., 2009; English et al., 2012). Observations of volcanic eruptions, frequently used as an analog for SRM (Robock et al., 2013), indicate that while stratospheric aerosols can reduce the global average surface air temperature, they can also produce regional drought (e.g., Oman et al., 2005, 2006; Trenberth and Dai, 2007), cause ozone depletion (Solomon, 1999), and reduce electricity generation from solar generators that use focused direct sunlight (Murphy, 2009). Climate modeling studies show that the risk of ozone depletion depends in detail on how much and when stratospheric aerosols would be released in the stratosphere (Tilmes et al., 2008) and find that global stratospheric SRM would produce uneven surface temperature responses and reduced precipitation (Schmidt et al., 2012; Kravitz et al., 2013), weaken the global hydrological cycle (Bala et al., 2008), and reduce summer monsoon rainfall relative to current climate in Asia and Africa (Robock et al., 2008). Hemispheric geoengineering would have even larger effects (Haywood et al., 2013).

The net effect on crop productivity would depend on the specific scenario and region (Pongratz et al., 2012). Use of SRM also poses a risk of rapid climate change if it fails or is halted suddenly (WGI AR5 Section 7.7; Jones et al., 2013), which would have large negative impacts on ecosystems (*high confidence*; Russell et al., 2012) and could offset the benefits of SRM (Goes et al., 2011). There is also a risk of "moral hazard"; if society thinks geoengineering will solve the global warming problem, there may be less attention given to mitigation (e.g., Lin, 2013). In addition, without global agreements on how and how much geoengineering to use, SRM presents a risk for international conflict (Brzoska et al., 2012). Because the direct costs of stratospheric SRM have been estimated to be in the tens of billions of U.S. dollars per year (Robock et al., 2009; McClellan et al., 2012), it could be undertaken by non-state actors or by small states acting on their own (Lloyd and Oppenheimer, 2014), potentially contributing to global or regional conflict (Robock, 2008a,b). Based on magnitude of consequences and exposure of societies with limited ability to cope, geoengineering poses a potential key risk.

19.6. Key Vulnerabilities, Key Risks, and Reasons for Concern

In this section, we present key vulnerabilities, key risks, and emergent risks that have been identified by many of the chapters of this report based on the material assessed by each in light of criteria discussed in Sections 19.2.2 and 19.2.3. We then discuss dynamic characteristics of exposure, vulnerability, and risk, features that are influenced by development pathways in the past, present, and future. Illustrative examples of climate-related hazards, key vulnerabilities, key risks, and emergent risks in Table 19-4 are representative, having been selected from a larger number provided by the chapters of this report. The table demonstrates how these four categories are related, as well as how they differ, and how they interact with non-climate stressors. The table also provides information on how key risks actually develop due to changing climatic hazards and vulnerabilities. This knowledge is an important prerequisite for effective adaptation and risk reduction strategies that must address climate-related hazards, non-climatic stressors, and various vulnerabilities that often interact in complex ways and change over time.

19.6.1. Key Vulnerabilities

Several of the risks discussed in this and other chapters and noted in Table 19-4 arise because vulnerable people must cope and adapt not only to changing climate conditions, but also to multiple, interacting stressors simultaneously (see Sections 19.3-4), which means that effective adaptation strategies would address these complexities and relationships.

19.6.1.1. Dynamics of Exposure and Vulnerability

This subsection deals with the meaning and the importance of dynamics of exposure and vulnerability, while Section 19.6.1.3 assesses recent literature regarding observed trends of vulnerability mostly at a global or regional scale. The literature provides increasing evidence that structures and processes that determine vulnerability are dynamic and spatially variable (IPCC, 2012a; Section 19.6.1.3). SREX states with *high confidence* that vulnerability and exposure of communities or social-ecological systems to climatic hazards related to extreme events are dynamic, thus varying across temporal and spatial scales due to influences of and changes in social, economic, demographic, cultural, environmental, and governance factors (IPCC, 2012c, SPM.B).

Examples of such dynamics in exposure and vulnerability encompass, for example, population dynamics, such as population growth or changes in poverty (Table 19-4; Birkmann et al., 2013b) and increasing exposure of people and settlements in low-lying coastal areas or flood plains in Asia (see Nicholls and Small, 2002; Fuchs et al., 2011; IPCC, 2012a; Peduzzi et al., 2012). Also, demographic changes, such as aging of societies, have a significant influence on people's vulnerability to heat stress (see Stafoggia et al., 2006; Gosling et al., 2009). Changes in poverty or socioeconomic status, ethnic compositions, as well as age structures had a significant influence on the outcome of past crises and in addition were modified and reinforced through disasters triggered by climate- and weather-related hazards. For the USA, for example, Cutter and Finch (2008) found that social vulnerability to natural hazards increased over time in some areas owing to changes in socioeconomic status, ethnic composition, age, and density of population. Changes in the strength of social networks (e.g., resulting in social isolation of elderly) and physical abilities to cope with such extreme events modify vulnerability (see, e.g., Khunwishit and Arlikatti, 2012).

In some cases human vulnerability might also change in different phases of crises and disasters. Hence, the factors that might determine vulnerability before a crisis or disaster (drought crises, flood disaster) might differ from those that determine vulnerability thereafter (post-disaster and recovery phases). Disaster response and reconstruction processes and policies can modify exposure and vulnerability, for example, of coastal communities (Birkmann and Fernando, 2008; Birkmann, 2011). A comprehensive assessment of vulnerability would account for these dynamics by evaluating long-distance impacts (e.g., resulting from migration or global influence of regional crop production failures following floods) and multiple stressors (e.g., recovery policies after disasters) that often influence dynamics and generate complex crises and even emergent risks. Furthermore, SREX also underscores that the increased intensity, frequency, and duration of some extreme events as climate continues to change might make adaptation based only on recent experience or the extrapolation of historical trends largely ineffective (Lavell et al., 2012, pp. 44–47); hence understanding the dynamics of vulnerability and its different facets is crucial.

19.6.1.2. Differential Vulnerability and Exposure

Wealth, education, ethnicity, religion, gender, age, class/caste, disability, and health status exemplify and contribute to the differential exposure and vulnerability of individuals or societies to climate and non-climate-related hazards (see IPCC, 2012a). Differential vulnerability is, for example, revealed by the fact that people and communities that are similarly exposed encounter different levels of harm, damage, and loss as well as success of recovery (see Birkmann, 2013). The uneven effects and uneven suffering of different population groups and particularly marginalized groups is well documented in various studies (Bohle et al., 1994; Kasperson and Kasperson, 2001; Birkmann, 2006a; Thomalla et al., 2006; Sietz et al., 2011, 2012). Factors that determine and influence these differential vulnerabilities to climate-related hazards include, for example, ethnicity (Fothergill et al., 1999; Elliott and Pais, 2006; Cutter and Finch, 2008), socioeconomic class, gender, and age (O'Keefe et al., 1976; Sen, 1981; Peacock, 1997; Jabry, 2003; Wisner, 2006; Bartlett, 2008; Ray-Bennett, 2009), as well as migration experience (Cutter and Finch, 2008) and homelessness (Wisner, 1998; IPCC, 2012a). Differential vulnerabilities of specific populations can often be discerned at a particular scale using quantitative or qualitative assessment methodologies (Cardona, 2006, 2008; Birkmann et al., 2013b). Various population groups are differentially exposed to and affected by hazards linked to climate change in terms of both gradual changes in mean properties and extreme events. For example, in urban areas, marginalized groups (particularly as a result of gender or wealth status or ethnicity) often settle along rivers or canals, where they are highly exposed to flood hazards or potential sea level rise (see Table 19-4; e.g., Neal and Phillips, 1990; Enarson and Morrow, 1998; Neumayer and Plümper, 2007; Sietz et al., 2012). Studies emphasize that vulnerability in terms of gender is not determined through biology, but in most cases by social structures, institutions, and rule systems; hence women and girls are often (not always) more vulnerable because they are marginalized from decision making or experience discrimination in development and reconstruction efforts (Fordham, 1998; Houghton, 2009; Sultana, 2010; IPCC, 2012a).

19.6.1.3. Trends in Exposure and Vulnerability

Vulnerability and exposure of societies and social-ecological systems to hazards linked to climate change are dynamic and depend on economic, social, demographic, cultural, institutional, and governance factors (see IPCC, 2012c, p. 7). The literature shows that there is a *high confidence* that rapid and unsustainable urban development, international financial pressures, increases in socioeconomic inequalities, failures in governance (e.g., corruption), and environmental degradation are key trends that modify vulnerability of societies, communities, and social-ecological systems (Maskrey, 1993a,b, 1994, 1998; Mansilla, 1996; Cannon, 2006; Birkmann, 2013; de Sherbinin, 2014) at different scales. Consequently, many of the factors that reveal and determine differential vulnerability change over time in terms of their spatial distribution. These dynamics unfold in different places differently and therefore local or regional specific strategies are needed that strengthen resilience (Garschagen and Kraas, 2011; Holdschlag and Ratter, 2013) and reduce exposure and vulnerability. For example, countries characterized by rapid urbanization coupled with low economic performance and high social development barriers face among the highest levels of climate change vulnerability. However, urbanization in some areas can yield conditions conducive to building up coping and adaptation capacities particularly when urban socioeconomic development and risk management is properly implemented (see Garschagen and Romero-Lankao, 2013). The following subsections outline observed trends in vulnerability according to different thematic dimensions (e.g., socioeconomic, environmental, institutional), within the constraint that relevant socioeconomic data are limited.

19.6.1.3.1. Trends in socioeconomic vulnerability

Multi-dimensional poverty is an important factor determining vulnerability of societies to climate change and extreme events (Section 13.1.4). For example, risk due to droughts, particularly in sub-Saharan Africa, is intimately linked to poverty and rural vulnerability (*high confidence*; see World Bank, 2010; Birkmann et al., 2011b; UNISDR, 2011, p. 62; Welle et al., 2012). In interpreting the following estimates, it should be borne in mind that diverse concepts of poverty lead to different estimates but that for some regions, e.g., sub-Saharan Africa, the trends are *robust*. Recent evaluation of conditions in 119 countries found that at the international level there had been a clear decrease in global poverty over the previous 6 years (Chandy and Gertz, 2011). The number of poor people globally fell, from more than 1.3 billion in 2005 to fewer than 900 million in 2010. This trend is expected to continue (e.g., Hughes et al., 2009; Chandy and Gertz 2011). However, regional trends vary, as do differences between emerging and least developed economies. As a result, there is a growing climate-related risk in some regions associated with chronic poverty. For example, in 2010, approximately 48.5% of the population of the highly drought exposed region sub-Saharan Africa still lives in poverty (poverty headcount ration at $1.25 per day; see World Bank, 2012) and this area already has been defined as a global risk hotspot (see Birkmann et al., 2011b; Welle et al., 2012). However, various national-level poverty statistics provide little information about the actual distribution of poverty, for example, between rural vs. urban areas. Income distribution trends show significant increases in inequality in some countries in Africa, and particularly in Asia, such as in China, India, Indonesia, and Bangladesh (World Bank, 2012). In Asia and Southeast Asia this trend overlaps with areas of compound climate risk (Section 19.3.2.4) in terms of people currently exposed to floods and tropical cyclones as well as sea level rise (Förster et al., 2011; IPCC, 2012a; Peduzzi et al., 2012). Assessing vulnerability (and risk) in these countries requires in-depth analysis of trends and distribution patterns of poverty, income disparities, and exposure of people to changing climatic hazards.

New socioeconomic vulnerabilities are emerging in some countries, for example, in developed countries, where the impoverishment of some population groups is observed. For example, research underscores that old age increases the risk of poverty in Greece, as the majority of people working as farmers or in the private sector receive small pensions that are below the poverty line (Karamessini, 2010, p. 279). These factors might interact with limited physical means of elderly to cope with climatic hazards, such as heat waves, and hence increase vulnerability.

Health status of individuals and population groups affects vulnerability to climate change by limiting capacities to cope and adapt to climate hazards (see Chapter 11). Although at a global scale the percentage of people undernourished is decreasing (FAO, 2012) and this trend is expected to continue (Hughes et al., 2009), the regional and national differences are significant: during 2010–2012, 870 million people remained chronically undernourished (FAO, 2012). Particularly in certain regions highly exposed to current and projected climate-related hazards, the number of people undernourished has increased. In sub-Saharan Africa, where exposure to drought is episodically high, the number of undernourished increased by 64 million or about 38% during 2010–2012 compared to 1990–1992 (Hughes et al., 2009; FAO, 2012, p. 10). Moreover, at many locations, climate change is expected to reduce the access to and the quality of natural resources that are important to sustain rural and urban livelihoods as well as the capacities of states to provide help to sustain livelihoods (Barnett and Adger, 2007; see also Section 19.3.2.1). These multi-risk contexts require new approaches for climate change adaptation.

While these trends mainly point to particularly large exposure and vulnerability in developing countries, studies regarding extreme heat vulnerability, for example, underscore that developed countries face increasing challenges to adaptation as well. Heat waves are projected to increase in duration, intensity, and extent (WGI AR5 Section 11.3.2). Advanced age represents one of the most significant risk factors for heat-related death (Bouchama and Knochel, 2002) because, in addition to limited thermoregulatory and physiologic heat-adaptation capacities, elderly have often reduced social contacts, and a higher prevalence of chronic illness and poor health (Section 11.3.3; Khosla and Guntupalli, 1999; Klinenberg, 2002; O'Neill, 2003). The trend toward an aging society, for example in Japan or Germany, therefore increases the vulnerability of these societies to extreme heat stress.

19.6.1.3.2. Trends in environmental vulnerability

Societies depend on ecosystem services for their survival; however, these ecosystem services and functions (see, e.g., Millenium Ecosystem Assessment, 2005a,b) are vulnerable to climate change (see Cardona et al., 2012, pp. 76–77; Table 19-4; Section 19.3.2.1). Various societies and communities that rely heavily on the quality of ecosystem services, such as rural populations dependent on rainfed agriculture where drying is projected (see also Table 19-4), will experience increased risk from climate change owing to its negative influence on ecosystem services (*high confidence*; see Sections 4.3.4, 6.4.1).

Although no global overview is available, recent reports (UNDP, 2007; IPCC, 2012a) underscore that a number of current environmental trends threaten human well-being and thus increase human vulnerability (UNEP, 2007). Many communities that have suffered large losses due to extreme weather events—for example, coastal flooding—also experienced earlier degradation of ecosystems providing protective services. Recent global studies and local studies, such as for the U.S. East Coast, underscore that intact ecosystems, such as marshes, can have an important protective role against coastal hazards for example, by wave attenuation (Shepard et al., 2011; Beck et al., 2013). Hence, coastal degradation, such as destruction of coral reefs in Asia, is increasing the exposure of communities to such hazards (Welle et al., 2012). Moreover, the extinctions of species and the loss of biodiversity pose a threat of diminution of genetic pools that otherwise buffer the adaptive capacities of social-ecological systems dependent on these services in the medium and long run (e.g., in terms of medicine and agricultural production).

19.6.1.3.3. Trends in institutional vulnerability

Institutional vulnerability refers, among other issues, to the role of governance. Governance is increasingly recognized as a key factor that influences vulnerability and adaptive capacity of societies and communities exposed to extreme events and gradual climate change (Kahn, 2005; Nordås and Gleditsch, 2007; Welle et al., 2012). People in countries or places that are facing severe failure of governance, such as violent conflicts (e.g., Somalia, Afghanistan) are particularly vulnerable to extreme events and climate change, as they are already exposed to complex emergency situations and hence have limited capacities to cope or undertake effective risk management (see Ahrens and Rudolph, 2006; Menkhaus, 2010). Countries classified as failed states are often not able to guarantee their citizens basic standards of human security and consequently do not provide adequate or any support in crises or disaster situations for vulnerable people. The Failed State Index (Foreign Policy Group, 2012; Fund for Peace, 2012) as well as the Corruption Perception Index (Transparency International, 2012) are used to characterize institutional vulnerability and governance failure. Trends in the Failed State Index from 2006 to 2011 show that countries with severe problems in the functioning of the state cannot easily shift or change their situation (persistence of institutional vulnerability). Studies at the global level also confirm that countries classified as failed states and affected, for example, by violence are not able to effectively reduce poverty compared to countries without violence (see World Bank, 2011). Countries characterized in the literature as substantially failing in governance or in some particular aspects of governance during some period, such as Somalia and Ethiopia, Afghanistan, or Haiti have shown in the past severe difficulties in dealing with extreme events or supporting people that have to cope and adapt to severe droughts, storms, or floods (see, e.g., Lautze et al., 2004; Ahrens and Rudolph, 2006; Menkhaus, 2010, pp. 320-341; Heine and Thompson, 2011; Khazai et al., 2011, pp. 30-31). In addition, it is probable that climate change will undermine the capacity of some states to provide the services and support that help people to sustain their livelihoods in a changing climate (Barnett and Adger, 2007). Governance failure and violence as characteristics of institutional vulnerability have significant influence on socioeconomic and therefore climatic vulnerability. Furthermore, corruption has been identified as an important factor that hinders effective adaptation policies and crisis response strategies (Birkmann et al., 2011b; Welle et al., 2012). At the local level, various aspects of governance in developing and developed countries, particularly institutional capacities and self-organization, as well as political and cultural factors, are critical for social learning, innovations, and actions that can improve risk management and adaptation to climate related risks and for empowering highly vulnerable groups (IPCC, 2012a). Overall, unless governance improves in countries with severe governance failure, risk will increase and human security will be further undermined there as a result of climate change and increased human vulnerability (*high confidence*; Lautze et al., 2004; Ahrens and Rudolph, 2006; Barnett and Adger, 2007; Menkhaus, 2010).

19.6.1.4. Risk Perception

Risk perceptions influence the behavior of people in terms of risk preparedness and adaptation to climate change (Burton et al., 1993; van Sluis and van Aalst, 2006; IPCC, 2012a). Factors that shape risk perceptions and therewith also influence actual and potential responses (and thus exposure, vulnerability, and risk) include (1) interpretations of the threat, including the understanding and knowledge of the root cause of the problem; (2) exposure and personal experience with the events and respective negative consequences, particularly recently (i.e., availability); (3) priorities of individuals; (4) environmental values and value systems in general (see, e.g., O'Connor et al., 1999; Grothmann and Patt, 2005; Weber, 2006; Kuruppu and Liverman, 2011). Furthermore, the perceptions of risk and reactions to such risk and actual events are also shaped by motivational processes (Weber, 2010). In this context people will often ignore predictions of climate-related hazards if those predictions fail to elicit emotional reactions. In contrast, if the event or forecast of such an event elicits strong emotional feelings of fear, people may overreact and panic (see Slovic et al., 1982; Slovic, 1993, 2010; Weber, 2006). Public perceptions of risks are not determined solely by the "objective" information, but rather are the product of the interaction of such information with psychological, social, institutional, and cultural processes and norms that are partly subjective, as demonstrated in various crises in the context of extreme events (Kasperson et al., 1988; Funabashi and Kitazawa, 2012). Risk perceptions particularly influence and increase vulnerability in terms of false perceptions of security (Cardona et al., 2012, p. 70). Finally, it is important to acknowledge that everyday concerns and satisfaction of basic needs may prove more pressing than attention and effort toward actions to address longer-term risk factors, e.g., climate change (Maskrey, 1989, 2011; Wisner et al., 2004). Rather, peoples' worldviews and political ideologies guide attention toward events that threaten their preferred social order (Douglas and Wildavsky, 1982; Kahan, 2010).

19.6.2. Key Risks

19.6.2.1. Assessing Key Risks

Key risks arise from the interaction of climate-related hazards and key vulnerabilities of societies, communities, or systems exposed (see Figure 19-1). Various chapters in this report have assessed key risks from their particular perspectives. We asked each chapter writing team to provide Chapter 19 authors with the key risks of highest concern to their chapter based on the criteria for defining key risks and key vulnerabilities as outlined in Section 19.2.2. A complete presentation of the key risks provided is found in Box CC-KR (allowing for some condensation by authors of Chapter 19 to avoid repetition).

The key risks provided by the chapters represent the issues most pressing to each set of experts. The list is neither unique nor exhaustive: other authors might express other preferences; however, this compilation provides important insights about key risks and their determinants—hazard, exposure, and vulnerability.

Chapter 19 authors further consolidated these key risks in Table 19-4 in order to produce the following list which, in their judgment (*high confidence*), is representative of the range of key risks forwarded. Roman numerals preceding each key risk correspond with entries in Table 19-4. Each key risk is followed with a notation in brackets indicating the Reason(s) for Concern (RFCs; see Section 19.6.3) with which it is aligned. In addition, a representative set of lines of sight is provided from across the chapters. Examples of these risks are also displayed geographically in Figure 19-2:

i) *Risk of death, injury, ill-health, or disrupted livelihoods in low-lying coastal zones and small island developing states and other small islands, due to storm surges, coastal flooding, and sea level rise*. These risks further increase in regions where the capacity to adapt long-lived coastal infrastructure (e.g. electricity, water and sanitation infrastructure) to local sea level rise beyond 1 m is limited. Urban populations with substandard housing and inadequate insurance, as well as marginalized rural populations with multidimensional poverty and limited alternative livelihoods are particularly vulnerable to these hazards. Inadequate local governmental attention to disaster risk reduction and adaptation can further increase the vulnerability of people and also the risk of adverse consequences (WGI AR5 Sections 3.7, 13.5; WGI AR5 Table 13.5; Sections 5.4.3, 8.1.4, 8.2.3-4, 13.1.4, 13.2.2, 24.4-5, 26.7-8, 29.3.1, 30.3.1; Boxes 25-1, 25-7). [RFC 1, 2, 3, 4, and 5]
ii) *Risk of severe ill-health and disrupted livelihoods for large urban populations due to inland flooding in some regions*. Particularly vulnerable are marginalized and poverty-stricken residents in low-income informal settlements as well as children, the elderly, and the disabled that have limited means to cope and adapt. Risks are increasing due to rapid and unsustainable urbanization especially in areas where risk governance capacities are constrained or limited attention is given to risk reduction and adaptation measures. Also, overwhelmed, aging, poorly maintained, and inadequate infrastructure (e.g., drainage infrastructure, electricity, water supply, etc.) can further increase the risk of severe harm and threats to human security in the case of inland flooding (WGI AR5 FAQ 12.2; Sections 3.2.7, 3.4.8, 8.2.3-4, 13.2.1, 25.10, 26.3, 26.7-8, 27.3.5; Box 25-8). [RFC 2 and 3]
iii) *Systemic risks due to extreme weather events leading to breakdown of infrastructure networks and critical services such as electricity, water supply, and health and emergency services*. Interdependency of critical infrastructure increases the risk of systemic breakdowns of vital services, for example, the risk of failure in systems dependent on electric power (such as drainage systems reliant on electric pumps) during extreme events. Health and emergency services rely on critical infrastructure (e.g., telecommunication) that can be disrupted during such power failures. For example, Hurricane Katrina left 1220 electricity-dependent drinking water systems in Louisiana, Mississippi, and Alabama inoperable for several weeks (Copeland, 2005). Overly hazard-specific management planning and infrastructure design and/or low forecasting capabilities exacerbate such risks (WGI AR5 Section 11.3.2; Sections 8.1.4, 8.2.4, 10.2-3, 12.6, 23.9, 25.10, 26.7-8). [RFC 2, 3, and 4]
iv) *Risk of mortality and morbidity during periods of extreme heat, particularly for vulnerable urban populations and those working outdoors in urban or rural areas*. Increasing frequency and intensity of extreme heat (including exposure to the urban heat island effect and air pollution) interacts with an inability of some local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups. In addition, the impact of heat stress on aging populations, such as during the heat wave disaster in 2003 in Europe, shows how changing climatic conditions interact with trends in population structure, health conditions, and social isolation (characteristics of vulnerability) to create key risks (WGI AR5 Section 11.3.2; Sections 8.2.3, 11.3,

11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, 26.8; Box CC-HS). [RFC 2 and 3]

v) *Risk of food insecurity and the breakdown of food systems linked to warming, drought, flooding, and precipitation variability and extremes, particularly for poorer populations in urban and rural settings*. This risk is a particular concern for farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers). Climatic hazards and the vulnerability of people (see above) may exacerbate malnutrition, giving rise to a larger burden of disease in these groups, especially among elderly and female-headed households having limited ability to cope. The reversal of progress in reducing malnutrition is a potential outcome (WGI AR5 Section 11.3.2; Sections 7.3-5, 11.3, 11.6.1, 13.2.1-2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, 27.3.4). [RFC 2, 3 and 4]

vi) *Risk of loss of rural livelihoods and income due to insufficient access to drinking and irrigation water and reduced agricultural productivity, particularly for farmers and pastoralists with minimal capital in semi-arid regions*. Interaction of warming and drought with lack of alternative sources of income, and the presence of regional and national conditions that lead to a breakdown of food

Table 19-4 | A selection of the hazards, key vulnerabilities, key risks, and emergent risks identified in various chapters in this report (Chapters 4, 6, 7, 8, 9, 11, 13, 19, 22, 23, 24, 25, 26, 27, 28, 29, and 30). Key risks are determined by hazards interacting with vulnerability and exposure of human systems and of ecosystems or species. The table underscores the complexity of risks determined by various climate-related hazards, non-climatic stressors, and multifaceted vulnerabilities. The examples show that underlying phenomena, such as poverty or insecure land tenure arrangements, unsustainable and rapid urbanization, other demographic changes, failure in governance and inadequate governmental attention to risk reduction, and tolerance limits of species and ecosystems that often provide important services to vulnerable communities, generate the context in which climatic change–related harm and loss can occur. The table illustrates that current global megatrends (e.g., urbanization and other demographic changes) in combination and in specific development contexts (e.g., in low-lying coastal zones) can generate new systemic risks in their interaction with climate hazards that exceed existing adaptation and risk management capacities, particularly in highly vulnerable regions, such as dense urban areas of low-lying deltas. Roman numerals correspond with key risks listed in Section 19.6.2.1. A representative set of lines of sight is provided from across WGI AR5 and WGII AR5. See Section 19.6.2.1 for a full description of the methods used to select these entries.

No.	Hazard	Key vulnerabilities	Key risks	Emergent risks
i	Sea level rise, coastal flooding including storm surges (WGI AR5 Sections 3.7 and 13.5; WGI AR5 Table 13.5; Sections 5.4.3, 8.1.4, 8.2.3, 8.2.4, 13.1.4, 13.2.2, 24.4, 24.5, 26.7, 26.8, 29.3.1, and 30.3.1; Boxes 25-1, 25-7)	High exposure of people, economic activity, and infrastructure in low-lying coastal zones, Small Island Developing States (SIDS), and other small islands Urban population unprotected due to substandard housing and inadequate insurance. Marginalized rural population with multidimensional poverty and limited alternative livelihoods Insufficient local governmental attention to disaster risk reduction	Death, injury, and disruption to livelihoods, food supplies, and drinking water Loss of common-pool resources, sense of place and identity, especially among indigenous populations in rural coastal zones	Interaction of rapid urbanization, sea level rise, increasing economic activity, disappearance of natural resources, and limits of insurance; burden of risk management shifted from the state to those at risk, leading to greater inequality
ii	Extreme precipitation and inland flooding (WGI AR5 FAQ 12.2; Sections 3.2.7, 3.4.8, 8.2.3, 8.2.4, 13.2.1, 25.10, 26.3, 26.7, 26.8, and 27.3.5; Box 25-8)	Large numbers of people exposed in urban areas to flood events, particularly in low-income informal settlements Overwhelmed, aging, poorly maintained, and inadequate urban drainage infrastructure and limited ability to cope and adapt due to marginalization, high poverty, and culturally imposed gender roles Inadequate governmental attention to disaster risk reduction	Death, injury, and disruption of human security, especially among children, elderly, and disabled persons	Interaction of increasing frequency of intense precipitation, urbanization, and limits of insurance; burden of risk management shifted from the state to those at risk, leading to greater inequality, eroded assets due to infrastructure damage, abandonment of urban districts, and the creation of high-risk/high-poverty spatial traps
iii	Novel hazards yielding systemic risks (WGI AR5 Section 11.3.2; Sections 8.1.4, 8.2.4, 10.2, 10.3, 12.6, 23.9, 25.10, 26.7, and 26.8)	Populations and infrastructure exposed and lacking historical experience with these hazards Overly hazard-specific management planning and infrastructure design, and/or low forecasting capability	Failure of systems coupled to electric power system, e.g., drainage systems reliant on electric pumps or emergency services reliant on telecommunications. Collapse of health and emergency services in extreme events	Interactions due to dependence on coupled systems lead to magnification of impacts of extreme events. Reduced social cohesion due to loss of faith in management institutions undermines preparation and capacity for response.
iv	Increasing frequency and intensity of extreme heat, including urban heat island effect (WGI AR5 Section 11.3.2; Sections 8.2.3, 11.3, 11.4.1, 13.2, 23.5.1, 24.4.6, 25.8.1, 26.6, and 26.8; Box CC-HS)	Increasing urban population of the elderly, the very young, expectant mothers, and people with chronic health problems in settlements subject to higher temperatures Inability of local organizations that provide health, emergency, and social services to adapt to new risk levels for vulnerable groups	Increased mortality and morbidity during periods of extreme heat	Interaction of changes in regional temperature extremes, local heat island, and air pollution, with demographic shifts Overloading of health and emergency services. Higher mortality, morbidity, and productivity loss among manual workers in hot climates
v	Warming, drought, and precipitation variability (WGI AR5 Section 11.3.2; Sections 7.3, 7.4, 7.5, 11.3, 11.6.1, 13.2.1, 13.2.2, 19.3.2, 19.4.1, 22.3.4, 24.4, 26.8, and 27.3.4)	Poorer populations in urban and rural settings are susceptible to resulting food insecurity; includes particularly farmers who are net food buyers and people in low-income, agriculturally dependent economies that are net food importers. Limited ability to cope among the elderly and female-headed households	Risk of harm and loss of life due to reversal of progress in reducing malnutrition	Interactions of climate changes, population growth, reduced productivity, biofuel crop cultivation, and food prices with persistent inequality and ongoing food insecurity for the poor increase malnutrition, giving rise to larger burden of disease. Exhaustion of social networks reduces coping capacity.

Continued next page →

Table 19-4 (continued)

No.	Hazard	Key vulnerabilities		Key risks	Emergent risks
vi	Drought (WGI AR5 Sections 12.4.1 and 12.4.5; Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3, 8.2.4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, and 24.4)	Urban populations with inadequate water services. Existing water shortages (and irregular supplies), and constraints on increasing supplies Lack of capacity and resilience in water management regimes including rural–urban linkages		Insufficient water supply for people and industry, yielding severe harm and economic impacts	Interaction of urbanization, infrastructure insufficiency, groundwater depletion
		Poorly endowed farmers in drylands or pastoralists with insufficient access to drinking and irrigation water Limited ability to compensate for losses in water-dependent farming and pastoral systems, and conflict over natural resources Lack of capacity and resilience in water management regimes, inappropriate land policy, and misperception and undermining of pastoral livelihoods		Loss of agricultural productivity and/or income of rural people. Destruction of livelihoods, particularly for those depending on water-intensive agriculture. Risk of food insecurity	Interactions across human vulnerabilities: deteriorating livelihoods, poverty traps, heightened food insecurity, decreased land productivity, rural outmigration, and increase in new urban poor in low- and middle-income countries. Potential tipping point in rain-fed farming system and/or pastoralism
vii	Rising ocean temperature, ocean acidification, and loss of Arctic sea ice (WGI AR5 Section 11.3.3; Sections 5.4.2, 6.3.1, 6.3.2, 7.4.2, 9.3.5, 22.3.2.3, 24.4, 25.6, 27.3.3, 28.2, 28.3, 29.3.1, 30.5, and 30.6; Boxes CC-OA and CC-CR)	High susceptibility of warm water coral reefs and respective ecosystem services for coastal communities; high susceptibility of polar systems, e.g., to invasive species Susceptibility of coastal and SIDS fishing communities depending on these ecosystem services; and of Arctic settlements and culture		Loss of coral cover, Arctic species, and associated ecosystems with reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interactions of stressors such as acidification and warming on calcareous organisms enhancing risk
viii	Rising land temperatures, changes in precipitation patterns, and frequency and intensity of extreme heat (WGI AR5 Section 11.3.2.5; Sections 4.3.4, 19.3.2.1, 22.4.5.6, and 27.3.2.1; FAQs 4.5 and 4.7; Boxes 23-1 and CC-WE)	Susceptibility of societies to loss of provisioning, regulation, and cultural services from terrestrial ecosystems Susceptibility of human systems, agro-ecosystems, and natural ecosystems to (1) loss of regulation of pests and diseases, fire, landslide, erosion, flooding, avalanche, water quality, and local climate; (2) loss of provision of food, livestock, fiber, bioenergy; (3) loss of recreation, tourism, aesthetic and heritage values, and biodiversity		Reduction of biodiversity and potential losses of important ecosystem services. Risk of loss of endemic species, mixing of ecosystem types, and increased dominance of invasive organisms	Interaction of social-ecological systems with loss of ecosystem services upon which they depend

Social vulnerability | Economic vulnerability | Environmental vulnerability | Institutional vulnerability | Exposure

distribution and storage systems, increase risk. Especially vulnerable are those with limited ability to compensate for losses in water-dependent farming and pastoral systems, as well as those subject to conflict over natural resources. In addition, insufficient supply of water due to droughts and institutional vulnerabilities (e.g., lack of state capacities, conflicts) for both industry and urban populations lacking running water, yielding severe economic impacts and other harms (WGI AR5 Sections 12.4.1, 12.4.5; Sections 3.2.7, 3.4.8, 3.5.1, 8.2.3-4, 9.3.3, 9.3.5, 13.2.1, 19.3.2.2, 24.4). [RFC 2 and 3]

vii) *Risk of loss of marine and coastal ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for coastal livelihoods, especially for fishing communities in the tropics and the Arctic*. These resources are especially at risk due to rising water temperature and the increase of stratification and ocean acidification. Loss of Arctic sea ice and degradation of coral reefs, as well as other natural barriers, presents a high risk to ecosystem services where many people are exposed to coastal hazards and also depend on coastal resources for livelihoods, such as Alaska, the Philippines, and Indonesia (WGI AR5 Section 11.3.3; Sections 5.4.2, 6.3.1-2, 7.4.2, 9.3.5, 22.3.2.3, 24.4, 25.6, 27.3.3, 28.2-3, 29.3.1, 30.5-6; Boxes CC-OA, CC-CR). [RFC 1, 2, and 4]

viii) *Risk of loss of terrestrial and inland water ecosystems, biodiversity, and the ecosystem goods, functions, and services they provide for livelihoods*. Biodiversity and terrestrial ecosystem services are important for rural and urban communities globally. These services are at risk due to rising temperatures, changes in precipitation patterns, and extreme weather events. Risks are high for communities whose livelihoods depend on provisioning services. Human and natural systems are susceptible to loss of provisioning services such as food and fiber, regulating services such as water quality, fire, and erosion, and cultural services such as aesthetic values and tourism (WGI AR5 Section 11.3.2.5; Sections 4.3.4, 19.3.2.1, 22.4.5.6, 27.3.2.1; Boxes 23-1, CC-WE; FAQs 4.5, 4.7). [RFC 1, 3 and 4]

An important common characteristic of all key risks associated with anthropogenic climate change is that they are determined by hazards due to changing climatic conditions on the one hand and the vulnerability of exposed societies, communities, and social-ecological systems, for example, in terms of livelihoods, infrastructure, ecosystem services and management/governance systems on the other (see Table 19-4). The compilation of key risks underscores that effective adaptation and risk reduction measures would address all three components of risk (*high confidence*).

19.6.2.2. The Role of Adaptation and Alternative Development Pathways

As discussed in Section 19.2.4, the identification of key risks depends in part on the underlying socioeconomic conditions assumed to occur in the future, which can differ widely across alternative development pathways. This section assesses literature that compares impacts across development pathways, compares the contributions of anthropogenic climate change and socioeconomic development (through changes in vulnerability and exposure) to climate-related impacts, and examines the potential for adaptation to reduce those impacts. Based on this assessment, risks vary substantially across plausible alternative development pathways and the relative importance of development and climate change varies by sector, region, and time period, but in general both are important to understanding possible outcomes (*high confidence*). In some cases, there is substantial potential for adaptation to reduce risks, with development pathways playing a critical role in determining challenges to adaptation, including through their effects on ecosystems and ecosystem services (Rothman et al., 2014).

Direct comparison of impacts across alternative development pathways shows, for example, that socioeconomic conditions are an important determinant of the impacts of climate change on food security, water stress, and the consequences of extreme events and sea level rise. The additional effect of climate change and CO_2 fertilization on the number of people at risk from hunger by 2080 generally spans a range of ± 10 to 30 million across the four marker SRES scenarios, each of which assumes different socioeconomic futures. However, in a scenario (A2) with high population growth and slow economic growth, this effect becomes as high as 120 to 170 million in some analyses (Schmidhuber and Tubiello, 2007). Similarly, the number of people exposed to water scarcity in a global study is sensitive to population growth assumptions (Gosling and Arnell, 2013), as are projected water resources in the Middle East under an A1B climate change scenario (Chenoweth et al., 2011). Assessments of the risks from river flooding depend on alternative future population and land use assumptions (Bouwer et al., 2010; te Linde et al., 2011), and sea level rise impacts depend on development pathways through their effect on the exposure of both the population and economic assets to coastal impacts, as well as on the capacity to invest in protection (Anthoff et al., 2010).

The view that development pathways are an important determinant of risk related to climate change impacts is further supported by two other types of studies: those that examine the vulnerability of subgroups of the current population, and those that compare the relative importance of climate and socioeconomic changes to future impacts. The first type finds that variation in current socioeconomic conditions explains some of the variation in risks associated with climate and climate change, supporting the idea that alternative development pathways, which describe different patterns of change in these conditions over time, should influence the future risks of climate change. For example, socioeconomic conditions have been found to be a key determinant of risks to low-income households due to climate change effects on agriculture (Ahmed et al., 2009; Hertel et al., 2010), to sub-populations due to exposure to heterogeneous regional climate change (Diffenbaugh et al., 2007), and to low-income coastal populations due to storm surges (Dasgupta et al., 2009). Assessments of environmentally induced migration have concluded that migration responses are mediated by a number of social and governance characteristics that can vary widely across societies (Warner, 2010; see Sections 12.4, 19.4.2.1).

The second type of study finds that, within a given projection of future climate change and change in socioeconomic conditions, typically both are important to determining risks. In fact, the effect of the physical impacts of climate change on globally aggregated changes in food consumption or risk of hunger have been found to be small relative to changes in these metrics driven by socioeconomic development alone (Schmidhuber and Tubiello, 2007; Nelson et al., 2010; Wiltshire et al., 2013). Similarly, future population growth is found to be an equally (Murray et al., 2012) or more (Fung et al., 2011; Schewe et al., 2013) important determinant of globally aggregated water stress as the level of climate change, and population growth, economic growth, and urbanization are expected to largely drive potential future damages to coastal cities due to flooding (*high confidence*; Section 5.4.3.1; Hallegatte et al., 2013) and to be important determinants of damages from tropical cyclones (Bouwer et al., 2007; Pielke Jr., 2007; Mendelsohn et al., 2012). At the regional level, socioeconomic development has also been found to be equally or more important than climate change to impacts in Europe due to sea level rise, through coastal development (Hinkel et al., 2010); heat stress, especially when acclimatization (Watkiss and Hunt, 2012) or aging (Lung et al., 2013) is taken into account; and flood risks, through exposure due to land use and distributions of buildings and infrastructure (Feyen et al., 2009; Bouwer et al., 2010). Climate change was the dominant driver of flood risks in Europe when future changes in the value of buildings and infrastructure at risk were excluded from the analysis (te Linde et al., 2011; Lung et al., 2013) or when biophysical impacts such as stream discharge, rather than its consequences, were assessed (Ward et al., 2011).

Land use is another socioeconomic factor that can affect risks in addition to climate change, but until recently few studies have addressed the combined impacts of climate change and land use on ecosystems (Warren et al., 2011). Studies including multiple drivers of extinction find that although land use change remains the dominant driver out to 2100, climate change is the next most important driver (Sala et al., 2000; Millenium Ecosystem Assessment, 2005b). A study of land bird extinction risk found some sensitivity to four alternative land use scenarios, but by 2100 risk was dominated by the climate change scenario (Şekercioğlu, 2008). A study of European land use found that while land use outcomes were more sensitive to the assumed socioeconomic scenario, consequences for species depended more on the climate scenario (Berry et al., 2006).

Explicit assessments of the potential for adaptation to reduce risks have indicated that there is substantial scope for reducing impacts of several types, but the capacity to undertake this adaptation is dependent on underlying development pathways. Assessments of the impacts of sea level rise, for example, show that if development pathways allow for substantial investment of resources in adaptation through coastal protection, as opposed to accommodation or abandonment strategies, reducing impacts by investing in coastal protection can be an economically rational response for large areas of coastline globally (Nicholls et al., 2008a,b; Anthoff et al., 2010; Nicholls and Cazenave, 2010; Hallegatte et al., 2013) and in Europe (Bosello et al., 2012b). For the specific case of sea level rise impacts in Europe, adaptation in the form of increasing dike heights and nourishing beaches, at a cost reaching about €3 billion per year by 2100, was found to reduce the number of people affected by coastal flooding in 2100 from hundreds of thousands to a few thousand per year depending on the socioeconomic and sea level rise scenario (A2 vs. B1), and total economic damages from about €17 billion to about €2 billion per year (Hinkel et al., 2010). In contrast, in some areas with higher current and anticipated future vulnerability such as low-lying island states and parts of Africa and Asia, impacts are expected to be greater and adaptation more difficult (Nicholls et al., 2011).

Similarly, the risk to food security in many regions could be reduced if development pathways increase the capacity for policy and institutional reform, although most impact studies have focused on agricultural production and accounted for adaptation to a limited and varying degree (Lobell et al., 2008; Nelson et al., 2009; Ziervogel and Ericksen, 2010). A study of response options in sub-Saharan Africa identified some scope for adapting to climate change associated with a global warming of 2°C above preindustrial levels (Thornton et al., 2011), given substantial investment in institutions, infrastructure, and technology, but was pessimistic about the prospects of adapting to a world with 4°C of warming (Thornton et al., 2011; see also Section 19.7.1). Improved water use efficiency and extension services have been identified as the highest priority agricultural adaptation options available in Europe (Iglesias et al., 2012), and a potentially large role for expanded desalination has been identified for the Middle East (Chenoweth et al., 2011).

19.6.3. Updating Reasons for Concern

The RFCs are the relationship between global mean temperature increase and five categories of impacts that were introduced in the IPCC TAR (Smith et al., 2001) in order to facilitate interpretation of Article 2

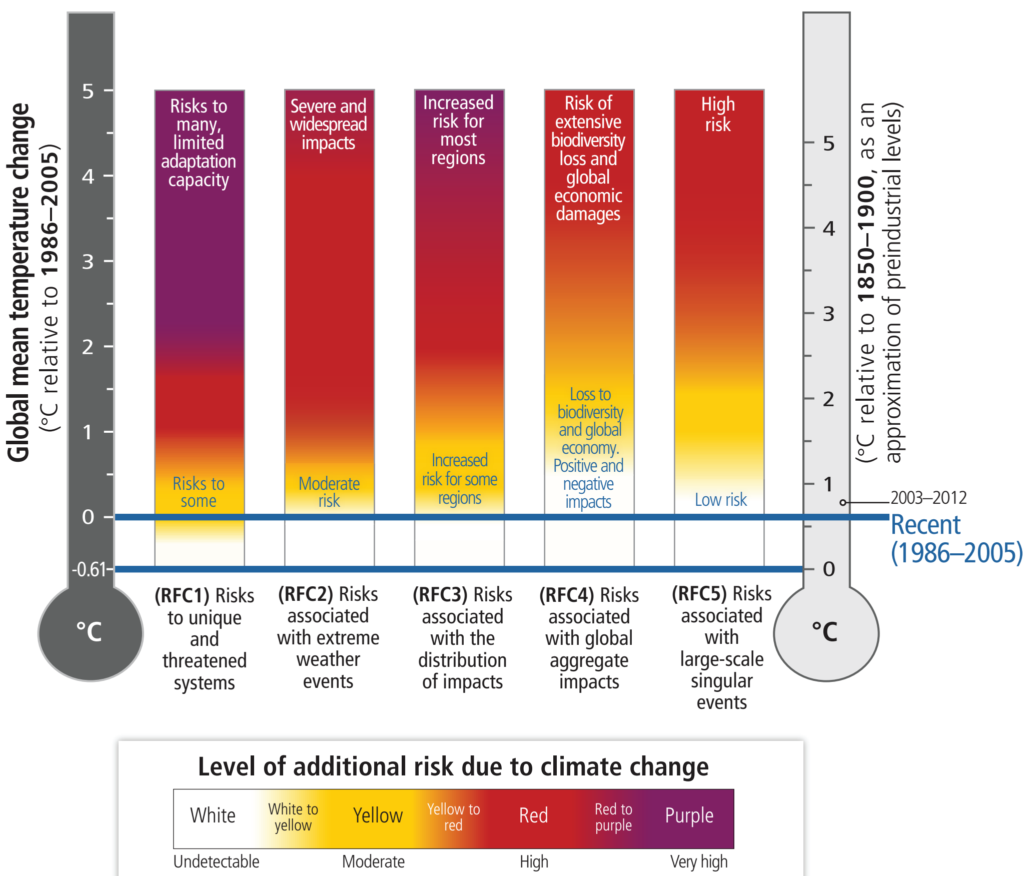

Figure 19-4 | The dependence of risk associated with the Reasons for Concern (RFCs) on the level of climate change, updated from the Third Assessment Report and Smith et al. (2009). The color shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. The shading of each ember provides a qualitative indication of the increase in risk with temperature for each individual "reason." Undetectable risk (white) indicates no associated impacts are detectable and attributable to climate change. Moderate risk (yellow) indicates that associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks. High risk (red) indicates severe and widespread impacts, also accounting for the other specific criteria for key risks. Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks. Comparison of the increase of risk across RFCs indicates the relative sensitivity of RFCs to increases in GMT. In general, assessment of RFCs takes autonomous adaptation into account, as was done previously (Smith et al., 2001, 2009; Schneider et al., 2007). In addition, this assessment took into account limits to adaptation in the case of RFC1, RFC3, and RFC5, independent of the development pathway. The rate and timing of climate change and physical impacts, not illustrated explicitly in this diagram, were taken into account in assessing RFC1 and RFC5. Comments superimposed on RFCs provide additional details that were factored into the assessment. The levels of risk illustrated reflect the judgments of Chapter 19 authors.

(Section 1.2.2; Box 19-2). In AR4, new literature related to the five RFCs was assessed, leading in most cases to confirmation or strengthening of the judgments about their relevance to defining dangerous anthropogenic interference based on evidence that some impacts were already apparent, higher likelihoods of some climate-related hazards, and improved identification of currently vulnerable populations (Schneider et al., 2007; Smith et al., 2009).

RFCs are related to the framework of key risks, climate-related hazards, and vulnerabilities used in this chapter because each RFC is understood to represent a broad category of key risks to society or ecosystems associated with a specific type of hazard (extreme weather events, large-scale singular events), system at risk (unique and threatened systems), or characteristic of risk to social-ecological systems (global aggregate impacts on those systems, distribution of impacts to those systems). For example, the RFC for extreme weather events implies a concern for risks to society and ecosystems posed by extreme events,

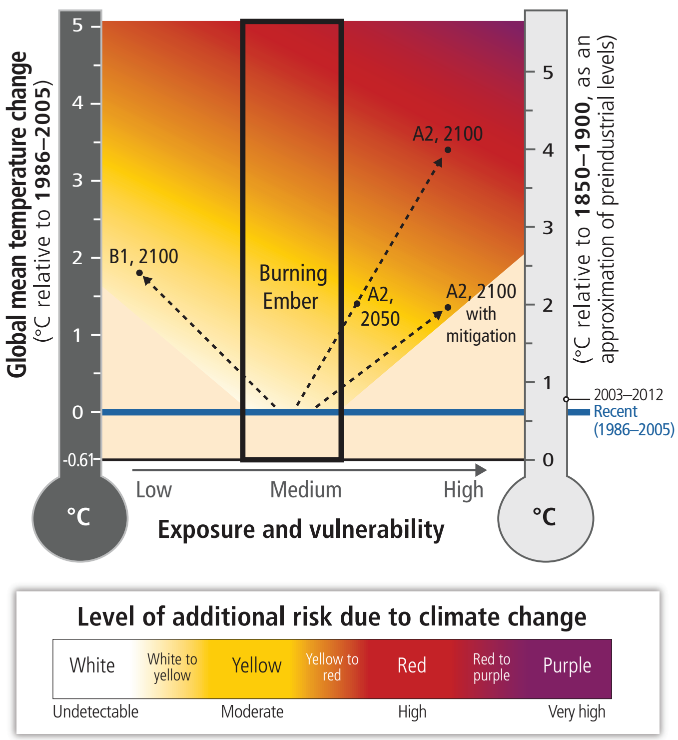

Figure 19-5 | Illustration of the dependence of risk associated with a Reason for Concern (RFC) on the level of climate change and exposure and vulnerability (E&V) of society. This figure is schematic; the degree of risk associated with particular levels of climate change or E&V has neither been based on a literature assessment nor associated with a particular RFC (the "burning ember" in the figure refers generically to any of the embers in Figure 19-4). The E&V axis is relative rather than absolute. "Medium" E&V indicates a future development path in which E&V changes over time are driven by moderate trends in socioeconomic conditions. "Low" and "High" E&V indicate futures that are substantially more optimistic or pessimistic, respectively, regarding exposure and vulnerability. Judgments made in other burning ember diagrams of the RFCs (Smith et al., 2001, 2009) including Figure 19-4, which do not explicitly take changes in E&V into account, are consistent with Medium future E&V. Arrows and dots illustrate the use of Special Report on Emission Scenarios (SRES)-based literature to locate particular impact or risk assessments on the figure according to the evolution of climate and socioeconomic conditions over time. This figure does not explicitly address issues related to the rates of climate change or when impacts might be realized.

rather than a concern for extreme events per se. Accordingly, in this chapter we have reworded the definition of RFCs to emphasize risk.

In this section we assess new literature related to each of the RFCs, concluding that, compared to judgments presented in AR4 and in Smith et al. (2009), levels of risk associated with extreme weather events and distribution of impacts can be assessed with higher confidence and are higher for large temperature rise than previously assessed; risks associated with global aggregate impacts are similar to AR4 and Smith et al (2009) and confidence in the assessment unchanged; and risks to unique and threatened systems and those associated with large-scale singular events are higher above 2°C (compared to a 1986–2005 baseline) than assessed previously. These judgments are illustrated in Figure 19-4, an updated version of the "burning embers" diagram that describes how the additional risk due to climate change for each RFC changes with increasing GMT. We retain the color scheme employed in previous versions of this figure (Smith et al., 2001, 2009) with some refinement. White, yellow, and red indicate undetectable, moderate, and high additional risk, respectively. Risk is low in the transition between white and yellow, and substantial in the transition between yellow and red. We add a new color (purple) indicating very high risk as elaborated below.

The following subsections assess risks for each RFC and locate transitions between colors using the criteria for key risks as a guide (Section 19.2.2.2). The transition from white to yellow is partly defined by the GMT at which there is at least *medium confidence* that impacts associated with a given risk are both detectable and attributable to climate change, while also accounting for the magnitude of the risk. We draw on Section 18.6.4 to inform the placement of this transition relative to recent GMT. The transition from yellow to red is defined by increasing magnitude (including pervasiveness) or likelihood of impacts, with high risk (red color) defined as risk of severe and widespread impacts that is judged to be high on one or more criteria for assessing key risks (Section 19.2.2.2). Purple, introduced in this assessment, shows that very high risk is indicated by all specific criteria for key risks, including limited ability to adapt. As was true in the TAR and Smith et al. (2009), transitions are fuzzy owing to uncertainties in a variety of factors determining the relation between GMT and risk, including the rate of climate change, the time at which the temperature is reached, and the extent and agreement of the evidence base in the literature.

We also clarify the concept of RFCs: because risks depend not only on physical impacts of climate change but also on exposure and vulnerability of societies and ecosystems to those impacts, RFCs as a reflection of those risks depend on both factors as well (see also Section 19.1).

19.6.3.1. Variations in RFCs across Socioeconomic Pathways

The determination of key risks as reflected in the RFCs has not previously been distinguished across alternative development pathways. In the TAR and AR4, RFCs took only autonomous adaptation into account (Smith et al., 2001; Schneider et al., 2007; WGII AR4 Chapter 19). However, the RFCs represent risks that are determined by both climate-related hazards and the vulnerability and exposure of social and ecological systems to climate change stressors. Figure 19-5 illustrates this dependence on vulnerability and exposure in a modified version of the burning embers diagram. Current literature is not sufficient to support confident assessment of specific RFCs using this approach.

As literature accumulates, it could inform new versions of this figure applied to specific RFCs. For example, studies that employ particular scenarios of socioeconomic conditions could be categorized according to the levels of vulnerability represented by those scenarios (van Vuuren et al., 2012) to locate results along the horizontal axes, while climate conditions assumed in those studies would locate results along the vertical axis. As with previous versions of the burning embers, however, this new figure does not explicitly address issues related to rates of climate change or to when impacts might be realized. The updates of RFCs in 19.6.3.2 to 19.6.3.6 that follow (and are illustrated in Figure 19-4) do not account for differences in vulnerability across development paths; rather, they are based on the same assessment framework as used in AR4 and Smith et al. (2009), but with additional elaboration.

19.6.3.2. Unique and Threatened Systems

Unique and threatened systems include a wide range of physical, biological, and human systems that are restricted to relatively narrow geographical ranges and are threatened by future changes in climate (Smith et al., 2001). Where consequences are *irreversible* and *importance* to society and other systems is high, the potential for loss of or damage to such systems constitutes a key risk. AR4 stated with *high confidence* that a warming of up to 2°C above preindustrial levels would result in significant impacts on many unique and vulnerable systems and would increase the endangered status of many threatened species, with increasing adverse impacts (and increasing confidence in this conclusion) at higher temperatures (Schneider et al., 2007). Since AR4, there is a growing body of literature suggesting that the number of threatened systems and species is greater than previously thought.

Chapters 4, 22, 23, 24, 25, 26, and 27 highlight areas where unique and threatened systems are particularly vulnerable to climate change. Evidence for severe and widespread impacts to humans and social systems, ecosystems, and species in polar regions as warming progresses has continued to accrue (Sections 4.3.3.4, 28.2). Projections of Arctic sea ice melt rates have increased since AR4 (WGI AR5 Section 12.4.6), increasing risks to the Inuit and the sea ice-dependent ecosystems upon which they subsist. CMIP5 model runs for September with all RCPs show substantial additional losses of Arctic Ocean ice for a global warming of 1°C relative to 1986–2005 and a nearly ice-free Arctic Ocean for global warming greater than 2°C (WGI AR5 Figure 12.30). Furthermore, a nearly ice-free Arctic Ocean in September before mid-century is *likely* under RCP8.5 (*medium confidence*; WGI AR5 Section 12.4.6).

Coral reef ecosystems are still considered amongst the most vulnerable of unique marine systems (Sections 5.4.2.4, 19.3.2.4), with corals' evolutionary responses being outpaced by climate change (Hoegh-Guldberg, 2012) resulting in projections of extensive reef decline throughout the 21st century. Globally, large-scale reef dissolution may occur if CO_2 concentrations reach 560 ppm (Section 5.4.2.4) due to the combined effects of warming and ocean acidification. Even if global temperature rise in the 2090s is constrained to 1.2 to 2.0°C above preindustrial levels (WGI AR5 Table 12.3, RCP2.6), and assuming rapid adaptation rates in corals, 9 to 60% of reefs are projected to be subject to long-term degradation, while 30 to 88% of reefs are projected to eventually degrade if global temperature rises in the 2090s by 1.9 to 2.9°C above preindustrial levels (RCP4.5; Box CC-CR; temperatures from WGI AR5 Table 12.3). Loss of corals and mangrove ecosystems would endanger the livelihoods of unique human communities and cause economic damage (Section 4.3.3 for global discussion; Sections 22.3.2.3, 24.4.3, 25.6 for Africa, Asia, and Australia; Section 26.4 for North America; Section 27.3.3.1 for South America).

There is a large and increasing amount of evidence for escalating risks of species range loss, extirpation, and extinction based on studies for global temperatures exceeding 2°C above preindustrial levels (1.4°C above 1986–2005; Warren et al., 2011; Şekercioğlu et al., 2012, Foden et al., 2013; Warren et al., 2013a). An assessment of 16,857 species (Foden et al., 2013) found that with approximately 2°C of warming above preindustrial (A1B, 2050s), 24 to 50% of the birds, 22 to 44% of the amphibians, and 15 to 32% of the corals were highly vulnerable to climate change defined as having high sensitivity, high exposure, and low adaptive capacity.

An increasing number of threatened systems has been identified, in the form of projected species range losses and extinction risks, although without yet tying risks to specific levels of warming. Evidence of climate risks to unique mountain ecosystems and their numerous endemic alpine species has continued to accrue in Europe, Asia, Australia, and South America (Sections 23.6.4, 24.4.2.3, 25.6.1, 27.3.2.1). Siberian, tropical, and desert ecosystems in Asia (Section 24.4.2.3), Africa (Warren et al., 2013a), and Mediterranean areas in Europe (Klausmeyer and Shaw, 2009; Maiorano et al., 2011), the Queensland rainforest, Kakadu National Park, and the southwestern region of Australia (Section 25.6.1), Amazonian ecosystems in South America (Foden et al., 2013; Warren et al., 2013a), and freshwater ecosystems in Africa (specifically Ethiopia, Malawi, Mozambique, Zambia, and Zimbabwe) (Section 22.3.2.2) are particularly at risk, as are the Fynbos and succulent Karoo areas of South Africa (Midgley and Thuiller, 2011; Kuhlmann et al., 2012; Huntley and Barnard, 2012) and dune systems in temperate climates (Section 23.6.5). Recent research has identified risks to highly biodiverse tropical wet and dry forests (Sections 4.3.3, 24.4.2.3; Kearney et al., 2009, Wright et al., 2009; Toms et al., 2012) and tropical island endemics (Fordham and Brook, 2010). Globally amphibians were found to be the most vulnerable of vertebrate taxa (Stuart et al., 2004; Brito, 2008; Rohr and Raffel, 2010; Liu et al., 2013; Warren et al., 2013a).

Owing to higher projections of sea level rise than in AR4 (WGI AR5 Sections 13.5-7), risk of partial inundation of small island states has increased.

"Since AR4, almost all glaciers worldwide have continued to shrink as revealed by the time series of measured changes in glacier length, area, volume and mass (*very high confidence*)" (WGI AR5 Chapter 4 ES). There is substantial new evidence that, across most of Asia, glaciers have been shrinking, except in some areas in the Karakorum and Pamir (Section 18.5.3). In the Andes, glacier loss threatens to reduce the water and electricity supplies of large cities and hydropower projects, as well as the agricultural and tourism sectors (Sections 27.3.1.1-2, 27.6.1; Table 27-3). Model simulations show a large projected loss of glacier ice volume in central Asia by end of the century: in particular, estimates for

RCP8.5 and RCP4.5 suggest the potential for loss of most of the 2006 ice volume (Section 24.9.2). Loss of glacial cover has been projected to significantly reduce water supplies in meltwater-dependent arid regions (Kaser et al., 2010), potentially threatening the food security of 60 million people in the Brahmaputra and Indus basins by the 2050s (Immerzeel et al., 2010). However, recent work has suggested the glacier melt rates in two Himalayan watersheds, Baltoro and Langtang, were previously overestimated and, since precipitation is projected to concurrently increase, runoff may actually rise until 2050 in these particular watersheds (Immerzeel et al., 2013). Large uncertainties in projections of Himalayan ice cover and runoff dynamics remain (Bolch et al., 2012).

In Figure 19-4, we locate the transition to moderate risk (white to yellow) below recent global temperatures because there is at least *medium confidence* in attribution of a major role for climate change for impacts on at least one each of ecosystems, physical systems, and human systems (Section 18.6.4). A transition to purple is located around 2°C above 1986–2005 levels to reflect the very high risk to species and ecosystems projected to occur beyond that level as well as limited ability to adapt to impacts on coral reef systems and on Arctic sea ice-dependent systems (Chapters 4, 5, 6, 28) if that level of warming were exceeded (*high confidence*). A transition to red is located around 1°C above 1986–2005 levels, midway between current temperature and the transition to purple, indicating the increasing risk to unique and threatened systems, including Arctic sea ice and coral reefs, as well as threatened species as temperature increases over this range.

19.6.3.3. Extreme Weather Events

Extreme weather events (e.g., heat waves, intense precipitation, drought, tropical cyclones) trigger impacts that can pose key risks to societies that are exposed and vulnerable (Lavell et al., 2012). With regard to the physical hazard aspect of risk, AR5 assesses a higher likelihood of attribution of heat waves and extreme hot days and nights to human activity than AR4. WGI AR5 states, "We assess that it is *very likely* that human influence has contributed to the observed changes in the frequency and intensity of daily temperature extremes on the global scale since the mid-20th century" (WGI AR5 Section 10.6.1.1) and "it is *likely* that human influence has substantially increased the probability of occurrence of heat waves in some locations" (WGI AR5 Section 10.6.2). WGI finds *medium confidence* in attribution of intensification of heavy precipitation over land areas with sufficient data (WGI AR5 Section 10.6.1.2), and "*low confidence* in detection and attribution of changes in drought over global land areas" (WGI AR5 Section 10.6.1.3) and global changes in tropical cyclone activity (WGI AR5 Section 10.6.1.5) to human influence. There is *high confidence* in attribution of impacts of weather extremes (as opposed to the physical hazards alone) on coral reef systems (Sections 18.6.4, 19.6.3.2; Table 18-10), with evidence for impact attribution limited and highly localized otherwise.

The likelihood of projected 21st century changes in extremes has not changed markedly since AR4 (WGI AR5 Chapters 10, 12), but for the first time near-term changes (for the period 2016–2035 relative to 1986–2005) are assessed (WGI AR5 Chapter 1), a period during which the increase in the model and scenario averaged GMT is projected to remain below 1°C relative to 1986–2005 (WGI AR5 Figure 11.8; WGI AR5 Section 11.3.6.3). Among the conclusions are, "In most land regions the frequency of warm days and warm nights will *likely* increase in the next decades, while that of cold days and cold nights will decrease" (WGI AR5 Chapter 11 ES). Specifically, about 15% of currently observed maximum daily temperatures exceed the historical 90th percentile values (rather than the historical 10%) and, by about 2035, 25 to 30% of daily maximums are projected to exceed the historical 90th percentile value (WGI AR5 Figure 11.17). WGI also notes that "Models project near-term increases in the duration, intensity and spatial extent of heat waves and warm spells" (WGI AR5 Chapter 11 ES; WGI AR5 Table SPM.1). With regard to extreme precipitation events, WGI finds "The frequency and intensity of heavy precipitation events over land will *likely* increase on average in the near term. However, this trend will not be apparent in all regions because of natural variability and possible influences of anthropogenic aerosols" (WGI AR5 Chapter 11 ES). In addition, SREX (IPCC, 2012a, Figure SPM.4B) projects a reduction in return period for historical once-in-20-year precipitation events globally (land only) to about once-in-14-year or less by 2046–2065.

With regard to the vulnerability and exposure aspects of risk, SREX reviewed literature on the relationship between changes in these factors and the risk of extreme events (IPCC, 2012a, Sections 4.5.4, 4.5.6). Increases in local vulnerability and exposure to extreme precipitation can lead to a disproportionate increase in overall risk (IPCC, 2012a, Sections 4.3.5.1, 9.2.8; Douglas et al., 2008; Douglas, 2009; Hallegate et al., 2011; Ranger, 2011). For example, growth of megacities both concentrates exposure and vulnerability and can generate "synchronous failure" that spreads beyond the immediate vicinity of extreme events. Megacities increase nighttime temperature extremes via the urban heat island effect (Section 8.2.3.1; IPCC, 2012a, Sections 4.3.5.1, 4.4.5.2) while also enhancing exposure to high air pollution levels (IPCC, 2012a, Sections 4.3.5.1, 9.2.1.2.3; Fang et al., 2013) and consequent health effects (Sections 11.5.3.2, 11.5.3.4), with widespread impacts by mid-century in some studies. Densely populated areas of East and South Asia and North America are projected to be especially affected by climate-related air pollution (Fang et al., 2013).

Projections of the global socioeconomic (Mendelsohn et al., 2012) impact of tropical cyclones demonstrate increasing risk due to interactions of increasing storm intensity with exposure. Hazard projection suggests a disproportionate increase in exposure to tropical cyclone risk with increasing temperature at New York City due to combined effects of storm intensification and sea level rise (Lin et al., 2012). Other studies (Jongman et al., 2012; Hallegate et al., 2013; Preston, 2013) project increasing coastal flood risk due to increasing exposure, although the first two do not disaggregate to specific types of extreme events. Taken together, this evidence supports a conclusion of disproportionate increase in risk associated with extreme events as temperature, and in many cases, exposure and vulnerability increase as well.

Based on the above assessments of the physical hazard alone, we find increased confidence in the AR4 assessment of the risk from extreme weather events. Based on the attribution of heat and precipitation extremes to anthropogenic climate change, the attribution to climate change of impacts of climate extremes on one unique and threatened system, and the current vulnerability of other exposed systems, we assign a yellow level of risk at recent temperatures in Figure 19-4 (*high*

19

confidence), consistent with Smith et al. (2009). We assign a transition to red beginning below 1°C compared to 1986–2005 (also consistent with Smith et al. (2009)) based primarily on the *magnitude* and *likelihood* and *timing* (see Section 19.2.2.2) of the projected change in hazard of extreme weather events, indicating that impacts will become more severe and widespread over the next few decades (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase further at higher temperatures (*high confidence*).

19.6.3.4. Distribution of Impacts

The distribution of impacts is a category of climate change consequences that includes key risks to particular societies and social-ecological systems that may be disproportionately affected due to unequal distribution of hazards, exposure, or vulnerability. AR4 concluded that there is *high confidence* that low-latitude, less-developed areas are generally at greatest risk and found that, because vulnerability to climate change is also highly variable within countries, some population groups in developed countries are also highly vulnerable even to a warming of less than 2°C above 1990–2000 (Schneider et al., 2007). These conclusions remain valid and are now supported by a limited number of impact studies that explicitly consider differences in socioeconomic conditions that affect vulnerability across regions or populations (Mougou et al., 2011; Müller et al., 2011; Gosling and Arnell, 2013; Schewe et al., 2013). Furthermore, we have increased confidence in the AR4 assessment of the risk arising in the near term from the distribution of impacts from extreme weather events because, by their very nature, these events change in a locally and temporally variable fashion with, for example, a larger change in extreme temperatures at higher latitudes (IPCC, 2012a, Figure SPM.4A).

Impacts of climate change on food security depend on both production and non-production aspects of the food system, including not just yield effects but also changes in the amount of land in production and adjustments in trade patterns (Section 7.1.1). Effects on prices are often taken as an indicator of impacts on food security, and the combined effect of climate and CO_2 change (but ignoring O_3 and pest and disease impacts) appears *about as likely as not* to increase prices by 2050, with few new studies examining prospects at longer time horizons (Section 7.4.4). Most studies have focused on geographical differences in the effects of climate change on crop yields. With regard to such distributional consequences, yields of maize and wheat begin to decline with about 1°C to 2°C of local warming in the tropics, with or without adaptation taken into account (Figure 7-4). Temperate maize and tropical rice yields are less clearly affected at these temperatures, but significantly affected with local warming of 3 to 5°C particularly without adaptation (based on studies with various baselines, see Section 7.3.2.1). These data confirm AR4 findings that even small warming will decrease yields in low-latitude regions (*medium evidence*, *high agreement*; Section 7.3.2.1.1), and increase the risk assigned to yields in mid- to high-latitude regions (compared to AR4), suggesting that temperate wheat yield decreases are *about as likely as not* for moderate warming.

Risks of climate change related to freshwater systems, such as water scarcity and flooding, increase with global mean temperature rise (*medium evidence*, *high agreement*; Chapter 3 ES; Table 3-2). Climate change is projected to reduce renewable surface water and groundwater resources significantly in most dry subtropical regions (*high agreement*, *robust evidence*; Section 3.5; Chapter 3 ES). One study using multiple climate and hydrological models to simulate impacts of scenario RCP8.5 and Shared Socioeconomic Pathway 2 (SSP2) project that global warming of 1.7°C above preindustrial will reduce water resources by more than one standard deviation, or by more than 20%, for 8% of the global population, while for warming of 2.7°C above preindustrial this increases to 14% (model range 10 to 30%), and for warming of 3.7°C above preindustrial it reaches a mean of 17% across models (Schewe et al., 2013). In addition, in another study (Gosling and Arnell, 2013), climate change amplifies water scarcity by 30 to 40% for 1.7 to 2.7°C of warming, with around 40% of the global population under increased water stress. In one model, exposure to water scarcity increases steeply up to 2.3°C above preindustrial in North and East Africa, Arabia, and South Asia (Gosling and Arnell, 2013). In Africa water resources risks are "medium-high" at 2°C and "high-very high" at 4°C (Table 22-6). Model projections generally agree that discharge will decrease in the Mediterranean and in large parts of North and South America (Schewe et al., 2013). However, there are opportunities for adaptation in the water resources sector, particularly for municipal water supply (Section 3.6).

The first global scale analysis of climate change impacts on almost 50,000 species of plants and animals has highlighted that risks are not distributed equally, with sub-Saharan Africa, Central America, Amazonia, and Australia at risk for plants and animals, and North Africa, Central Asia, and southeastern Europe for many plants (Warren et al., 2013a). A traits-based analysis of more than 16,000 species identified Amazonia and Mesoamerica as being at risk for birds and amphibians; central Eurasia, the Congo Basin, the Himalayas, and Sundaland for birds; and the Coral Triangle region for corals (Foden et al., 2013).

In summary, since AR4, new evidence has emerged highlighting the *magnitude* of risk for particular regions, for example, in relation to the potential for regional impacts on ecosystems (see Section 19.6.3.2), megadeltas (see Section 8.2.3.3; Chapter 5), and agricultural systems, which is exacerbated by the potential for changes in the monsoon systems (see WGI AR5 Sections 12.5.5, 14.2). Overall there is increased evidence that low-latitude and less developed areas generally face greater risk than higher latitude and more developed countries (Smith et al., 2009). At the same time, there has been an increase in appreciation for vulnerability (e.g., to extreme events) in developed countries, especially, localized issues of differential vulnerability in particular areas of the developed world (IPCC, 2012a, Section 2.5.1.2).

Regionally differentiated impacts on crop production have been detected and attributed to climate change with *medium* to *high confidence* (Section 18.4.1.1), and we interpret this as an early warning sign of attributable impacts on food security. For this reason, as well as for reasons of *timing* and *likelihood* and *magnitude* of these risks, we assign a yellow level of risk at recent temperatures in Figure 19-4. Based on risks to regional crop production and water resources the transition from yellow to red is assessed to occur between 1°C and 2°C above the 1986–2005 global mean temperature (*medium confidence*). Both assessments are consistent with Smith et al. (2009). Furthermore, given evidence that agronomic adaptations would be more than offset for tropical wheat and maize where increases in local temperature of more than 3°C above preindustrial occur (*limited evidence*, *medium agreement*; Chapter 7 ES; Section 7.5.1.1.1; Figure 7-4), the intensity of red increases nonlinearly toward purple in recognition of the temperature sensitivity of crop productivity and limited efficacy of agronomic adaptation above 2°C compared to 1986–2005.

19.6.3.5. Global Aggregate Impacts

The RFC pertaining to aggregate impacts includes risks that are aggregated globally into a single metric, such as monetary damages, lives affected, lives lost, or species or ecosystems lost. Estimates of the aggregate, economy-wide risks of climate change since AR4 continue to exhibit a *low level of agreement*. Studies at the sectoral level have been refined with new data and models, and have assessed new sectors.

AR4 stated with *medium confidence* that approximately 20 to 30% of the plant and animal species assessed to date are likely at increasing risk of extinction as global mean temperatures exceed a warming of 2°C to 3°C above preindustrial levels (Fischlin et al., 2007). There is *high confidence* that climate change will contribute to increased extinction risk for terrestrial, freshwater, and marine species over the coming century (Sections 4.3.2.5, 30.5; Box CC-CR). Since AR4 a substantial amount of additional work has been done, looking at many more species and using new and/or improved modeling and traits-based techniques, strengthening the evidence of increasing risk of extinction with increasing temperature (e.g., Lenoir et al., 2008; Amstrup et al., 2010; Hunter et al., 2010; Bálint et al., 2011; Pearman et al., 2011; Barnosky et al., 2012; Bellard et al., 2012; Norberg et al., 2012; Foden et al., 2013). More studies have scrutinized caveats to previous studies and assessed their role in either under- or overestimating extinction risks (e.g., Beale et al., 2008; Cressey, 2008; Randin et al., 2009; He and Hubbell, 2011; Harte and Kitzes, 2012), including the role of evolution (Norberg et al., 2012), while others have carefully examined risk considering other species traits (looking at exposure, sensitivity, and potential adaptive capacity for large numbers of species; Foden et al., 2013). Literature incorporating multiple new assessment techniques quantifying extinction risks supports the conclusion that the dependence between increasing extinction risk and temperature is *robust* (*medium confidence*), albeit varying across biota. However, there is *low agreement* on assigning specific numerical values for species at risk (Sections 19.3.2.1, 19.5.1). Since AR4 it has been found that not only endemics (which have tended to be the focus of many previous studies) but species geographically widespread are at risk (Warren et al., 2013a), implying a significant and widespread potential loss of ecosystem services (Section 4.3.2.5; Gaston and Fuller, 2008; Allesina et al., 2009; Staudinger et al., 2012), comprising a new emergent risk (Table 19-4). At a global temperature rise of 3.5°C to 4°C above preindustrial, Foden et al. (2013) estimated that 30 to 60% of the birds and amphibians and 40 to 62% of the corals studied are highly vulnerable to climate change. Taking this estimate conservatively as a maximum (i.e., assuming all species not studied are able to adapt at least as well as the groups investigated), and combining this estimate with the finding of ≥50% loss of potential range in 57% of plants and 34% of animals studied globally for a global temperature rise of 3.5°C to 4°C by the 2080s allowing for realistic dispersal rates (Warren et al., 2013a), there is *high confidence* that climate change will significantly affect biodiversity and related ecosystem services.

Much new work has focused on future projected synergistic impacts of climate change-induced increases in fire, drought, disease, and pests (Flannigan et al., 2009; Hegland et al., 2009; Koeller et al., 2009; Krawchuk et al., 2009; Garamszegi, 2011). New work has demonstrated that the expected large turnovers of more than 60% in marine species assemblages by the 2050s in response to climate change (under SRES scenarios A1B and B1), combined with shrinkage of fish body weight of 14 to 24% (SRES A2; Cheung et al., 2009, 2013), put marine ecosystem functioning at risk with negative consequences for fishing industries, coastal communities, and wildlife that are dependent on marine resources (Lam et al., 2012).

Consistent with AR4, global aggregate economic impacts from climate change are highly uncertain, with most estimates a small fraction of gross world product up until at least 2.5°C of warming above preindustrial (Section 10.9.2; Figure 10-1). Some studies suggest net benefits of climate change at 1°C of warming (Section 10.9.2; Figure 10-1). Little is known about global aggregate damages above 3°C (Sections 10.9.2, 19.5.1; Figure 10-1; Ackerman et al., 2010; Weitzman, 2010; Ackerman and Stanton, 2012; Kopp et al., 2012). Aggregate damages vary with alternative development pathways, but the relationship between development pathway and aggregate damages is not well explored. In many sectors, damages as a fraction of output are expected to be larger in low-income economies, although monetized damages are expected to be larger in high-income economies (e.g., Anthoff and Tol, 2010). Adaptation is treated differently across modeling studies (Hope, 2006; de Bruin et al., 2009; Bosello et al., 2010; Füssel, 2010; Patt et al., 2010) and affects aggregate damage estimates in ambiguous ways.

Estimates of global aggregate economic damages omit a number of factors (Yohe and Tirpak, 2008; Kopp and Mignone, 2012). While some studies of aggregate economic damages include market interactions between sectors in a computable general equilibrium framework (e.g., Bosello et al., 2012a; Roson and van der Mensbrugghe, 2012), none treat non-market interactions between impacts (Warren, 2011), such as the effects of the loss of biodiversity among pollinators and wild crops on agriculture or the effects of land conversions owing to shifts in agriculture on terrestrial ecosystems (see Sections 19.3-4). They do not include the effects of the degradation of ecosystem services by climate change (Section 19.3.2.1) and ocean acidification (Section 19.5.2), and in general assume that market services can substitute perfectly for degraded environmental services (Sterner and Persson, 2008; Weitzman, 2010; Kopp et al., 2012). The global aggregate damages associated with large-scale singular events (Section 19.6.3.6) are not well explored (Kopp and Mignone, 2012; Lenton and Ciscar, 2013).

The risk associated with global aggregate impacts is similar to that expressed in AR4 and Smith et al. (2009), as indicated in Figure 19-4, with risk based primarily on economic damages and confidence in the assessment unchanged. For aggregate economic impacts, there is *low* to *medium confidence* in attribution of climate change influence on a few sectors (Section 18.6.4; Table 18-11) so that this RFC is still shaded white at recent temperature in Figure 19-4. Risks of global aggregate impacts are moderate for additional warming between 1°C to 2°C compared to 1986–2005, reflecting impacts to both Earth's biodiversity and the overall global economy (*medium confidence*). Extensive biodiversity loss with associated loss of ecosystem goods and services results in high risks around 3°C additional warming (*high confidence*). Aggregate economic damages accelerate with increasing temperature (*limited evidence*, *high agreement*) but few quantitative estimates have been completed for additional warming around 3°C or above.

19.6.3.6. Large-Scale Singular Events: Physical, Ecological, and Social System Thresholds and Irreversible Change

Large-scale singular events (sometimes called "tipping points," or critical thresholds) are abrupt and drastic changes in physical, ecological, or social systems in response to smooth variations in driving forces (Smith et al., 2001, 2009; McNeall et al., 2011). Combined with widespread vulnerability and exposure, they pose key risks because of the potential magnitude of the consequences; the rate at which they would occur; and, depending on this rate, the limited ability of society to cope with them. Research on the societal impacts associated with such events is limited; we focus in this section on physical hazards and ecological thresholds.

Regarding singular events in physical systems, AR4 expressed *medium confidence* that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet (WAIS), would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1°C to 4°C (relative to 1990–2000), causing a contribution to sea level rise of 4 to 6 m or more (Schneider et al., 2007). Studies since AR4 are consistent with these judgments but provide a more detailed view (see WGI AR5 Chapter 13). The Greenland ice sheet (*very likely*) and the Antarctic ice sheet (*medium confidence*) contributed to the 5 m higher than present (*very high confidence*) to 10 m above present (*high confidence*) sea level rise that occurred during the Last Interglacial (WGI AR5 SPM; Kopp et al., 2009; McKay et al., 2011; Dutton and Lambeck, 2012). This period provides a partial analog for the magnitude of mid- to late-21st century warming because GMT was not more than 2°C warmer than preindustrial (*medium confidence*; WGI AR5 SPM; Section 5.3.4). However, the resulting sea level rise may have taken millennia to complete.

With regard to projection, WGI AR5 finds that "There is *high confidence* that sustained warming greater than some threshold would lead to the near-complete loss of the Greenland ice sheet over a millennium or more, causing a global mean sea level rise of up to 7 m. Current estimates indicate that the threshold is greater than about 1°C (*low confidence*) but less than about 4°C (*medium confidence*) global mean warming with respect to preindustrial" (WGI AR5 SPM). A threshold for the disintegration of WAIS remains difficult to identify due to shortcomings in various aspects of ice sheet modeling, including representation of the dynamical component of ice loss and ocean processes. For RCP8.5, projected sea level rise is 1 to more than 3 m (*medium confidence*) by 2300. Beyond 2300, "Sustained mass loss by ice sheets would cause larger sea level rise, and some part of the mass loss might be irreversible" (WGI AR5 SPM). Extreme exposure and vulnerability to the *magnitude* of sea level rise associated with loss of a significant fraction of either ice sheet is found worldwide (Nicholls and Tol, 2006) but millennial time scales for ice loss allow greater opportunities to adapt successfully than do century scales, so *timing* is a critical and highly uncertain factor in assessing the risk.

There is also additional evidence regarding singular events in other physical systems. Feedback processes in the Earth system could cause accelerated emissions of CH_4 from wetlands, permafrost, and ocean hydrates. There are large uncertainties in the size of carbon stores, the time scales of release, and the fate of the carbon once released. The probability of substantial carbon release in the form of CH_4 or CO_2 increases with warming (Archer et al., 2009; O'Connor et al., 2010). WGI AR5 finds "*low confidence* in modelling abilities to simulate transient changes in hydrate inventories, but large CH_4 release to the atmosphere during this century is *unlikely*" (WGI AR5 Section 6.4.7.3). Owing to such uncertainties, the existence of a tipping point cannot be ascertained.

AR4 stated that Arctic summer sea ice disappears almost entirely in some projections by the end of the century (WGI AR4 Section 10.3); WGI AR5 finds that a "nearly ice-free Arctic Ocean (sea ice extent less than 1×10^6 km^2 for at least 5 consecutive years) in September before mid-century is *likely* under RCP8.5 (*medium confidence*)." Furthermore, "There is little evidence in global climate models of a tipping point (or critical threshold) in the transition from a perennially ice-covered to a seasonally ice-free Arctic Ocean beyond which further sea ice loss is unstoppable and irreversible" (WGI AR5 Chapter 12 ES). Whether or not the physical process is reversible, effects of ice loss on biodiversity may not be.

Large uncertainties remain in estimating the probability of a shutdown of the AMOC. One expert elicitation finds the chance of a shutdown to be between 0 and 60% for global average warming between 2°C and 4°C, and between 5 and 95% for 4°C to 8°C of warming relative to 2000 (Zickfeld et al., 2007; Kriegler et al., 2009). AR5 judges that "It is *very unlikely* that the AMOC will undergo an abrupt transition or collapse in the 21st century for the scenarios considered. There is *low confidence* in assessing the evolution of the AMOC beyond the 21st century because of the limited number of analyses and equivocal results. However, a collapse beyond the 21st century for large sustained warming cannot be excluded" (WGI AR5 SPM).

Regarding regime shifts in ecosystems, there are "early warning signs" from detection and attribution analysis that both Arctic and warmwater coral reef systems are experiencing irreversible regime shifts (Section 18.6.4). Recent observational evidence confirms the susceptibility of the Amazon to drought and fire (Adams et al., 2009; Phillips et al., 2009), and recent improvements to models provide increased confidence in the existence of a tipping point in the Amazon from humid tropical forest to seasonal forest or grassland as the dominant ecosystem (Jones et al., 2009; Lapola et al., 2009; Malhi et al., 2009; Section 4.3.3.1; Figure 4-8; Box 4-3). In contrast, one recent study suggests that the Amazon may be less susceptible to crossing a tipping point than previously thought (Cox et al., 2013), although this is contingent on the uncertain role of CO_2 fertilization being as strong as models project. Overall, recent "multi-model estimates based on different CMIP3 climate scenarios and different dynamic global vegetation models predict a moderate risk of tropical forest reduction in South America and even lower risk for African and Asian tropical forests" (WGI AR5 Section 12.4.8.2).

Based on the weight of the above evidence, we judge that the overall risk from large-scale singular events is somewhat higher than assessed in AR4 and indicated by Smith et al. (2009). The position of the transition from white to yellow between 0°C and 1°C compared to 1986–2005 remains as before but with higher confidence due to the existence of early warning signs regarding regime shifts in Arctic and warmwater coral reef systems. The transition from yellow to red occurs over a range from 1°C to more than 3°C, consistent with Smith et al. (2009) and based primarily on the uncertainty in the warming level associated with eventual ice sheet loss. However, we assess a faster increase in risk as temperature increases between 1°C and 2°C compared to 1986–2005, largely determined by the risk arising from a very large sea level rise due to ice sheet loss as occurred during the Last Interglacial when GMT was no more than 2°C warmer than preindustrial (*medium confidence*; WGI AR5 Sections 5.3.4, 5.6.2). This assessment of risk is based primarily on the *magnitude* and *irreversibility* of such sea level rise and the widespread exposure and vulnerability to it. However, as noted, the slower the rate of rise, the more feasible becomes adaptation to reduce vulnerability and exposure. Owing to this uncertainty in *timing*, we refrain from imposing a transition to purple in Figure 19-4.

19.7. Assessment of Response Strategies to Manage Risks

The management of key and newly identified risks of climate change can include mitigation that reduces the likelihood of climate changes and physical impacts and adaptation that reduces the exposure and vulnerability of society and ecosystems to both. Key risks, impacts, and vulnerabilities to which societies and ecosystems may be subject will depend in large part on the mix of mitigation and adaptation measures undertaken, as will the evaluation of RFCs (Section 19.6.3). This section therefore assesses relationships between mitigation, adaptation, and the residual impacts that generate key risks. It also considers limits to both mitigation and adaptation responses, because understanding where these limits lie is critical to anticipating risks that may be unavoidable. Potential impacts involving thresholds for large changes in physical, ecological, and social systems (Section 19.6.3.6) are particularly important elements of key risks, and the section therefore assesses response strategies aimed at avoiding them or adapting to crossing them.

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19.7.1. Relationship between Adaptation Efforts, Mitigation Efforts, and Residual Impacts

Under any plausible scenario for mitigation and adaptation, some degree of risk from residual damages is unavoidable (*very high confidence*). Evaluating potential mixes of mitigation, adaptation, and impacts requires joint consideration of outcomes for climate change and socioeconomic development. A principal way in which these different mixes are assessed is comparing the impacts that result from scenarios with little or no mitigation (and therefore more climate change) to those with substantial mitigation (and less climate change). Climate change mitigation costs have been extensively explored (WGIII AR5 Chapter 6), but there has been less work on quantifying the impacts avoided by mitigation and, with the exception of studies of the impacts of sea level rise (Nicholls et al., 2011), treatment of adaptation has been limited and uneven. In this section, unless otherwise stated, global temperature rise is given relative to preindustrial (1850–1900) levels.

Impact studies generally indicate that mitigation can reduce a large proportion of climate change impacts that would otherwise occur (*high confidence*). In one study, mitigation that stabilizes global CO_2 concentrations at 550 ppm reduces by 80 to 95% the number of people additionally at risk of hunger (largely in Africa) in 2080 under an SRES A2 scenario with CO_2 concentrations of 800 ppm, creating an estimated benefit of US$23 to 34 billion of agricultural output compared to the un-mitigated case (Tubiello and Fischer, 2007). In Africa, there are much greater impacts on crop productivity, freshwater resources, and ecosystems at 4°C than at 2°C, with adaptation failing to reduce risk below a "high" level at 4°C ("very high" for crop productivity), whereas at 2°C risks are lower and adaptation could reduce these risks to a "medium" level (Table 22-6). In North America, with 4°C warming, adaptation is not expected to reduce risks below "high" for urban flooding (both riverine and coastal) or for fire damage in ecosystems, or below "medium" for heat-related human mortality. Without adaptation, risk is "very high" for these sectors. In contrast, at 2°C risks are at the "high" level for urban flooding and heat-related human mortality, but the risk of fire in ecosystems is still "very high." At 2°C, adaptation is expected to reduce urban flooding risk to "medium" and heat-related human mortality risk to "low" (Table 26-1). Impacts on water resources would also be reduced (Table 3-2). Fung et al. (2011) and Gosling and Arnell et al. (2013) both found that climate change-induced increases in water stress (defined as persons with <1700 or <1000 m^3 per capita per year respectively in the two studies) globally would be reduced significantly were global temperature rise to be constrained to 2°C rather than 4°C. Reducing climate change from an RCP8.5 scenario to an RCP2.6 scenario reduces the proportion of the global population that experiences >10% declines in available groundwater from 27 to 50% to 11 to 39% (Portmann et al., 2013).

Figure 19-6 highlights results from three studies that estimated the global avoided impacts for multiple sectors when global average temperature is limited to 2°C rather than following scenarios with no mitigation, such as the SRES A1B or A1FI baseline scenarios in which global average temperature reaches 4°C and 5.6°C, respectively (Arnell et al., 2013; Warren et al., 2013a,b). The studies isolate the effects of climate change by using common socioeconomic assumptions in mitigation and baseline scenarios. Overall, sector-specific impacts were reduced by 20 to 80%, with aggregate global economic damages reduced by about one-half (Warren et al., 2013b). The largest impacts avoided were for crop productivity, drought in cropland, biodiversity, exposure to coastal and pluvial flooding, and energy use for cooling, while avoided impacts were smaller for water resources stress. Because some areas become wetter and others drier (WGI AR5 Section 12.4.5), there are regions where climate change results in decreases in flood, drought, or water stress, which may be beneficial. (Note that reduced water stress is not necessarily beneficial; for example, if increased precipitation occurs in a small number of isolated heavy rainfall events, water cannot easily be stored and can cause flooding). This means that as well as avoiding a large amount of negative impacts, mitigation is projected to result in the avoidance of some benefits that are projected to result from climate change, although these avoided benefits are much smaller than the avoided impacts. There are shown as the blue bars in Figure 19-6. Avoided impacts are significantly larger when an A1FI baseline is used compared to an A1B baseline (Figure 19-6) because emissions and global temperature rise are greater in the A1FI baseline scenario. All of these studies employed an ensemble of climate change projections based on emulation of seven different Global Climate Models (GCMs). The proportion of impacts avoided at the global scale was relatively robust to uncertainties in regional climate projection, but the magnitude of avoided impacts varied considerably with climate projection uncertainty.

The timing of emissions reductions strongly affects impacts. In general fewer impacts can be avoided when mitigation is delayed (Arnell et al., 2013; Warren et al., 2013a,b; Figure 19-6b) because there are limits to how fast emissions can be reduced subsequently to compensate for the delay (Section 19.7.2). For example, if global emissions peak in 2016 and are then reduced at 5% annually, one half of global aggregate economic

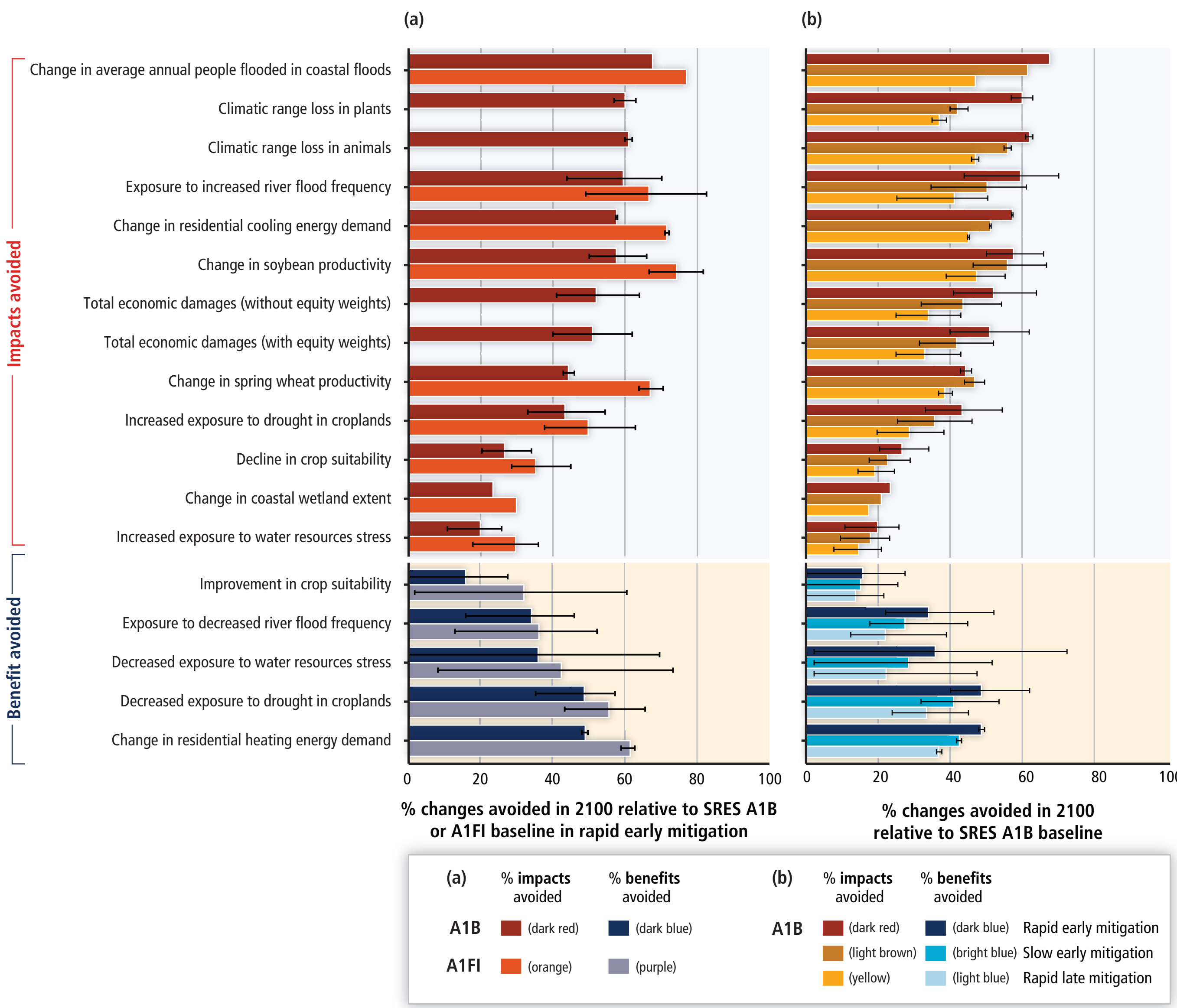

Figure 19-6 | (a) Climate change impacts avoided by an early, rapid mitigation scenario in which global emissions peak in 2016 and are reduced at 5% thereafter, compared to two no-mitigation baseline cases, Special Report on Emission Scenarios (SRES) A1B (dark red bars) and SRES A1FI (orange bars). Impacts avoided are larger if the A1FI baseline scenario is used than if the A1B baseline is used, because greenhouse gas emissions in A1FI exceed those in A1B (see Section 19.7.1). Since the literature does not provide estimates of avoided impacts relative to the A1FI baseline for all sectors considered here, some bars are absent from the panel (a). (b) The dependence of the potential to avoid climate change impacts upon the timing of emission reductions is illustrated. Climate change impacts avoided by the same early, rapid mitigation scenario compared to the no-mitigation baseline case SRES A1B (dark red bars) are shown. The information displayed is identical to the orange bars in (a), but a comparison is now made with the impacts avoided from two other less stringent mitigation scenarios. Impacts avoided if global emissions peak in 2016 but are subsequently reduced more slowly (2% annually) are lower (light brown bars compared to dark red bars). However, if mitigation occurs later, so that global emissions do not peak until 2030, even if emissions are subsequently reduced at 5% annually, the avoided impacts are smaller than in either of the other two cases (yellow bars compared to dark red and light brown bars). Both panels show the uncertainty range (error bars) due to regional climate change projected with seven global climate models. Errors due to uncertainty within impacts models are not shown. Uncertainties associated with sea level rise related impacts are not provided because the models used a single sea level rise projection. Because increases and decreases in water stress, flood risks, and crop suitability are not co-located and affect different regions, these effects are not combined. Since some areas become wetter and others drier (WGI AR5 Section 12.4.5), there are regions where climate change results in decreases in flood, drought, or water stress, which may be beneficial. This means that avoided benefits of climate change, as well as avoided impacts of climate change, are also shown here, as the shorter blue bars. Overall the avoided impacts greatly outweigh the avoided benefits (Arnell et al., 2013; Warren et al., 2013a,b).

impacts might be avoided (Figure 19-6b, orange bars), or around 43% if emissions are reduced more slowly at 2% annually (Figure 19-6b, pink bars); compared to only one-third if emissions peak in 2030 even if emissions are reduced at 5% thereafter (Warren et al., 2013b, Figure 19-6b, brown bars). This applies irrespective of whether or not equity weighting is used in the impact valuation process.

Avoided impacts vary significantly across regions as well as sectors (*high confidence*) due to (1) differing levels of regional climate change, (2) differing numbers of people and levels of resources at risk in different regions, and (3) differing sensitivities and adaptive capacities of humans, species, or ecosystems (Tubiello and Fischer, 2007; Ciscar et al., 2011; Arnell et al., 2013; Section 25.10.1). The length of time it takes for avoided impacts to accrue is determined partly by the nature of the climate system. Benefits accrue least rapidly for impacts associated with sea level rise such as coastal flooding and loss of mangroves and coastal wetlands because sea level rise responds very slowly to mitigation efforts (Meehl et al., 2012). Nevertheless, mitigation may limit 21st century impacts of increased coastal flood damage, dry land loss, and wetland loss substantially (*limited evidence*, *medium agreement*) albeit there is *little agreement* on the exact magnitude of this reduction (Section 5.4.3.1). Benefits accrue more rapidly for impacts associated with global temperature change (WGI AR5 Section 12.5.2, Figure 12.44) and those associated with reduced ocean acidification because surface pH responds relatively quickly to changes in emissions of CO_2 (FAQ 30.1).

In WGIII AR5 Chapter 6, the emission scenarios in the literature (as collected in the AR5 database) have been categorized on the basis of the 2100 radiative forcing (in a total of seven categories). Most Integrated Assessment Models (IAMs) provide information on concentration, forcing, and temperature. However, as the climate components of the IAMs differ, all scenarios were reanalyzed in the simple climate model Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC; Meinshausen et al., 2011) using its probabilistic set-up. The results of this categorization can be used to connect emission trajectories to climate outcomes (Figure 19-7a) and impacts and risks (Figure 19-7b; Table 19-4).

Mitigation scenarios in category 1 with a 2100 CO_2-eq concentration of 430 to 480 ppm result in a median projected 2100 global temperature rise of between 1.5°C and 1.7°C above preindustrial (10–90% range 1.0–2.8°C) (Figure 19-7a; WGIII AR5 Table 6.3). These scenarios correspond to a 2011–2100 cumulative emission level of around 630–1180 $GtCO_2$ (WGIII AR5 Table 6.3). Under these scenarios, based on the MAGICC calculations, warming is *likely* to stay below 2°C and *very likely* to stay below 3°C during the 21st century. This significantly reduces the key risks listed in Table 19-4, as well as others discussed in this chapter. Constraining global temperature rise to 2°C would constrain the risks associated with global aggregate impacts and large-scale singular events to the yellow or moderate level and the risks associated with the distribution of impacts, extreme weather events, and to unique and threatened systems to the lower part of the red or high level. If global

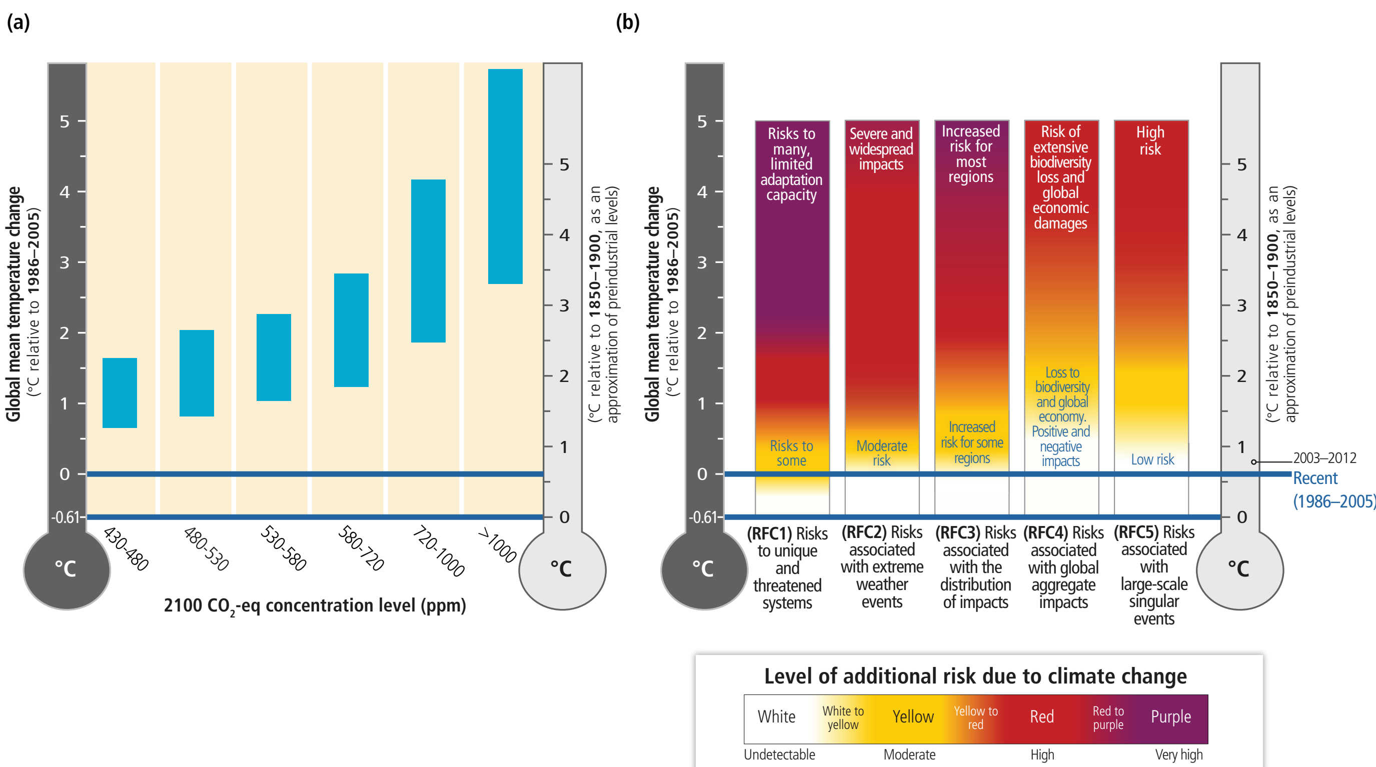

Figure 19-7 | Relationship between mitigation scenario categories considered in WGIII AR5, in terms of their CO_2-eq concentrations and global temperature rise outcomes in 2100, and level of risk associated with Reasons for Concern. (a) The projected increase in global mean temperature in 2100 compared to pre-industrial and recent (1986–2005), calculated using the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) climate model for the scenario categories defined in WGIII AR5 Chapter 6, indicating the uncertainty range resulting both from the range of emission scenario projections within each category (10–90th percentile) and the uncertainty in the climate system as represented by MAGICC (16–84th percentile) (data taken from WGIII AR5 Chapter 6). (b) Reproduction of Figure 19-4 for ease of comparison. Beyond 2100, temperature, and therefore risk, decreases in most of the lowest three scenarios and increases further in most of the others.

temperature rise were 1.5–1.7°C only, risks to unique and threatened systems and risks associated with extreme weather events would be further constrained to the transition between moderate and high risk levels. The temperature levels in the RCP2.6 scenario are 1.2°C to 2.0°C (WGI AR5 Table 12.2) matching closely the scenarios in this category.

Mitigation scenarios in category 2 with a concentration of 480 to 530 ppm CO_2-eq in 2100 correspond to a median projected 2100 global temperature rise of between 1.7°C and 2.1°C (10–90% range 1.2–3.3°C) in the MAGICC calculations. These scenarios correspond to a cumulative emission level over the 2011–2100 period on the order of 960–1550 $GtCO_2$ (WGIII AR5 Table 6.3) and are *as likely as not* to stay below 2°C, but are still *very unlikely* to rise above 3°C. Thus, scenarios in category 2 also reduce risks, but to a lesser extent than for category 1. If global temperature rise reaches 2.5°C in 2100, levels of risk due to extreme weather events are at the red or high level, while those to unique and threatened systems now reach the very high or purple level reflecting inability to adapt. Risks associated with global aggregate impacts reach the transition zone from yellow or moderate level to red or high risk, while risks associated with the distribution of impacts and large-scale singular events reach the red or high level.

Mitigation scenarios in category 3 with 530 to 580 ppm CO_2-eq in 2100 correspond to a median projected temperature rise of between 2.0°C and 2.3°C (range 1.4–3.6°C) above preindustrial levels (WGIII AR5 Table 6.3) such that it is *very unlikely* that temperature rise would stay below 1.5°C, and less probable than category 2 to remain below 2°C, affording little protection to coral reefs. In this category, risks to unique and threatened systems remain high or very high indicating inability to adapt. Risks associated with extreme weather events remain at the high level. Risks associated with the distribution of impacts, global aggregate impacts and large-scale singular events range from moderate to high.

Mitigation scenarios in category 4 with 580 to 720 ppm CO_2-eq in 2100 result in a range of possible temperature outcomes between 2.3°C and 2.9°C (10–90% range 1.5–4.5°C) above preindustrial levels, affording no protection to coral reefs. In these scenarios, it is *more likely than not* that global temperature rise would exceed 2°C (WGIII AR5 Table 6.3) so that risks to unique and threatened systems remain high or very high indicating inability to adapt. Risks associated with extreme weather events and the distribution of impacts are high. Levels of risk associated with global aggregate impacts and large-scale singular events may be moderate or high (*high confidence*). Global temperature rise in RCP4.5 in 2100 is 1.9 to 2.9°C above preindustrial levels (WGI AR5 Table 12.2), matching the low scenarios in this category.

Onset of large-scale dissolution of coral reefs is projected if CO_2 concentrations reach 560 ppm (Sections 5.4.1.6, 5.4.2.4, 19.6.3.2, 26.4.3.2; Silverman, 2009), due to the combined effects of warming and ocean acidification. However, already at 450 ppm, reef growth rates are projected to be reduced by more than 60% globally and by at least 20% globally at 380 ppm (Silverman, 2009). Coral organisms themselves are projected to be damaged by warming at concentrations below 560 ppm: specifically, even with optimistic assumptions regarding the ability of corals to rapidly adapt to thermal stress, RCP4.5 is projected to result in long-term degradation of two-thirds of coral reefs, compared with one-third of them under RCP3PD (Box CC-CR). Hence, maintenance of moderately healthy coral reefs is consistent only with scenarios in the scenarios in the 430 to 480 ppm CO_2-eq category; while some reef protection is achieved with scenarios in the category 480 to 530 ppm CO_2-eq. A low level of protection exists for the category 530 to 580 ppm CO_2-eq while all other categories exceed the 560 ppm level.

Finally, scenarios in category 6 with a concentration level of >1000 ppm CO_2-eq are projected to result in median 2100 temperature rise of 4.1°C to 4.8°C (range 2.8–7.8°C) above preindustrial with negligible chances to constrain it below 2°C above preindustrial (Figure 19-7a) and would allow significant key risks to persist in all the areas listed in Table 19-4. Risk is at the red level for all RFCs except unique and threatened systems, where risk is at the purple level indicating infeasibility of adaptation. For the distribution of impacts, risk reaches the transition to purple if temperatures rise in excess of 4°C above preindustrial levels. For the scenarios with a concentration level between 720 ppm and 1000 ppm (category 5) outcomes for risk levels are high or very high, except that risk of global aggregate impacts ranges from the transition zone from moderate risk up to high risk.

Scenarios with rapid, early mitigation (particularly those with a 2100 CO_2-eq concentration of 430 to 480 ppm) generally delay the onset of a given global annual mean temperature rise until several decades later in the century than is the case for scenarios with slower, delayed mitigation or no mitigation (such as those with a 2100 CO_2-eq concentration of 720 to 1000 ppm), thus allowing impacts to be further reduced by adaptation during this time.

19.7.2. Limits to Mitigation

Mitigation possibilities, such as those implicit in scenarios discussed in Section 19.7.1, are not unlimited. Assessment of maximum feasible mitigation (and lowest feasible emissions pathways) must account for the fact that feasibility is a subjective concept encompassing technological, economic, political, and social dimensions (Hare et al., 2010). Most mitigation studies have focused on technical feasibility, for example, demonstrating that it is possible to reduce emissions enough to have at least a 50% chance of limiting warming to less than 2°C relative to preindustrial (den Elzen and van Vuuren, 2007; Clarke et al., 2009; Edenhofer et al., 2010; Hare et al., 2010; O'Neill et al., 2010), taking into account uncertainty in climate and carbon cycle response to emissions (see WGI AR5 Section 12.5.4 for a discussion of uncertainties in the relationship between emissions and long-term climate stabilization targets). RCP2.6, based on an integrated assessment model-based mitigation scenario (van Vuuren et al., 2012), is *unlikely* to produce more than 2°C of warming relative to preindustrial (*medium confidence*; WGI AR5 Section 12.4.1.1). Such scenarios lead to pathways in which global emissions peak within the next 1 to 2 decades and decline to 50 to 85% below 2000 levels by 2050 (or 40 to 70% compared to 1990 levels), and in some cases exhibit negative emissions before the end of the century (den Elzen et al., 2007, 2010; IPCC, 2007b; van Vuuren et al. 2012). Very few integrated assessment model-based scenarios in the literature demonstrate the feasibility of limiting warming to a maximum of 1.5°C with at least 50% likelihood (Rogelj et al., 2012); most 1.5°C scenarios have been based on stylized emissions pathways (Hare et al.., 2010;

Ranger et al., 2012). The highest emission reduction rate considered in most integrated modeling studies that attempt to minimize mitigation cost is typically between 3 and 4% but with larger values not ruled out although some studies find that for an additional cost higher rates may be achievable (den Elzen et al., 2010; O'Neill et al., 2010).

However, most studies of feasibility include a number of idealized assumptions, including availability of a wide range of mitigation technologies such as carbon capture and storage (CCS) and large-scale renewable and biomass energy. Most also assume universal participation in mitigation efforts beginning immediately, economically optimal reductions (i.e., reductions are made wherever they are cheapest), and no constraints on policy implementation. Any deviation from these idealized assumptions can significantly limit feasible mitigation reductions (Knopf et al., 2010; Rogelj et al., 2012). For example, delayed participation in reductions by non-Organisation for Economic Co-operation and Development (OECD) countries made concentration limits such as not exceeding 450 ppm CO_2-eq (roughly consistent with a 50% chance of remaining below 2°C relative to preindustrial), and in some cases even 550 ppm CO_2-eq, unachievable in some models unless temporary overshoot of these targets (Izrael and Semenov, 2006) were allowed (Clarke et al., 2009), but not in others (Waldhoff and Fawcett, 2011). Technology limits, such as unavailability of CCS or limited expansion of renewables or biomass, makes stabilization at 450 ppm CO_2-eq (or 2°C with a 50% chance) unachievable in some models (Krey and Riahi, 2009; van Vliet et al., 2012). Similarly, if the political will to implement coordinated mitigation policies within or across a large number of countries were limited, peak emissions and subsequent reductions would be delayed (Webster, 2008).

These considerations have led some analysts to doubt the plausibility of limiting warming to 2°C (Anderson and Bows, 2008, 2011; Tol, 2009). "Emergency mitigation" options have also been considered that would go beyond the measures considered in most mitigation analyses (Swart and Marinova, 2010). These include drastic emissions reductions achieved through limits on energy consumption (Anderson and Bows, 2011) or geoengineering through management of the Earth's radiation budget (Section 19.5.4; WGI AR5 Chapters 6, 7).

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19.7.3. Avoiding Thresholds, Irreversible Change, and Large-Scale Singularities in the Earth System

Section 19.6.3.6 discussed the RFC related to nonlinear changes in the Earth system ("large-scale singular events"), whereby anthropogenic forcings might cause irreversible and potentially rapid transitions over a wide range of time scales (see Section 19.6.3; WGI AR5 SPM, TS, TFE.5, Section 12.5; Lenton et al., 2008). The risk of triggering such transitions generally increases with increasing anthropogenic climate forcings/climate change (Lenton et al., 2008; Kriegler et al., 2009; Levermann et al., 2012). Reducing GHG emissions is projected to reduce the risks of triggering such transitions (*medium confidence*). Adaptation could reduce their potential consequences, but the efficacy of adaptation might be limited, for example for rapid transitions (Section 19.7.5).

Several studies have sought to identify levels of atmospheric GHG concentrations or global average temperature change that would limit the risks of triggering these transitions (e.g., Keller et al., 2005, 2008; Lenton et al., 2008; Kriegler et al., 2009). Section 19.6.3.6 assesses evidence regarding the relationship between global average temperature and risks of disintegration of major ice sheets, loss of Arctic sea ice, shutdown of the AMOC, carbon releases from temperature-related feedback processes, and regime shifts in ecosystems. Additional aspects of these risks are important to mitigation strategies. For example, it is important to distinguish between triggering and experiencing a threshold response because model simulations suggest that there can be sizable delays between the two (e.g., Lenton et al., 2008). The location of these trigger points can be difficult to determine from process-based models alone, as some of these models lack potentially important processes (see e.g., WGI AR5 Chapter 13).

In this situation, expert elicitations can provide additional useful information for risk assessments. One such assessment based on expert elicitation (Lenton et al., 2008) finds that limiting global mean temperature increase to approximately 3°C above recent (1980–1999) values would considerably reduce the risks of triggering some nonlinear responses. In general, there is *low confidence* in the location of such temperature limits owing to disagreements among experts. Estimates of such temperature limits can change over time (Oppenheimer et al., 2008) and may be subject to overconfidence that can introduce a downward bias in risk estimates of low-probability events (Morgan and Henrion, 1990). The climate threshold responses can interact (e.g., Kriegler et al., 2009). Other climate change metrics (e.g., rates of changes or atmospheric CO_2 concentrations) can also be important in the consideration of response strategies aimed at reducing the risk of crossing thresholds (McAlpine et al., 2010; Lenton, 2011a).

Several analyses have performed risk- and decision-analyses for specific thresholds, mostly focusing on a persistent weakening or collapse of the AMOC (Zickfeld and Bruckner, 2008; Urban and Keller, 2010; Bahn et al., 2011; McInerney et al., 2012). Experiencing AMOC collapse has been assessed as *very unlikely* in this century and there is *low confidence* in assessing the AMOC beyond the 21st century (WGI AR5 SPM). However, owing to lags in the ocean system, the probability of triggering an eventual collapse differs from that of experiencing such an outcome (Urban and Keller, 2010). A probabilistic analysis sampling a subset of the relevant uncertainties concluded that reducing the probability of a collapse within the next few centuries to one in ten requires emissions reductions of roughly 60% relative to a business-as-usual strategy by 2050 (McInerney and Keller, 2008). Bruckner and Zickfeld (2009) show that, under their worst-case assumptions about key parameter values, emissions mitigation would need to begin within the next 2 decades to avoid reducing the overturning rate by more than 50%.

Threshold risk estimates and evaluations of risk-management strategies are sensitive to factors such as the representation of uncertainties and the decision-making frameworks used (Polasky et al., 2011; McInerney et al., 2012). Several analyses have examined how the consideration of threshold events affects response strategies. For example, the design of risk-management strategies could be informed by observation and projection systems that would provide an actionable early warning signal of an approaching threshold response. Learning about key uncertain parameters (e.g., climate sensitivity or impacts of a threshold response) can considerably affect risk-management strategies and have a sizable economic value of information (Keller et al., 2004; Lorenz et al., 2012). However, there is limited evidence about the feasibility and requirements for such systems owing to the small number of studies and their focus on highly simplified situations (Keller and McInerney, 2008; Lenton, 2011b; Lorenz et al., 2012). In some decision-analytic frameworks, knowing that a threshold has been crossed can lead to reductions in emissions mitigation and a shift of resources toward adaptation and/or geoengineering (Keller et al., 2004; Guillerminet and Tol, 2008; Swart and Marinova, 2010; Lenton, 2011b).

19.7.4. Avoiding Tipping Points in Social/Ecological Systems

Tipping points (see Glossary) in socio-ecological systems are defined as thresholds beyond which impacts increase nonlinearly to the detriment of both human and natural systems. These can be initiated rapidly, inducing a need for rapid response. For example, regime shifts have already occurred in marine food webs (Byrnes et al., 2007; Green et al., 2008; Alheit, 2009; Section 6.3.6) due to (observed) changes in sea surface temperature, changes in salinity, natural climate variability, and/or overfishing.

Because human and ecological systems are linked by the services that ecosystems provide to society (McLeod and Leslie, 2009; Lubchenco and Petes, 2010), tipping points may be crossed when either the ecosystem services are disrupted and/or social/economic networks are disrupted (Renaud et al., 2010). Climate change provides a stress that increases the risk that tipping points will be crossed, although they may be crossed due to other types of stresses even in the absence of climate change. For example, in dryland ecosystems, overgrazing has caused grassland-to-desert transitions (Pimm, 2009).

The likelihood of crossing tipping points due to climate change may be reduced by preserving ecosystem services through (1) limiting the level and rate of climate change (*medium confidence*) and/or (2) removing concomitant stresses such as overgrazing, fishing, habitat destruction, and pollution. Most literature currently focuses on strategy (2), and there is limited information about the exact levels and rates of climate change that specific coupled socioeconomic systems can withstand. Examples of strategy (2) include maintaining resilience of coral reefs and cephalopod or piscivorous seabird populations by removal of concomitant stress from fishing (Andre et al., 2010; Anthony et al., 2011; see also Sections 6.3.6, 30.6.2) or expanding protected area networks (Brodie et al., 2012). Removal of concomitant stress such as nutrient loading can reduce the chance of a regime shift (Jurgensone et al., 2011) in coral reef ecosystems (De'ath et al., 2012). Sometimes management can reverse the crossing of a tipping point, for example, by adding sediment to a submerged salt marsh (Stagg and Mendelssohn, 2010). Strategy (2) is enhanced by resilience-based management approaches in ecosystems (Walker and Salt, 2006; Lubchenco and Petes, 2010; Allen et al., 2011; Selig et al., 2012). A high level of biodiversity increases ecosystem resilience and can enable recovery after crossing a tipping point (Brierley and Kingsford, 2009; Lubchenco and Petes, 2010). Strategy (2) generally becomes ineffective once climate changes beyond an uncertain and spatially variable threshold; also successive thresholds may be crossed as stress increases (Renaud et al., 2010).

Monitoring that aims to detect a slowdown in the recovery of systems from small changes (van Nes and Scheffer, 2005) or to measure an appropriate indicator (Biggs et al., 2008) may give warning that a system is a approaching a regime shift, justifying intervention of type (2) (Guttal and Jayaprakash, 2009; Brock and Carpenter, 2010). Such indicators have been identified for the desertification process in the Mediterranean (Kéfi et al., 2007) and for landscape fire dynamics (Zinck et al., 2011; McKenzie and Kennedy, 2012).

19.7.5. Limits to Adaptation

Sections 16.2 and 16.4 provide a thorough assessment of the literature on limits to adaptation. Discussions are beginning on the nature of such limits, for example, in terms of different dimensions of the limits to adaptation, including financial or economic limits to adapt, but also social and political or cognitive limits of adaptation. Limits to adaptation (see, e.g., Adger et al., 2009) are also recognized in terms of specific geographies, for example, SIDS and their limited ability to adapt to increasing impacts of sea level rise, the limits to adaptation of urban agglomerations and urban dwellers in low-lying coastal zones (see, e.g., Birkmann et al., 2010), or in relation to loss of water supplies as a result of glacier retreat (Orlove, 2009). Overall, the concept of limits to adaptation is closely related to key vulnerabilities and key risks including those identified in Table 19-4 and Box CC-KR, because this concept helps define residual risk.

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